THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Structurally Informed Architectural Design

Proposals for a Creative Collaboration between

Architect and Structural Engineer

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Proposals for a Creative Collaboration between Architect and Structural Engineer
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Abstract

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Architectural form and its supporting structure are results of interdependent design processes that do not always develop in harmony: often major outlines of architectural form are decided before structural design is involved. This doctoral work investigates design collaborations between architects and structural engineers in which architecture and structure are designed in mutual agreement, and structural design is able to guide and inspire a creation of architectural form and space.

The research is based on case studies derived from my practices as an independent structural engineer and a teacher of structures at Sint-Lucas School of Architecture. Participatory action research is applied to design collaborations in which I work as structural engineer together with architects and groups of architecture students. In different phases of design, collaborative design meetings are staged in which changes in the collaboration process and conceptual design communication are implemented and evaluated. Each evaluated change enables an improved understanding of design collaborations, and a design of more adapted changes to implement. This cyclic process of action research leads to a development of two sets of proposals for a structurally informed architectural design process.

A first set of proposals stimulates a mutually informed design collaboration through a cyclic process of information exchange in which a conceptual design proposition is expressed as a wide range of possible design solutions by articulating its defining characteristics. This articulation of conceptual design characteristics enables the architect and the structural engineer to negotiate for common design goals.

A second part of my findings presents a proposal for a new structural language that organizes structural knowledge for architectural design. This language focuses on expressing structural logic as a defining characteristic of structural conceptual design propositions through its layers of structural order, function, dimensions and design possibilities.

These proposals for a mutually informed collaboration and a new structural language are applied and evaluated in both my practices. Inquiries show that architecture students appreciate the language to express structural behaviour, and that they relate to its underlying organization of structural knowledge. Analysing different design collaborations in both practices indicates that both sets of proposals enable structural design to guide and inspire architectural design.

Keywords: design collaboration, architect, structural engineer, architectural design, structural design, conceptual design.

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On this journey I was gladly able to rely on a sturdy and accurate compass that kept me on course: Dr Karl-Gunnar Olsson at the Department of Architecture, Chalmers, has guided and supported me as main supervisor with his sharp analysis of my work and by pointing out which course of action to undertake. I am very grateful to him for promoting my work, especially in the last phase of piloting this vessel into the harbour. I also wish to specially thank my examiner, Dr Fredrik Nilsson at the Department of Architecture, Chalmers, for his many helpful words of advice and for making this project possible at Chalmers. Thanks are also in order to my co-supervisor Guy Mouton at the Associated Faculty of Architecture, Campus Sint-Lucas, for supporting me in my endeavours and for sharing his rich experience as a practicing engineer.

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Many of the explorations I undertook required support from fellow adventurers willing to accompany me on my search. The participation and enthusiasm of several architects, engineers and students in my investigations have filled my sails with favourable winds. I am very thankful to them and especially to Karolien Vanmerhaeghe, Jo Liekens, Tom Van Mieghem, Edith Wouters, Tomas Nollet, Gerrit Verbeeck and the late Hendrik Van Liedekerke for their voluntary support and for providing their insights on my reflections.

At times the journey felt solitary, but on many occasions I was reminded that I was not traveling alone. I want to thank the colleagues, friends and family who kept me in their thoughts and supported me along the way, especially Dr Nel Janssens for her encouragement and for sharing her research experience.

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Laurens Luyten
Ghent, 2012

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1. Introduction

1.1 Collaboration example

In 2008 this dissertation began with a personal curiosity and longing to support design processes in which architectural form is created not only through architectural aspirations but through structural ones as well. Back then I was working as an independent structural engineer with fifteen years of experience on over three hundred architectural projects, and at the same time working as a teacher of building structures for architectural design with twelve years of experience. In both of these practices, I am involved as a structural designer in architectural design projects. In my view, my most valuable contribution to these projects is to design structures that enhance the quality of the architectural design project. This requires that I sufficiently understand the architectural concept – even to the point that I can further the architectural design process myself to some degree – and that I help the architect to grasp the wide variety of structural design possibilities that my conceptual design proposals entail. Calculating and dimensioning structural designs are then merely tools to structurally evaluate my design proposals and to provide for structurally sound designs.

During my doctoral research, these on-going practices are at the centre of my investigations as an important source of information. They help me understand the nature of design processes that involve interaction between architectural and structural design, and enable me to explore these processes by implementing changes to them.

One of the projects that I have been involved in during my doctoral work is a dormitory facility for youth organizations. At the start of this collaboration, the architecture firm contacted me to give them structural advice on their architectural design proposal. One of the elements of the project is a canopy roof that links a dormitory with various boxes dispersed over the site. These boxes contain bathrooms and toilets.

The architects emailed me three-dimensional computer sketches of the architectural design, together with two-dimensional plans and a request to design a structure for a canopy roof. The architecture firm explicitly asked to limit the number of columns supporting the canopy roof in order to let this roof disappear into the surrounding woods. The architects did not want this roof to be noticeable.

In this thesis, I will call such a design proposal that is externalised through pictorial and verbal descriptions a *design proposition*. It refers to the term 'proposition drawing' as defined by Bryan Lawson to describe a drawing that externalizes certain features of a design proposal in order to examine them from a distance (Lawson 2004, pp.45–49).

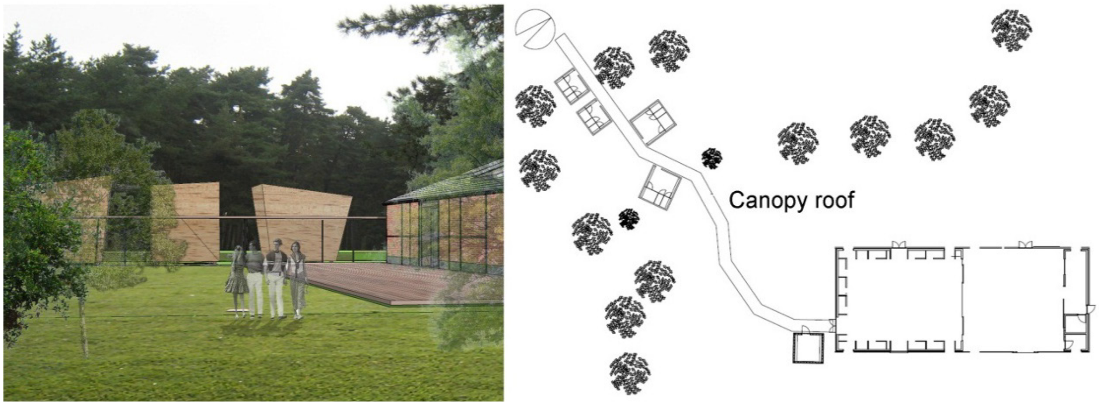


Figure 1-1. Sketch and plan of architectural conceptual design proposition.

In this example, the architectural design proposition is rudimentary and not yet detailed. There are hints of forms and materials for the boxes, but the canopy roof itself is only a floating plate with no indication of texture on the presented sketches. In these drawings the presented forms and configurations are not to be considered fixed, but rather impressions of how the design should look. I will call this kind of abstract design that is as yet neither detailed nor concrete a *conceptual design*, and when externalised a *conceptual design proposition*.

The canopy roof as presented in the architects' conceptual design has the characteristics of linking the different building blocks on the site and of disappearing in the surrounding woods. These characteristics are at the heart of the design: they bring to the fore design issues the architects find essential in answering. In this thesis I will call the sum of such abstract characteristics, which together form the architect's fundamental answer to a design question, an *architectural design concept*. Such a concept does not have to contain a designed form.

A (conceptual) design then is a possible concretisation into form and space of such a *design concept* as developed by the designer.

The design of this canopy roof will eventually result in a buildable design outcome. I will call the precisely defined and detailed outcome of a design process a *design solution*.

The proposed conceptual design of the canopy roof can, for example, result in the design of a concrete, steel or wooden roof. Thus this conceptual design proposition represents a wide range of possible design solutions.

Being an architect by education, I have some ability to understand the underlying architectural concept of a design project. This ability helps me to design structures as I find them appropriate for the presented architectural design proposition: I try to form the structure and make structural choices the way the architect would want them from an architectural perspective in his or her particular project. I might even change the architectural form – within the underlying architectural concept – if the change provides a significant benefit for my structural design. The structures I design are tailored to a specific architectural design proposition and to the specific architect involved. Both elements are important in the design choices I make as an engineer.

In this particular project, the architectural concept of letting the roof disappear into the surrounding woods takes form – among different possibilities – in the architect's request to provide a structural design that limits the number of columns. It is possible for me to develop a structure with as few columns as possible, and even to make them so slender they are hardly noticeable.

But from a structural point of view I distinguish two different types of *design conditions* to take into account: one structure for the canopy roof near one of the boxes and one for the roof where it is far from any building. These two different conditions lead me to consider two different types of structural design solution: one that can use the structure of the boxes as support and one that needs to stand independently by finding its own supports on the ground.

With the addition that the structural design also is required to have as few columns as possible, I can further refine these two different types of possible design solutions: one without columns but in cantilever from the boxes, and one with columns when standing independently. Both types of solutions are defined by identifying and answering structural design issues that I understand as essential to this particular structural design: where to find support and how to minimize the number of columns. In this thesis, I will call such an abstract answer to a structural design question a *structural concept.* It brings to the fore the essence of how a system of structural elements transfers loads to its supports.

These two different structural concepts, one with columns and one without, make the roof – from an architectural perspective – seem to be not one connecting element but two different elements. This division appears to me to contradict the *conceptual design characteristics* of the architectural proposition as I understand it.

In order to inform the architects of the different structural concepts that can be applied for the roof, I send a couple of sketches through e-mail (Figure 1-2; left image). In these sketches I try to explain the structural logic of the different concepts. But the problem seems too complex to be solved at a distance, so we set up a meeting at the architects' office.

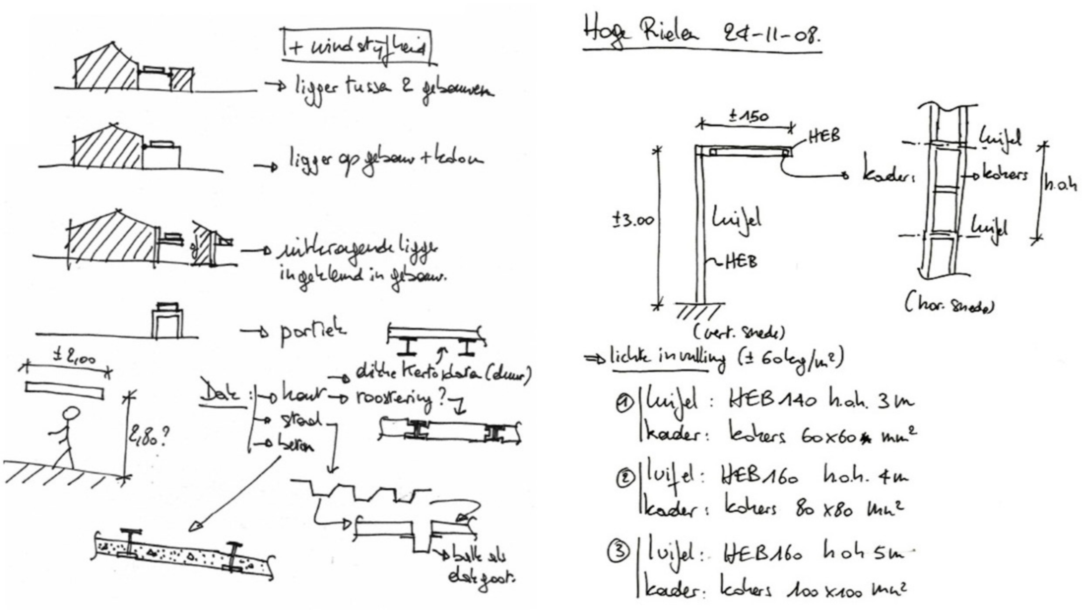


Figure 1-2. Engineer's sketches before and after the face-to-face meeting. (structural concepts; conceptual design proposition with steel dimensions)

During this face-to-face meeting, I explain several possible structural concepts to the involved architect and put forward the two mentioned above. At first the architect sees no problem in these two different structural concepts according to the position of the canopy roof. The architect explains that the essence of this canopy architecturally lies in its ability to visually connect the different objects on the site, as well as to provide protection against the rain.

Together we both go deeper into the conceptual design characteristic of trying to make this canopy disappear into the surrounding woods. It is my impression that even with the most slender columns possible, the roof will always be a visibly present object. In this discussion, both structural concepts – of a roof cantilevered from nearby boxes and of a self-supporting roof – are developed in further detail. During this design negotiation, in which essential characteristics of the conceptual designs of architect and engineer are exchanged, the architectural concept for the canopy roof shifts from being an invisible element to primarily being part of the path that connects the different boxes. This means that this path/canopy roof now becomes an independent architectural element that requires its own independent structure. This structure is thus part of the 'path' concept and has no connection with the surrounding boxes. The two initial design conditions of structural support are now reduced to a single condition that is independent of the structure's position. The architect is much in favour of this newly developed conceptual design characteristic.

For this path/canopy roof I propose a set of different structural concepts, and together we decide which main structural concept to follow. I explain the *structural logic* of this concept to the architect by expressing the *structural order* of the different structural elements, how each element *functions* and the implication for the *dimensions* of each. It is decided that I will later submit a range of *design possibilities* by providing a variety of cross-sections in steel for the different elements of a more specific conceptual design proposition that follows this agreed structural concept.

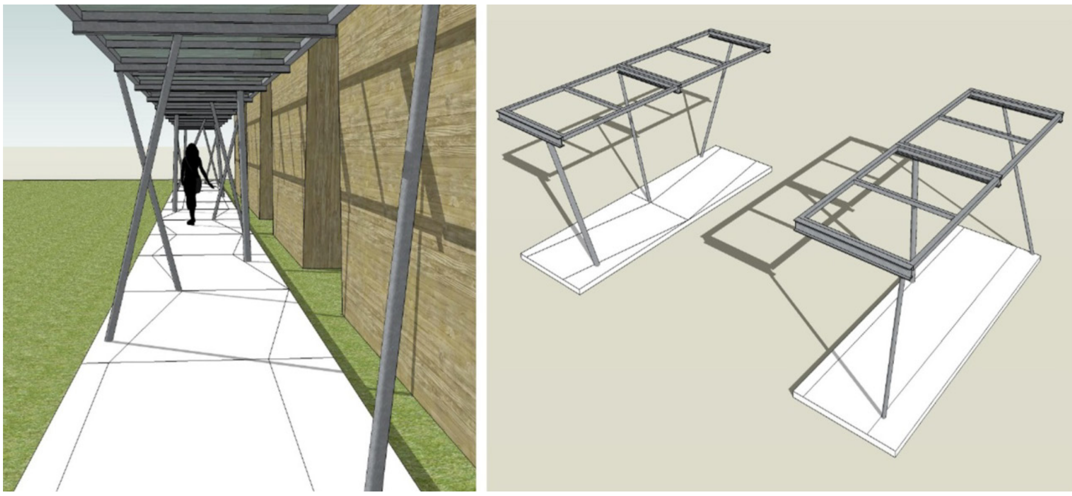


Figure 1-3. Final architectural design of the canopy roof.

After reviewing some possible steel dimensions for this particular conceptual design proposition (Figure 1-2; right image), the architect designs a new, final canopy roof. It is free-standing and it contains a multitude of (clearly visible) columns. This multitude of columns seems contradictory to the initial request of relying on as few as possible. But now the columns act as trunks in a grove of trees, making the canopy roof still 'disappear in the surrounding woods'. The initial underlying architectural concept is maintained, but with a different architectural concretisation and structural implication.

Based upon the architect's understanding of the structural logic of my conceptual design proposition, she modifies the form of the structural design object as I have presented it to her. To improve the quality of her architectural design, she changes the position of the different columns of my structural design to make them look like organically crisscrossed trunks (Figure 1-3). She makes these changes according to the structural logic of my proposition. This means that her newly developed structural design maintains the initial conceptual design characteristics of my proposition and is hereby still structurally sound. So it poses for me no problem to finalise my structural design according to the architect's adjustments.

This example of a structurally informed architectural design, shows the importance of face-to-face communication for a cyclic process of information exchange. Here, designers communicate architectural and structural conceptual design propositions – rather than single design solutions – by articulating their defining design characteristics and by managing to grasp the wide range of design solutions entailed by each of the other designer's various propositions. This understanding enables each to further develop the other's design proposition within the proposed conceptual design characteristics to the benefit of his or her own design. Common goals for architectural and structural design are established through a design negotiation between the two designers for a congruent set of conceptual design characteristics of both designs.

During interpersonal communication, structural conceptual design propositions are presented and understood through their structural logic by expressing the structural order of each proposition and the function of its elements – together with the implications of these functions on its dimensions – and by providing for each element different structural design possibilities. This organization of structural knowledge enables the architect to gradually deploy the provided structural input to the benefit of her own design process.

1.2 Research aims

This collaboration project stands in contrast to many other projects in which the architect expects me to design a structure that will not affect the architectural form initially presented to me. In these cases structural form is supposed to merge into, for example, the walls and floors of the presented architectural volume. Sometimes this kind of collaboration leads to a negotiation process in which architects accept an additional visible structural element in the architectural form, but this is not a design process by which general architectural form is developed through structural guidance.

It seems that architects often design the form of their projects with limited structural guidance. For example, engineers of the renowned structural design firm Arup feel that nine out of ten of their projects do not require 'engineering' but just 'responding': the architects have already decided the main design issues and the engineers are relegated to 'designing to specifications' (Salter

& Gann 2003). According to Glenn Ballard and Lauri Koskela, the traditional method of design collaboration between architect and engineer in the construction industry is sequential rather than concurrent (Ballard & Koskela 1998).

A collaboration in which structure is designed after the architectural form has already been decided is typical not only in the professional world but also in the educational world of design studios. Structural engineer Laurent Ney states that architectural education is devoted to learning about research on form, but that form usually is conceived before considering structure (Strauven & Ney 2005).

In projects in which the architectural form is fixed and the structure still needs to be designed, it can be creatively challenging to design a structure that does not affect the intended architectural form while achieving a high efficiency of material use or cost. Such collaborations do not take advantage of the opportunity to bundle together the creative design capabilities of architect and structural engineer to form a synergetic team that delivers more than the two designers apart in a sequential process. And as the two designs are closely intertwined, it is hard to believe the structural and architectural qualities of these sequential design outcomes are not affected by neglecting structural design considerations during the development of the architectural form.

So why don't the architect and the structural engineer not bundle together their creative design capabilities in these projects? Are they too different to work together as a design team? Are their design paradigms too divergent to get their design process in tune for collaboration? Is it too hard for an architect to grasp the essence of a structural conceptual design in order to understand the engineer's contribution to architectural design? And vice versa: are engineers unable to understand an architectural conceptual design well enough to provide adequate structural information for a design collaboration?

In the architectural project presented above, the final architectural and structural design of the canopy roof is the result of two designers, expert in different disciplines, each informing the other of their own conceptual design process in order to make mutually approved design decisions that affect both their designs. This design procedure leads to a design solution that neither of the involved designers would have come up with on their own. This creative process involves an almost simultaneous implementation of both areas of expertise: for example, the architect further develops the structural design by positioning the columns according to structural logic, and the engineer engages in an architectural investigation of the conceptual role of the canopy roof as a connecting element. This enables a design creativity that transcends the single disciplinary design paradigm and operates simultaneously in both paradigms. As I have not come across an appropriate definition for such creativity in the literature on design collaboration between different disciplines (Fruchter et al. 1996; Chen & Lewis 1999; Lewis & Mistree 1997; Lottaz et al. 2000; Zeiler & Quanjel 2007), I define such creativity in this thesis as *multi-disciplinary creativity.*

A sequential design procedure in which a finished architectural form is developed first, followed by the design of a structure for this form, does not provide for such *multi-disciplinary creativity* between both designers. In that case, design creativity operates only within one discipline at the time. For this thesis I therefore define such creativity as *mono-disciplinary creativity*.

In order to instigate multi-disciplinary creativity, the following questions arise: what is required to allow such creativity to take place? Are the best results achieved by supporting architects to conceptually design architecture and structure on their own, or by enabling a conceptual design collaboration between architect and structural engineer? And if the latter is the case, what knowledge of the other discipline do does each need to acquire? What kind of verbal and/or pictorial language is required to enable an adequate communication of conceptual designs to sufficiently inform this kind of creative collaboration? Could providing certain collaboration proposals stimulate multi-disciplinary creativity between architects and structural engineers?

In both my practices, these moments of multi-disciplinary creativity have occurred during collaboration with architects or architecture students, but they are more the exception than the rule. As a rule the task is to find creative structural solutions for an architectural form already designed by an architect or architecture student. In those cases I regret that architectural decisions are sometimes taken almost arbitrarily to enable a further development of the architectural design process, while these decisions have unfavourable structural repercussions. An architect who is well informed of these structural repercussions is in my opinion surely capable of making design decisions that will favour both architectural as structural design. But to enable this, an architect needs to be structurally informed in the first place when designing architectural form. This information needs to be acquired early in the architectural design process, when form is being created.

The general underlying purpose of my doctoral research is to find supportive ways for structural design to guide and inform architectural design processes so that multi-disciplinary creativity as I have experienced it can take place. Throughout my research this general purpose, linked to my collaboration experiences, has guided and helped me to identify and develop my principle research aims.

To support architects in developing structurally sound designs, Heino Engel developed a book full of different conceptual structural design propositions as an inspiration for architects when designing architectural form (Engel & Rapson 1967). This approach to improving the structural design ability of architects was a primary focus at the start of my research. My aim was to reorganize structural knowledge to make it accessible to architects working independently with software tools during their design process. Explorative investigations showed me the important role of the creative design ability of the structural engineer in structural design that software cannot replace. This has refocused my research on the creative collaboration between architects and structural engineers, and more specifically on the process by which they collaborate and exchange information about structural conceptual design propositions. This has led to two main principle research aims.

The first research aim is to understand general characteristics and mechanisms of the collaboration and communication processes when architects and structural engineers design with multi-disciplinary creativity, and through this understanding to develop proposals to enable such design collaborations.

In the above example, the architect and the structural engineer inform each other of their design process through a communication of conceptual design characteristics. Each designer takes into account information obtained from the other before further developing his or her own design. This cyclic information exchange even leads to a negotiation of architectural and structural conceptual design characteristics towards congruence, and allows for new directions in conceptual design. A more conceptual understanding of the other designer's design proposition enables each one to adjust this proposition to his or her own design preferences without creating a collaboration conflict (as when the architect adjusted the columns of the structural proposition). This research aim leads to a set of collaboration and communication proposals for a *mutually informed design process* between architect and structural engineer.

The second research aim is to develop design tools that would enable architects to be sufficiently and adequately informed of the structural engineer's design proposition during their early collaboration.

In the above example the architect was not able to grasp the structural essence of the various design propositions I presented by e-mail, prior to our face-to-face meeting. The information provided was too dense and required too much specific structural engineering knowledge to understand. Our meeting allowed the structural information to be better tailored to an architectural understanding, enabling the architect not only to correctly alter the presented structural design object but also to choose appropriate structural profiles. This research aim leads to the development of a proposal for a new structural language that communicates – in the architect's own field of expertise – the wide range of structural design possibilities that follow from an engineer's conceptual design proposition. The basis for this language lies in a reorganization of structural knowledge for architectural design.

1.3 Research limitations and extrapolations

The cases used in this research are set in the context of a Belgian architect and structural engineer working together. Compared to other countries, here the architect – as natural or legal person – is responsible by law (Articles 1792 and 2270 of the Belgian Civil Law) for all aspects of an architectural design, including its structure, for a period of ten years after the building has been completed. Although a structural engineer is not required by law to be involved in an architectural design project, important aspects of the architect's responsibility for the structural design can be transferred to a structural engineer: in such case the engineer can limit the scale of his or her own ten-years-responsibilities by contract. Still, even if a design collaboration with a structural engineer is established, the architect will always retain certain structural responsibilities pertaining to a general structural understanding. This Belgian condition applies not only to the cases investigated here, taken from my professional practice in which an architect and a structural engineer work together, but also to those cases from my educational practice in which architecture students are trained for professional practice in Belgium.

This Belgian condition has only a limited influence on the generality of my research findings. The nature of the designers' interdependency and of the professional responsibilities on which their collaboration is based are assumed to be similar worldwide. However, since the Belgian condition requires that the responsibility of the structural engineer be actively initiated and determined, it will also influence the extent of the design collaboration between architect and structural engineer.

All the case studies are drawn from my own practice, where I work as a structural engineer. Although different architects and architecture students are involved, each collaboration is influenced by my personal approach to structural and architectural design. The proposals developed are tailored to my understanding of design collaborations from the viewpoint of a structural engineer and to my personal abilities as a structural and architectural designer.

Various findings in this research show that architects and students benefit from the proposals when they collaborate with me as structural engineer.

But it is likely that with another structural engineer equally able to comprehend architectural concepts and to communicate structural answers as conceptual designs instead of solutions, the application of these proposals will lead to different results.

The proposals are developed to promote a mutually informed design collaboration and a language for communicating structural conceptual designs. They are certainly influenced by the environment in which they have been developed, but they are applied and developed in different design contexts through the method of participatory action research, and backed up through analytical argumentations of case study theory, in order to extract their general features.

The collaboration between architect and structural engineer is a socio-cultural activity. It depends on interpersonal relations, on cultural background and habits, on their working environment and on other elements important in such a complex collaboration setting (Cross & Clayburn Cross 1995; Zolin et al. 2004).

Although my research does not focus on improving socio-cultural settings for design collaboration, the findings take into account various socio-cultural dynamics of the case studies in which the collaboration settings involve architects and engineers who are generally willing and able to work together without important external hindrances. The particular setting of each case has an impact on the findings, but through an articulation of these socio-cultural dynamics, premises are presented for applying the findings to a variety of different collaboration settings.

This research focuses on the collaboration between architect and structural engineer. This is a design collaboration between different professions. Certain research findings are not related to the specific professions involved, but address multi-disciplinary aspects of design collaboration generally. These findings also find value in design collaborations between professions other than the ones investigated, such as between architect and mechanical or acoustical engineer, between different types of engineers, and even in other creative collaborations outside architectural projects.

The cases investigated involve collaborations that start early in the design process and involve conceptual design negotiations. Various research results that address these conceptual design negotiations are applicable not only in the early phase of a design process, but also in later phases that involve a discourse on the more conceptual level of design propositions.

My research studies design projects of a rather small scale. Compared to large-scale projects, they are limited in the number and complexity of design issues at stake, and in the number of different designers involved. Although the research presented does not bring to the fore certain characteristics specific to large-scale projects, the findings address similar characteristics and mechanisms of conceptual design negotiation in both types of projects where designers take into account design aims and limitations of other designers in their own design process.

1.4 Research approach and thesis format

My investigations lead to an articulation of various phenomena observed in design collaborations between architects and structural engineers through a study of (1) their design professions, (2) collaboration and (3) communication. In order to comprehend both (1) design professions, I develop a referential background on the schism of their professional skills throughout history and on their design processes and cultures. This background is extended with explorations of (2) design collaboration that address its multi-disciplinary character, and of (3) design communication in the field of architecture, engineering, and construction.

Based on this background, on my professional experience, and on informal inquiries with various designers, schemes are developed that describe different characteristics and mechanisms of architects' and engineers' (1) design processes, (2) collaboration and (3) communication.

In this doctoral work I have chosen to investigate design collaborations between architects and structural engineers through participatory action research in my own professional practices. I staged several design workshops in different phases of design collaboration in which I worked together with architects and architecture students. In these workshops, changes in the collaboration process and in conceptual design communication were proposed, implemented and evaluated. Each change enabled an improved understanding of design collaborations, which in turn allowed me to develop a more adapted change for implementation. This cyclic process of planning a change, acting, observing, reflecting and replanning, led to the development of proposals that support a structurally informed architectural design process.

This study investigates each case through the principles of research design and data collection of case study theory (Yin 2003), in which a distinction is made between exploratory and explanatory research. Various techniques are applied to retrieve data from these cases: interviews of participants, questionnaires, group discussions, transcription and analysis of workshops, note keeping, and analysis of students' design reports and outcomes. At the start of my doctoral work, most of my design workshops were held early in the design process to discover and explore the various mechanisms involved in the communication and collaboration between architect and structural engineer. This improved understanding of design collaboration leads to a proposal for a new language to express structural conceptual design, and to a set of proposals for a collaboration process that supports a mutually informed collaboration. These proposals are implemented and evaluated in more explanatory research cases to provide analytical argumentations for a generalization of the research findings. These cases involve exercises for architecture students to learn and use the proposed language, and design workshops in which various proposals for language and collaboration processes are implemented in an architectural design studio.

One of the first case studies in this thesis involves an architectural design studio (Research Seminar 2009) in which I collaborated as a structural engineer with different groups of architecture students starting from the early phase of design. In this studio, I held several design workshops in which I implemented a first proposal for a new structural language, giving attention to the communication of architectural and structural design propositions.

From my engineering practice, the 'Jo & Karolien' project is used as a case study to investigate the defining characteristics of the architect's conceptual design proposition, to evaluate the value of these characteristics during design negotiation, and to implement a technique for paraphrasing in design communication. This case involves a design workshop between the architects and myself as the structural engineer, and further instances of more distant communication.

In the 'Tomas' project, I used a design workshop between an experienced architect and myself as the consulting structural engineer to apply a more elaborate proposal for a new structural language and to implement a technique for paraphrasing together with an articulation of conceptual design characteristics during this conceptual design collaboration.

As the proposal for a new structural language became more refined, I held a more elaborate seminar (Structural Seminar 2010) to evaluate the ability and appreciation of (interior) architecture students to learn this language, and to read and write a structural story with this language. Similar tests were arranged with architecture students in Research Seminar 2010, in which their appreciation for the language was evaluated through a more direct and personal contact.

As part of the same Research Seminar 2010, I held an architectural design studio (with architecture students, myself as structural engineer and an extra architectural design consultant) to implement and evaluate the use of the proposed structural language and of various collaboration proposals in design workshops beginning in the early stages of the design process.

My doctoral work is described in three parts: 'Research Design', 'Research Findings through Case Studies' and 'Research Conclusions'. In the first part, I present a referential background for architects' and structural engineers' design professions, their collaboration, and their communication (**Chapter 2**). In the following chapter (**Chapter 3**) this background is further developed on the level of design process, communication and collaboration, and leads to a set of proposals for design collaboration. This part concludes with a presentation of the applied research approach that finds its basis in participatory action research and case study theory (**Chapter 4**).

The middle part of this thesis describes the case studies. **Chapter 5** gives an overview of preliminary case studies that gave a general direction for this research. **Chapter 6** presents the different cases used for explorative research into design collaborations. These cases lead to the development of a proposal for a new structural language that is presented and argued for in **Chapter 7**. Through explanatory research, this language and certain collaboration proposals to support mutually informed design are then applied and analysed in the final cases of this thesis (**Chapter 8**).

In the final part, findings on mutually informed design processes are summarised and various collaboration proposals are presented (**Chapter 9**). In **Chapter 10** the proposals for a new structural language are described, and possible applications for this language are listed. The last chapter (**Chapter 11**) proposes a variety of possible investigations that would build on this thesis.

Research design

2. Referential background

This chapter presents a referential background for the professions of architect and structural engineer in their creative endeavours as designers. It describes various characteristics of the design processes, cultures, collaboration and communication of both professions with a focus on the conceptual phase of their design work.

The background presented here provides for an articulated understanding of differences and similarities between architect and structural engineer as designers. It brings to the fore intellectual mechanisms involved in a development of design propositions and the role design concepts play in that development. I present various characteristics of design vocabulary and grammar that both kinds of designers apply in creating their designs. The chapter further helps to understand fundamental aspects of design communication and collaboration processes in multi-disciplinary design teams.

I present a literature review of the professional history of architects and structural engineers, on the theory of design methodology, multi-disciplinary design optimization, and communication. This study is corroborated by various descriptions of design practices of architects and structural engineers.

In order to make this text more readable, the terms ‘architect’ and ‘engineer’ will be used to represent individuals as well as teams of designers responsible for a design from concept to execution.

First, a description of the design professions of architects and structural engineers starts here in their history by explaining how both professions came into being and led to a difference in design skills. Later I sketch out a description of both current professional design cultures and provide some background on their design processes. This chapter concludes with aspects of their design collaboration and communication.

2.1 Architect and structural engineer: a schism of skills over time

According to Bill Addis, the words ‘engineer’ and ‘architect’ are anachronism for anyone active before about 1450 (Addis 2007, p.8).

The word ‘architect’ is derived from the ancient Greek word ἀρχιτέκτων (*architekton)*. This can best be translated as ‘master builder’ or ‘construction manager’, which does not correspond to the current definition of architect.

According to Andrew Saint the term ‘architect’ was familiar from Vitrivius. In mediaeval times it referred sometimes to technicians, sometimes to patrons or clients as the moving force behind a project. Around the same time the term 'ingeniator' was used for an expert adept at machinery for water management or warfare (Saint 2007, p.485).

In the late middle ages, people involved in the technical coordination and design of western buildings were deeply versed in masonry and carpentry: these 'master builders' were experienced craftsmen, but could not provide an 'objective rationale by which one (structural) opinion could be demonstrated to have more weight than another' (Addis 2007, p.109).

Saint states that during the Renaissance the distinction between architect and engineer was not a matter of skills but of the types of design undertaken. An architect designed secular or religious buildings, while an engineer would design forts, walls, towns, ports, canals or machinery for warfare.

This difference in job description led to different training and talent development between architects and engineers, but few of them specialized in either profession and most practiced in both (Saint 2007, p.486). For example, Brunelleschi was an engineer and an architect with the background of a goldsmith. (Most architects and designers at that time had a craftsman's background). As a military engineer he worked on the fortifications of Pistoia and Malmantile, and as an architect he designed the churches of Santa Croce, San Lorenzo and Santo Spirito in Florence. He also invented various machines for construction. Brunelleschi is of course well known today as the designer of the dome of Santa Maria del Fiore (the Duomo) in Florence, which is even more a masterpiece of construction than of structure (Addis 2007, pp.119–126).

According to Addis, the essence of engineering design is the ability to plan, before the start of the construction, how a building is to be built and how it will work structurally (Addis 2007, p.8). This requires a means to communicate the designer's imagined creation to the constructors of the building. This communication is key not only in the building process, but also in the education and development of the design profession. That which cannot be conveyed is destined to remain in the mind of the designer. In engineering design, this resulted in the emergence of technical drawing as a means to communicate with other building professionals, but also as a design tool for the engineer.

During the Renaissance, book printing technology enabled architecture to present itself as an independent discipline because of its developed ability to communicate through representational illustrations. This brought architecture to the fore as a matter of style based largely upon the appearance of facades and ornamental detailing. These books of architecture underemphasised the role of the engineer and the craftsmen in the creation of the building. The technical expertise needed to execute these buildings could not yet be communicated on paper, and had to be learned in practice. According to Addis, Palladio's *I Quatro Libri dell' Architettura* demonstrates this final stage of separation between the role of architect and engineer: in this work the author – though he was originally a mason – pays little attention to the genius of engineering skills, focusing much more on the volumetric and aesthetic qualities of the buildings' architecture (Addis 2007, pp.145–150).

According to Saint, this separation between the architecture and engineering professions was institutionalised during the eighteenth century in France in the Corps du Génie, whose engineers took charge of war and infrastructure, and the Bâtiments du Roi, whose architects housed the king and helped to articulate his magnificence. This separation was then determined by the hierarchy to which they belonged and by the tasks they executed rather than by the building technologies or design skills they deployed (Saint 2007, p.486).

In the eighteenth century, engineers were still educated in mostly empirical, practical knowledge gained through observation and generalization. Although an important body of structural, scientific theory was already developed by the eighteenth century (e.g. by Simon Stevin, Bernardino Baldi, Galileo Galilei, Robert Hooke, Johann and Jakob Bernouilli, Isaac Newton, Leonhard Euler and Charles Augustin Coulomb), it had not reached the practice of construction: builders saw no need to apply structural theory, they thought to do well without it (Addis 2007).

It wasn't until the nineteenth century that structural theory became part of practice due to the educational system of polytechnic schools (e.g. Ecole des Ponts et Chaussées and Ecole Polytechnique in France) and appropriate textbooks, due to the influence of the building industry, and due to the introduction of new materials like iron. The economics of the building industry drove engineers toward precise calculation skills in order to optimize building profits for these new materials with a sufficient level of safety. This led to a division between architect and engineer that had less to do with career structures and tasks and more with skills. The engineer became an expert in calculating structures with these new materials. And in this industrial era of efficiently dividing labour, there was no need for the expert to develop another type of expertise to maintain an income, as had been the case previously when engineers at times worked as architects. Now there was ample work for the engineer's calculating ability (Saint 2007, pp.487–489).

William Rankine divides mechanical knowledge into three types: a purely scientific knowledge, purely practical knowledge, and an intermediate type that relates to the application of scientific principles to practical purposes.

And thus Rankine describes a more current interpretation of engineering design:

> The study of scientific principles with a view to their practical application is a distinct art, requiring methods of its own...This kind of knowledge (intermediate between purely scientific and purely practical)... enables its possessor to plan a structure or machine for a given purpose without the necessity of copying some existing example - to compute the theoretical limit of strength and stability of a structure, or the efficiency of a machine of a particular kind - to ascertain by how far an actual structure or machine fails to attain that limit, and to discover the cause and the remedy of such shortcoming - to determine to what extent, in laying down principles for practical use, it is advantageous, for the sake of simplicity, to deviate from the exactness required by pure science; and to judge how far an existing practical rule is founded on reason, how far on mere custom, and how far on error. (Rankine 1855, pp.201–202 cited in Addis 2007, pp.316–317)

According to Saint, this focus on technological knowledge in the engineering profession has led to today's more pronounced mathematical-scientific or rational strain in engineering skills, which has made it distinct from architectural design skills.

Next to this division in skills, a difference between architect and engineer can still be made on the type of objects they design, as was the case in previous eras: architects are seldom authors of infrastructural work, and engineers are little involved in domestic projects. This would seem to indicate that little has changed over time in the core business of architect and engineer.

Before the Enlightenment, it was not uncommon for one person to take up the profession of architect as well as of engineer because the skills involved were so similar. In general an architect or engineer was capable of designing a project on his or her own: they were not dependent of each other's help. But starting from the end of the nineteenth century, the separation in design skills forced architects and engineers to work together as separate individuals on the same architecture projects, with each designer contributing through his or her distinct professional expertise. Today the engineer plays the role of consultant to the architect. Because architects have not been trained in these engineering calculations, they rely on support from consulting engineers. These consulting engineers first came into existence through the construction industry, whose builders needed engineers to design economically feasible products. But in the second half of the twentieth century, those consulting engineers became independent or worked within interdisciplinary firms of architects and engineers (Saint 2007, pp.489–493).

This separation in professional skills, and the need to involve both kinds of expertise in an architecture project, has put architects and engineers in a more dialectic position in which opposite opinions sometimes need to be reconciled. Ove Arup described the relation between architect and engineer as marital, able to be harmonious but also conflicting (Saint 2007, p.493). And thus developing a qualitative architectural project is not only a matter of the design skill of the architect and the structural engineer, but also a matter of their ability to collaborate.

2.2 Design culture

Architectural design culture

According to Simon Unwin, it is fair to say that the issues of the definition and purpose of architecture have never been settled. In his book *Analysing Architecture*, he defines the architecture of a building, a group of buildings, a city, or a garden as its conceptual organization, its intellectual structure. It is the ‘identification of place’ as an idea that he considers to be the generative core of architecture (Unwin 1997, pp.14–15).

Iain Borden provides for a particular understanding of what an architect-designer is and what architecture provides. ‘Every time we consider a building in a different way, move through space in a new trajectory, remember a place in relation to some long-forgotten memory trace – that is being an architect.’ This is a different type of architect than the architect as designer and coordinator of a construction project. ‘These “other” architects might perhaps be better thought of as architectural reproducers – those who experience architecture according to their own lives, interests and activities, and who consequently reproduce it to their own measure’ (Borden 2003, p.105).

Architecture can address a wide variety of issues. According to Francis Ching, architecture is designed and built in response to an existing set of conditions that may be purely functional in nature, or reflect social, economic, political, symbolic or even whimsical intentions. This existing set of conditions is considered less than satisfactory and a new set is desired (Ching 2007, p.10). Designing architecture is then the process of planning and creating such a new set of conditions.

The role an architect performs in a design process that leads to a built project is described by architects Jan Benthem and Mels Crouwel as followed:

> the architect is a generalist conducting a team that transforms ideas, dreams, or demands into real and useful hardware. Architecture is an applied art. …. He (the architect) is the one who oversees the whole spectrum of activity, while the other dream members are only responsible for parts. (Borden 2003, p.88)

Architect Tadao Ando finds it essential for an architect to maintain an overview of the different design issues at stake and to guide the design process. ‘However precise computer analysis may be, and whatever expanded expressive possibilities the computer offers, the architect is someone who must always think in a comprehensive way and make decisions' (Ando 2003, p.67).

Architect Ben Van Berkel of UN Studio even sees a shift in the role an architect is to perform. He believes that an architect is no longer a masterbuilder, but sees his or her role as a public scientist whose endeavours lie in the management of knowledge:

> With UN Studio, we have learnt to see projects as public constructions and have organized ourselves as a flexible platform organization, in which the architect, as the coordinating and networking expert of the public realm, has replaced the Baumeister. (Van Berkel & Bos 2006, pp.60–61)

As with Van Berkel, architect Rem Koolhaas is part of a team of architectural designers in a design project. Here an architectural design process is a result of individual contributions of the different actors involved. Koolhaas describes his designer’s role in the projects of the Office of Metropolitan Architecture (OMA): ‘It is not me, but made by OMA’ (Yaneva 2009a, p.11).

When it comes to designing an architectural form to be built, different architects have different approaches in design. Van Berkel, for example, likes to mix different kinds of designers in a team and puts emphasis on a network of clients, investors, management experts, specialists, structural engineers, designers and stylists for design reviews. He believes in the importance of communication in a design process and consciously focuses his communication with the design team by expressing his visions of potential design schemes verbally rather than through drawings (Krasny 2008).

Architect Renzo Piano believes that good architecture is the result of teamwork with professionals other than architects as genuine actors in design and not merely advisors. Here architectural creativity is confronted with humanistic, scientific and organizational creativity, which he considers all components of architecture. These different actors of various professions, with their diverse building knowledge and craft experience, are brought together in building workshops with a common goal to realize a built project. There is no hierarchy among these actors when working together (Lorente & Sudjic 2003).

In Renzo Piano's office a lot of importance for design is given to the making of physical models. The same is true of OMA, where models are used on two different scales to deal with design on a more abstract level and at the same time in greater detail. These physical models are used to express design ideas within a design team context (Yaneva 2009a, p.42). At OMA computers are used only in a later stage of the process for production and representational work, and are not an important tool during the creative or innovative part of the design process (Yaneva 2009a, pp.37–38).

The same importance of physical models can also be found with architect Frank Gehry, who has a preference for paper models: 'Models are Gehry's preferred design tools on every job, and only when he feels he has resolved all the key questions does he bring in the computer experts to scan the models and produce working drawings' (Webb 2003, p.117).

But not all architects leave out computers during their creative design process. Architect Norman Foster, for example, finds a lot of benefit in parametric design, which enables a wide design search: 'New computer technology offers architects more freedom in terms of time and creativity than they had before' (Glancey et al. 2001, p.35). Van Berkel, however, sees pitfalls in this power of parametric design, as it can easily disguise crucial design decisions when choosing parameters that will determine the possibilities of the design outcome (Van Berkel & Bos 2006).

Architectural design is a very complex process, according to architect Wiel Arets: 'designing a building requires to do research, to develop your own ideas, develop your concept, be part of the larger debates, find out about what is going on in the world, design a budget' (Borden 2003, p.28).

Brian Lawson states that designing in the architectural, engineering and construction industry requires technical knowledge and expertise as well as (visual) imagination and creative abilities. This design is a mixture that deals with precise and vague ideas, requires systematic and chaotic thinking, and needs both imaginative thought and mechanical calculation (Lawson 2005, p.4).

Albena Yaneva describes an architectural design process as 'no gradual progression to reality, no realization of a previously conceived plan, but vertiginous hesitation, tentative moves, mistakes, miscalculated gestures, fundamental meandering' (Yaneva 2009b, p.6).

Henry Achten (Achten 2008) states that research in architectural design practices indicates that this design is less of a rational problem solving process as described by Herbert Simon (Simon 1996) but rather follows characteristics of a reflective practice as described by Donald Schön (Schön 1983, cf. Chapter 2.3).

In architectural design culture much attention is given to the design concept (cf. *architectural design concept* in Chapter 1.1). According to Yaneva, 'architects call a "concept" the main idea of the building, taken in its relationships with the client demand, the city, the urban fabric, and the broader social, political and cultural context' (Yaneva 2005, p.891).

Architects have a long tradition of developing design concepts. Many important design competitions – both past and present – have required participants to present only design concepts and not elaborated design propositions (cf. *design proposition* in Chapter 1.1). The importance of these competitions has found its way into the design studio of architecture schools, where concept creation is considered an essential component (Bousbaci 2002, pp.51–54).

The significance of the design concept is also recognised by Ann Heylighen et al.:

> Many architects and most architectural students today seem to consider the 'concept' as the essence of architectural design. … Nowadays, a building is appreciated because of its concept, its meaning, its underlying and integrating idea, which gives it an added value with regard to the commonplace. (Heylighen et al. 1999, p.211)

In architectural education the design studio plays a prominent role in developing design skills. Professor Heylighen of the department of Architecture at Katholieke Universiteit Leuven states:

> Most architectural schools today are organised around two parallel axes. The first axis consists of a programme of theoretical lectures, which stack the student's mind with relevant components and concepts… Design, however, requires the transition from technical rationality to practical cognition, from passive knowledge to active knowing. Hence the crucial role of the second axis, the design studio, where students work on small, yet realistic design projects tutored by more experienced designers. In these design studios much attention is given to a development within students of an ability to generate concepts. (Heylighen et al. 1999)

Wiel Arets, an architect and former dean of the Berlage Institute, believes that architectural education should be in the first place a learning into making which can result in a project, but also a text or a video (Borden 2003, p.20).

Alejandro Zaera-Polo, also an architect and former dean of the Berlage Institute, is convinced that there is a need for a different kind of architect and thus also of architectural education. It seems to him that the architect-artist or the architect-performer with a strong character and ‘vision’ is unable to engage effectively in the swarm-like reality of current architectural practice. ‘It [education] is not about constructing individualities but about understanding multiplicities; not about visions but about opportunities.' Zaera-Polo is convinced that the liberal arts model has been exhausted, having systematically produced eccentricity and authorship rather than developing models to handle the generic, the multiple, the impersonal (Borden 2003, p.24).

Structural design culture

According to Heino Engel, structure is one of the most essential basic conditions contributing to the existence of material form: ‘Without structure, material forms cannot be preserved, and without preservance of form, the very destination of the form object cannot assert itself’.

In relation to architecture, Engel attributes a fundamental role to structure as an instrument for generating form and space that is subject to the laws of natural sciences, but also as an aesthetic, inventive medium for both shaping and experiencing buildings (Engel 2009, p.19).

Addis believes that ‘structure is all about doing more with less – using less material to support a given load or enclose a given volume, or making a stiffer or stronger object without using more material’. And even though engineers are fascinated by minimum-weight structures, structural design is to Addis more a matter of balancing structural performance with the cost of achieving it (Addis 1994, p.9). (This structural performance is determined by building codes and regulations that take into consideration rules of safety.)

Addis makes a distinction in structural design between the later stages that lead to convergence through objective processes, and the earlier, highly divergent and turbulent stages that precedes them (Addis 1994, p.9).

Similar parts in a structural design process are recognized by Angus Macdonald. First, there is a preliminary design stage, when the form and general arrangement of the structure are devised. Then there is a second stage in which the structural calculations are performed and the dimensions of the various structural elements are determined (Macdonald 1997, p.22).

Mike Schlaich makes a more thorough division of the structural design process: conceiving (i.e. developing a structural concept), modelling (i.e. turning a planned reality into a calculation model), dimensioning (i.e. giving appropriate form to structural elements) and detailing (i.e. designing element connections) (Schlaich 2007). In Schlaich’s view, structural design has on the one hand a scientific basis and on the other hand a creative component (VGTU News 2012).

The creative component in structural design is largely determined by the engineer's qualities. Structural engineer Eduardo Torroja reveals that there is no method that enables engineers to automatically discover 'the most adequate' structural type to fit a specific structural design problem:

> The achievement of the final solution is largely a matter of habit, intuition, imagination, common sense and personal attitude. Only the accumulation of experience can shorten the necessary labour of trial and error involved in the selection of one among the different possible alternatives. (Addis 1994, p.22)

Structural engineer Jörg Schlaich confirms that structural design importantly depends on personal choices:

> It appears to be forgotten that for every engineering task there are a practically unlimited number of solutions and that, because of this, it is never possible to make a choice according to purely functional considerations. Of necessity, it must be hit upon subjectively. (Holgate 1997, p.293)

He even argues for a personal 'creative accountancy' to compare merits of alternative structural solutions, which introduces a fair measure of subjectivity into engineering design and its criticism (Holgate 1997, p. 284).

Although structural design has an important subjective component, engineers and their environment give more attention to the objective, scientific aspect of structural design: a structural design that cannot be proven valid according to the building codes, or in most cases through calculation software, is not supposed to be built. Engineers need to produce rational explanations and calculations to justify their various decisions. This leads to the misguided perception that structural design is mainly based upon scientific laws devoid of personal choices (Addis 1994, p.9). Alison Ahearn subscribes this limited perception of engineering design as she states that communication about engineering is focused on 'failure' (of materials) and is underdeveloped for showing its creative ingenuity. Engineering communication needs an adapted vocabulary, metaphors and descriptions of engineering concepts (Ahearn 2000).

The power that the building codes and calculation in general exert over structural design practice is much deplored by engineer Peter Rice. He finds that natural engineering talent, as possessed for example by self-taught designer Jean Prouvé, is becoming rare since only engineers able to master the calculations are designing structures. People with insight and understanding of structural behaviour but no formal education in structural calculation find their way into different professions in which proof does not need to be calculated but can be achieved by performance. Rice believes that codification has become more important than the original source of structural understanding from which it springs (Rice 1996, p.81).

Mike Schlaich sees a challenge for the future to simplify these strangling codes and regulations and make them easier to apply in order to support engineers as responsible and creative members of society rather than users of recipes (VGTU News 2012).

Calculation software, with its ability to quickly and easily analyse structures, has simplified the work of the engineer and influenced the way engineers design structures. Addis points out that software has enabled more complex structures to be built than were previously possible, but this software is also responsible for a realisation of 'inelegant and unnecessarily convoluted structures' (Addis 1994, p.15).

David Billington and Frederick Gottemoeller point out that engineers focus on analysing structures in the belief that form (i.e. general shape and dimensions) will be determined by the forces as calculated in the analysis. However, a large number of forms can be shown by analysis to work equally well. It is in choosing a form that an engineer determines the forces and not the other way around.

Billington and Gottemoeller believe that structural engineers disregard their own role as creative designer:

> Many of today's engineers see themselves as a type of applied scientist, analysing pre-existing structural forms that have been established by others. Seeing oneself as an applied scientist is an unfortunate state of mind for a design engineer. It eliminates the imaginative half of the design process and forfeits the opportunity for the integration of form and structural requirements that can result in structural art. (Billington & Gottemoeller 2000)

Structural design involves more than developing a form to withstand forces. According to Bjørn Sandaker, in a structure for an architectural design there is not only a mechanical function to consider, but also a spatial one. The mechanical function relates to the scientific laws of strength and stiffness a structure must follow in order to transfer loads to its supports, and it relates to laws of technology to enable its manufacturing and construction. The spatial function of a structure can be subdivided in its architectural utility (e.g. a bearing wall as space divider), its contextuality (i.e. the relationship of the structural form with its architectural and spatial context), and its iconography (i.e. the ability of structural form to represent an object outside itself). And thus ‘scientific laws and technological requirements offer merely a set of minimum necessary requirements for structural form’ (Sandaker 2008, p.99).

The value of structural design beyond its mechanical function is for example expressed by engineer Jörg Schlaich, who appreciates ‘honesty’ in structures, meaning that loads should be carried to the ground by the most direct load paths consistent with the structure’s function as an encloser of space or a provider of pathway. Schlaich feels – rather than proving or asserting – that structural forms are particularly honest when acting mainly in direct tension or compression with a minimum of bending (Holgate 1997, p.13).

Engineer Peter Rice sees honesty in the way materials are used according to their properties. He believes that an engineer should contribute to the work of the architects by exploring the nature of the structural materials and use that knowledge to produce a special quality in how materials are applied (Rice 1996, p.77).

The same appreciation is expressed by engineer Eduardo Torroja: ‘If the structural shape does not correspond to the materials of which it is made there can be no aesthetic satisfaction’ (Addis 1994).

In structural design, important design choices are made during the conceptual design phase (cf. Mike Schlaich’s ‘conceiving’ in the above). The influence of conceptual design on the quality of the design solution is shown on different occasions by structural engineer Cecil Balmond. In his project of a villa in Bordeaux with architect Rem Koolhaas, Balmond demonstrates how the search for supports and for the position, order and function of the different structural elements in structural design leads to a creative or innovative solution. Here structural calculations do not lie at the basis of creation, but merely enable us to refine and adjust the conceptual design proposition towards a final design solution (Balmond 2002, pp.17–56).

In his work with architects Peter Kulka and Ulrich Königs on the roof structure for the sport stadium of Chemnitz, Balmond found a creative or innovative design solution by reflecting on and understanding the structural behaviour of a structural system he was developing for the roof. For Balmond, calculation comes second to this creative process (Balmond 2002, pp.138–143).

Even though conceptual design is essential to achieving an innovative design, structural engineer Laurent Ney identifies a lack of conceptual design skills in structural engineers. He says that engineers today are well equipped to dimension structures, but not to conceptualize them (Strauven & Ney

2005). And even when they do come up with innovative concepts, engineers like Peter Rice are often unclear as to how they created them. These concepts often seem to come to Rice all worked out, and all at once, even though it is clear he has been working on related design issues for some time (Rice 1996, p.79).

Mike Schlaich is a professor in the Department of Conceptual and Structural Design at Technische Universität in Berlin. He argues for giving special attention in engineering education to developing skills for designing structural concepts since, while this aspect of design is often underexposed, it is essential for creative or innovative design. Most engineering programs focus on developing the skills to calculate and dimension structures, but not on conceiving structural designs on a conceptual level. Mike Schlaich is surprised that at most universities basic engineering courses such as mathematics, mechanics and structural analysis are taught rather intensely and in the beginning of the curriculum, which then reduces structural design to the dimensioning of sections. At best the conceptual and creative aspects of the engineering profession are taught in the end, when it may be too late, if they are taught at all. Engineering education should focus not only on deductive, scientific-technical knowledge but also on developing the inductive, creative capabilities of the engineer designer (Schlaich 2007).

Comparing to architectural degree programs, there are more differences with the engineer's curriculum than just the limited attention given to conceptual design. Structural criticism, for example, is also underexposed in the education of engineers:

> Surely the formation of structural engineers should include structural criticism, analogous to architectural or music criticism. It would improve their powers of analysis and understanding. It would enhance their ability to explain why a certain structure is well designed and another less well designed. (Addis 1994)

Besides structural criticism, the history of the art of engineering is also lacking in the teaching of structural engineers (Schlaich 2007).

Comparison of professional appraisal of architect and engineer

In design, a different kind of contribution is expected from engineers than from architects. Alan Holgate calls engineering an unforgiving discipline. While architects may ignore classical rules of proportion or design inconvenient buildings, no irreparable harm is done. But engineers cannot ignore the laws of nature because a collapsing structure might cause death or heavy financial loss. 'Engineers who are innovative must be prepared to carry the resulting burden of responsibility', Holgate notes. It takes special qualities and attitudes for an engineer to design structures apart from the known, familiar solutions and calculations. Many engineers believe that unconventional and untried solutions should not be used, but Jörg Schlaich is convinced that it is the engineer's duty to advance the art of structural engineering, even in small steps, by introducing and testing innovations (Holgate 1997, p.282).

Ömar Akin expresses a rather extreme view of architectural design culture. He perceives a culture of developing and praising creative and original designs while dismissing routine and plain ones. Here, literal repetition of existing designs or concepts is not valued and needs to be avoided: architects are expected to design original and unique objects and in so doing can lift their design name to the level of stardom. They are rewarded in spite of the risks they take and in spite of the poor technical results they may achieve in their built objects, while engineers are less famous by name and sometimes condemned for the mistakes they make in blindly trusting technology (Akin 2001). As described above, Zaero-Polo believes there is a need for a kind of architect other than the eccentric architect-artist (as described by Akin), a need for designers to handle the multiple, the generic and the impersonal (Borden 2003, p.24).

Addis distinguishes two approaches to structural design: one leads to routine design by using the existing body of engineering knowledge and known structural solutions; the other leads to innovative design by going back to first principles and using inspiration and logic. 'While architects are usually educated to take this [innovative design] approach, even to the extent of challenging a project brief by questioning the need for a building at all, it is not common in the formation of engineering students' (Addis 1994, p.13). Engineer Jörg Schlaich admits that it took him almost thirty years of structural design experience before he had enough self-confidence to be able to design with the same freedom and confidence that architects bring to their proposals (Holgate 1997, p. 282).

2.3 Design process

In order to establish a better understanding how architectural and structural design propositions are developed in the early phases of a design process, we will now take a closer look both at design processes and at the importance of design concepts and design vocabulary.

There are different types of design to distinguish: routine, innovative and creative design. These types are described by John Gero in computational terms (Gero 1994, p.10) and by David Brown and B. Chandrasekaran in designer terms (Brown & Chandrasekaran 1985 cited in Achten 2008, p.22). Routine design is an instance of an already known type or class of design by which a procedure can be followed to come to a design solution. According to Achten, innovative design adds 'something new but does not change the structure of the type or class', while 'in creative design an altogether new structure for a type or class created'. As both distinctions are hard to make in architectural design, the difference between innovative and creative design is mostly a matter of degree of pushing the existing limits of design innovation (Achten 2008, p.23-24). In this thesis, 'design' is always considered to be creative or innovative unless described otherwise.

Theory on design methodology

Architectural design is sometimes called a 'wicked' problem (Achten 2008) as Horst Rittel and Melvin Webber have defined it in their research on social city planning (Rittel & Webber 1973). As opposed to a tame problem, for which an exhaustive formulation of the problem can contain all the necessary information to solve it, a wicked problem can only be understood after it is solved. In other words, the information required to understand the problem depends upon one's own approach to solving it. And thus the process of formulating the problem and of conceiving a solution are one and the same.

Rittel and Webber have described certain characteristics of this wicked problem that can be attributed to design as well:

1. Wicked problems have no stopping rule: there are no criteria telling when a solution has been found.
2. Solutions to wicked problems are not true or false, but good or bad: there are no objective criteria to evaluate if a solution is correct or false. The assessment of a proposed solution is expressed as 'good' or 'bad', or even as 'better' or 'worse'.
3. Every solution to a wicked problem is a 'one-shot operation': there is neither place nor time for testing different prototypes. The end design is the only prototype.
4. Every wicked problem is essentially unique: there are no classes of wicked problems in which a principle solution can be applied to fit all members of such a class.

At the start of an architectural design, there is no clear problem definition, which would allow us to follow or apply a preconceived step-by-step procedure. There is no predetermined design goal to achieve (only certain requirements), and it is unclear which information at hand will be needed to come to a design solution. The same description can also be applied to structural design – as Addis calls it, 'a process in which the problems themselves first need to be established (and to which there may not be feasible solutions)' (Addis 1994).

Nigel Cross recognizes the importance of a bridging concept between problem and solution in design. According to Cross, the underlying creative insight in design is more a matter of 'bridging' than of 'leaping' across the chasm between design problem and solution by creating an apposite concept (Cross 1997). Design seems to proceed by oscillating between sub-solution and sub-problem areas, as well as decomposing the problem and combining sub-solutions. Partial models of the problem and of its solution are constructed side-by-side. The essence of design, according to Cross, is to bridge both partial models by an apposite concept:

> Such an apposite 'bridge' concept recognisably embodies satisfactory relationships between problem and solution. It is the recognition of a satisfactory bridging concept that provides the 'illumination' of the creative 'flash of insight'. (Cross 1997, pp.439–440)

A process of concurrent investigation into the whole and detailed parts of a design can be seen in the design exploration by OMA: they simultaneously use small-scale models for design inquiry and speculation and large-scale models for practical concerns (Yaneva 2005). This scaling up and down between models involves moving up and down in levels of abstraction of design, after which the abstract and the precise can be brought together (Lerdahl 2001). This process enables detail to be used as a generator of design ideas (Lawson 2004, p.48).

Jane Dark has developed a descriptive model for a design process through the concepts 'primary generator', 'conjecture' and 'analysis' (Dark 1984). In Dark's view, the complexity of a design problem needs to be reduced by the designer to a mentally manageable size. This is done by focusing on what the designer believes to be the essential aspects of the problem. This is the primary generator. It is a way into the problem. Based upon that particular understanding of the problem, a designer develops a rough design proposal – i.e. the conjecture – that is then analysed. This analysis enables the designer to better understand the complex design problem and enables him or her to develop a more adapted conjecture. Thus a design process cycle can be established.

Similar mechanisms in design are described by Donald Schön (Schön 1983). According to Schön, every design problem is unique and requires a specific, personal approach by the designer. A designer distinguishes certain elements from among a huge amount of data from which to construct a problem definition and a solution proposal. The designer reframes the problem in a way that looks solvable and manageable to him or her:

> First, although design is integrative, it is often not possible to think about the totality of the problem or indeed the solution at all times. It simply is too complex and confusing a matter. Instead designers seem to narrow their attention by setting up a situation, focusing, or 'framing'. These structuring ideas are commonly found in design protocols, whether we call them 'frames', 'primary generators', or in the more common parlance of the design studio 'partis'. Indeed they seem to be the very essence of design thinking and at the heart of the design process. (Schön 1983, p.92)

Through this reframing, the situation talks back to the designer and gives him or her new ideas that keep the inquiry moving. Inquiries are undertaken by exploratory experiments, move-testing experiments and hypothesis testing as defined by Schön. The design process evolves by taking into account the evaluation results of these experiments.

Schön recognizes the importance of 'delivering an action' in the design process with little to no premeditation. He calls it 'reflection-in-action'. (This is in contrast to action as a result of extensive previous reflection.) For an architect this can mean drawing design ideas on paper, reflecting upon those ideas through the act of drawing, and evaluating the situation in order to let the design evolve: a reflective conversation with the situation. The design solution is not preconceived before putting it on paper. Drawing and designing are in this case not separate actions.

This reflective conversation with a drawing is also recognized by Lawson. He describes different types of drawings architects make, and considers the proposition drawing at the very centre of a design process. In these drawings, a designer makes a 'move' by proposing a possible design outcome (Lawson 2004, pp.45–49). In this drawing an architect externalizes certain features of the design situation in order to examine them in a more focused way. By drawing on paper, an architect is able to stand back and look at his or her design proposal in order to explore its implications in a more remote manner. (This mechanism of reflection-in-action through drawings can also be established between two collaborating designers, where one designer reflects from a distance on what the other designer draws.)

Investigation into a range of possibilities versus a single design solution

Ömer Akin describes architects as designers who use a hybrid search strategy of breadth-first followed by depth-first: in developing design solutions, architects tend to look for a variety of design answers before going in depth into one array of solutions. In other words, architects spend much attention in investigating different concepts and conceptual designs before choosing one to develop in further detail. Engineers, on the other hand, are much more likely to be content with finding one possible solution and sticking to it without investigating other possible solutions that might be valuable (Akin 2001).

Rice, an engineer, confirms that once a solution appears to solve the problem for him, he does not feel any desire or compulsion to change it. 'If it's a solution it is a solution and so be it' (Rice 1996, p.79). Rice states that it is characteristic for engineers to come to only one conclusion in design since in his view they are working with objective parameters (Rice 1996, p.79).

Akin contrasts the engineer's search for absolute, positivistic truth with the architect's search for a temporary truth that is situated in a specific context (Akin 2001). This temporary truth in design acknowledges that still other possible solutions are out there and are worth searching for. (In the above, Jörg Schlaich (Holgate 1997, p.293) and Billington & Gottemoeller (Billington & Gottemoeller 2000) recognize that a structural design problem also contains a variety of possible design solutions.)

Most architects are aware of the variety of possible valuable solutions and of the subjectivity of the process required to come to a design solution. This allows them to understand during design collaboration that architectural design is negotiable. Engineers tend to perceive their design proposition as absolute, often making them less willing to negotiate. According to Addis,

> engineers are generally brought up on a diet of correct (or incorrect) answers to specified problems – not much room there for debate. Even in open-ended projects there often tends to be an underlying idea that proposals are either right or wrong, rather than having different good and bad points. (Addis 1994)

Developing a design proposition

When architects develop design propositions, they can rely on a body of knowledge of existing solutions to architectural design problems. Such design solutions are called 'references' by Gabi Goldschmidt (Goldschmidt 1998) while Brian Lawson calls them 'precedents', both having the same meaning:

> Precedents are often either whole or partial pieces of designs that the designer is aware of. They may be previously employed solutions by the same designer, by famous designers, buildings, landscapes or towns seen on study visits or even on holiday. (Lawson 2004, p.96)

A precedent finds meaning in an architect's design process through the interpretation(s) the architect attributes to the precedent as a design solution. There are different types of interpretation to be recognized, such as organization, expression, function, construction and so on. Each type of interpretation gives meaning to a precedent (as a solution to a design problem) within its own system of terms and rules (cf. system of thoughts of Chapter 2.5). For example, Ching identifies different types of interpretation (e.g. spatial relationships) of architectural design in his book *Architecture: Form, Space & Order* through an articulation of terms and rules (Ching 2007).

In design creation, precedents are not intended to be used as duplicable solutions to identical design problems – if identical problems even exist in architectural design; rather, they provide a useful point of departure for design aspects that are similar in precedent to the design task at hand (Lawson 2004, p.96). Precedents can be adapted, transformed and combined in the different types of interpretation in which a designer finds meaning. The physical models used in design at OMA, for example, can be seen as such precedents:

> Design does not start from scratch. Models at OMA are kept because they can be recycled in design, and for that they are deliberately maintained to create a prolific ontological milieu for design invention. Re-using, re-collecting, re-interpreting, adapting, re-making – these are all synonyms of creating. (Yaneva 2009b, p.6)

Goldschmidt believes in a catalogue of precedents as a design knowledge database for architects (Goldschmidt 1998). Such a catalogue contains experiential knowledge rather than theoretical or semantic knowledge, which is not very helpful during the creative process of design (Lawson 2004, pp.104–105).

Similar use of existing design solutions can be found in structural design development. Structural engineers often find meaning in structural design solutions through interpretations within structural analysis. 'In general, engineers tend to categorise structures according to which mathematical model and technique of structural analysis they might use, …' (Addis 1994, p.12). This leads to an interpretation by engineers of structural design solutions in terms of typologies like beam, column, slab, tie, Vierendeel-girder, truss-girder, dome shell and peak tent. Each of these typologies possesses distinctive characteristics pertaining to an interpretation within structural analysis. For example, a tie is a linear element characterized by its normal forces of tension. (Structural typologies have been categorized by, for example, Heino Engel and Frei Otto (Engel 2009; Otto 1966).)

In turn a typology (as a design solution within certain types of interpretation) can be applied to the development of a structural design proposition for its ability to solve a (partial) structural problem. For example, a steel I-beam can be used to transfer lateral loads to the supports of the beam, and is accompanied by a calculation method for designing its dimensions. (The development of a design solution like an I-beam is often the result of a cumulative effort of many engineers and then copied for further use by others (Addis 1994, p.13).)

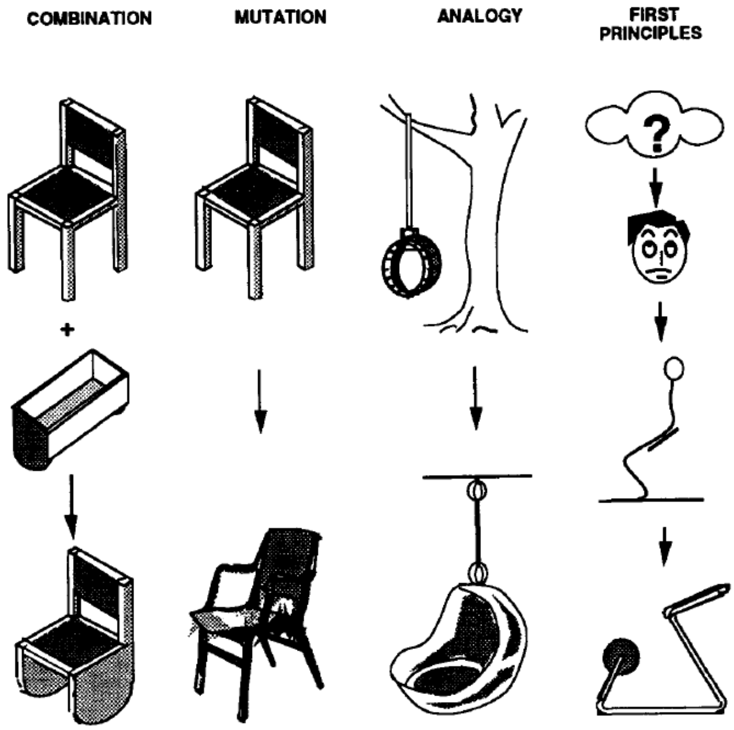


Figure 2-1. Four of the five procedures for creative design.

The design mechanism of adapting, combining and transforming precedents in the types of interpretation in which they find meaning can also be found in the five procedures Michael Rosenman and John Gero describe by which creative design can occur: combination, mutation, analogy, first principles and emergence (Rosenman & Gero 1996; Gero 1994). In combination, design occurs by combining different characteristics of existing designs; in mutation by modifying form or certain characteristics of an existing design; in analogy by adopting a behavioural feature of an existing design; in first principle by determining essential attributes for the design requirements; and in emergence by discovering new, previously unrecognized characteristics of existing designs.

There are many examples showing how architects use precedents in design. The architect Stéphane Beel, for example, describes how he came to design the entrance of the Museum M in the city of Leuven (*Goudvis, Stéphane Beel* 2011). The precedent he applied was that of the entrance of the Altes Museum in Berlin, where a colonnade provides a first entrance to the building. But after passing through the colonnade, a new entrance arises behind a glass door. The architect describes how he loves this double entering and uses the same approach in his new design. Although both the existing and the new design have a colonnade and double entrances, Beel has not made a literal copy and rescaling of a physical form. He has adapted and transformed this precedent on a limited number of types of interpretation (e.g. organisation of space and expression) that seemed meaningful for his design in order to develop a new entrance and create a new form. Such a precedent has more meaning as a mental construct in design than as an actual form.

Figure 2-2. Entrance of the Altes Museum in Berlin; Museum M.

A similar example can be found in the work of Frank Gehry. The steeply banked tiers of his Walt Disney Concert Hall were partly inspired by Renaissance anatomy theatres (Webb 2003, p.118). An even more extreme example of re-using and adapting a (self-developed) precedent occurred when OMA developed the design of the Casa da Musica in Porto out of a re-used physical model of an earlier design for an urban house (Yaneva 2009a).

Similar re-use and adaptations of existing design solutions can be found in structural design. For example, the engineer Cecil Balmond designed horizontal wind bracing for a roof in the Kunsthal in Rotterdam through a horizontal arch structure. This structural solution of an arch is normally used in a vertical position to transfer vertical loads to the supports of the arch. Here Balmond interprets this arch as a structural system – independent of its orientation – to transfer loads to its outer supports. Balmond adapts this solution for horizontal use to have the visitor experience an ambiguous reading of the building's structure (Balmond 2002).

In the discourse of precedents, a special place in architectural design is reserved for design prototypes or archetypes. They present conceptual or abstract design answers to certain design problems and are used as a starting point in projects with similar design problems. Such design prototypes or archetypes are developed by architects like Frank Lloyd Wright, Aalvar Aalto and Le Corbusier, and often expressed in conceptual schemes without any physical form (Laseau 2001, pp.150–155). A similar concept of prototype can also be found in the application of 'design models' as described by the architect Van Berkel of UN Studio: 'Diagram-turned-design-models are profoundly abstracted, yet fully formed design concepts that are developed further by working out a catalogue of options and transformations, culminating in distinctive projects' (Van Berkel & Bos 2006, p.17).

2.4 Design collaboration

As early as 1967 Heino Engel was convinced that in order to design 'contemporary' buildings, teamwork between experts in science (i.e. engineers) and architecture was necessary (Engel & Rapson 1967). In such a design collaboration between architect and structural engineer, the relationship between architectural form and the structure that supports it can be explored and established. Angus Macdonald defines different types of these relationships (Macdonald 1997): structure ignored, structure accepted, structure symbolized and true structural high tech. They vary from structure that has no visible implication on the architectural form to structure that determines not only the architectural form but also the nature of the adopted architectural vocabulary.

In professional practice there are various types of collaboration to be recognized between architect and structural engineer. The structural engineer Jörg Schlaich, for example, believes that on matters of structure and materials the architect should follow the advice of the engineer and not just put it aside. Schlaich prefers to work with architects who convey in broad terms the desired functional and aesthetic effects of their design projects. In response, Schlaich will then provide five conceptual design propositions for a structure consistent with these desires. If none of these propositions are to the satisfaction of the architect, he will then provide new ones until one is approved by the architect. Schlaich has, however, experienced that not all architects prefer this kind of collaboration where form is created by both designers: some architects impose their self-designed form – created with no external structural advice – as fixed for the engineer, even when the project is a typical engineering object like a bridge (Holgate 1997, p.287).

Gehry likes to create architectural form with paper models, which specialized software is then able to translate into digital form (cf. Chapter 2.2). Gehry is sometimes portrayed in the media as having created his forms for certain projects with paper without direct guidance from structural engineers (Gerace & White 2003; Kjeldsen et al. 1998; *Sketches of Frank Gehry*, 2006). Projects in which the form is mainly designed by architects are partly made possible through the power of calculation software that enables engineers to develop a structure to support such a fixed form.

As mentioned in Chapter 2.2, the architect Renzo Piano believes that creative architectural design is the result of teamwork with other professionals – including engineers – in building workshops, where there is no hierarchy among the various participants. Here architect and structural engineer are then working together as genuine architectural designers instead of the engineer being an advisor to the architect (Lorente & Sudjic 2003).

In his book *Informal*, the structural engineer Cecil Balmond shows his willingness to follow an architect's understanding of the direction a design project should take, even when this direction is averse to a common engineering understanding. For example, in the project for a villa in Bordeaux with Rem Koolhaas, Balmond is willing to investigate the architect's desire to make the building 'fly' even when this makes little sense in an engineer's understanding of the world. This disposition to follow an architect's vision is not unconditional: Balmond first needed to be convinced that it was worth making this building fly (Balmond 2002).

The engineers of Studieburo Mouton describe architect and structural engineer designing together as 'the intense cooperation between the architect and the engineer in which architecture and structure both reinforce and challenge one another'. Here architecture and structure are not separate entities but find a powerful expression in their consolidation as partners. In this collaboration, structural design provides an underlayer for architectural design (Boone 2009, p.4). This impact of structural design on architectural design is also described by Unwin as the 'structural strategy' of an engineer's design proposition and its influence on an organization of architectural space and form (Unwin 1997).

In this close relationship between architectural and structural design, Balmond sees the role of the engineer not just as a 'supreme technological legislator – a hard person of science – who makes the impossible work, but as a catalyst to inspire a creativity' (Balmond 2002).

When architects and engineers are designing architectural and structural form together, they are working as a design team. According to Joan Zunde and Hocine Bougdah, a team can be defined 'as a group working together to a common goal. In doing this, it develops synergy. This is the characteristic of a set of parts, when properly assembled, to perform more than the parts could do individually' (Zunde & Bougdah 2006, p.54).

Van Berkel believes that current innovative or creative architectural design can only be accomplished through teamwork by diverse skilled experts who collaborate towards a common goal:

> You just have to accept that today innovation is impossible on your own. Real, significant innovation occurs when several people simultaneously have the same idea and move in the same direction, following subliminally emitted and received signals. (Van Berkel & Bos 2006, p.126)

Regarding design collaboration, the engineer Ove Arup expresses his appreciation for what he defines as 'Total Architecture' in which it is implied 'that all relevant design decisions [i.e. from all involved design disciplines] have been considered together and have been integrated into a whole by a well organised team empowered to fix priorities' (Arup 1970).

There is a consensus about the importance of having all experts in the fields of the architecture, engineering and construction work together early on in the design process to come to a creative or innovative design in which diverse areas of expertise are integrated (Quanjel et al. 2006; Zeiler & Quanjel 2007). According to Jörg Schlaich,

> Good solutions will emerge if both professions [i.e. architect and structural engineer] know their job, share the same goals, respect each other, most importantly, if the involvement of the engineer starts early in the architect's programmatic and conceptual phase. The architect will not get the best results by demanding a structure from an engineer under already fixed and constraining boundary conditions. (Addis 1994)

Through literature study, Wim Zeiler and Emil Quanjel (Quanjel & Zeiler 2007) come to the conclusion that concept generation is the basis of design processes, and that for solving complex design problems a creative concept generation involves a multi-disciplinary approach of experts in a team setting.

They also establish that multi-disciplinary teams will generate larger variations in objectives than mono-disciplinary teams (Wallace 1987) and also a wider range of solutions (Ysseldyke et al. 1982). They conclude that a wider range of solutions and objectives will increase the possibilities of innovative designs that will better suite the client's needs. And thus they make a case for a multi-disciplinary approach to concept creation for creative or innovative design.

Collaboration processes among designers of different disciplines that lead to creative or innovative design have been studied extensively in other design fields like aviation, car and product design. Here different disciplinary designers are dependent on and influenced by each other for their own design process. This type of relationship among designers of different disciplines working on the same project has been described by Kemper Lewis and Farrokh Mistree in multi-disciplinary design processes with the use of game theory (Lewis & Mistree 1997). This theory is derived from decision science, and models the interactions between different designers as a sequence of games among a set of players. In a game, each player controls only a specified subset of design variables instead of all the design variables needed to come to a design solution within his or her own discipline. The goal of each player is to achieve the best possible design solution within his or her own discipline. Because all the designers are dependent on the decisions of the other players, they lack control over all the design variables that affect the quality of the outcome. This is what makes the game a game.

In this theory, three protocols of collaboration have been developed: cooperative (each designer is aware of the others and the decisions made by each of the others), non-cooperative (designers cannot attain the information about the other designers necessary to make design decisions), and sequential or Stackelberg leader/follower (Lewis & Mistree 1997; Chen & Lewis 1999). The latter contains characteristics that help to describe design collaborations between architects and structural engineers.

In the sequential protocol, one designer (the leader) finalizes his or her design and delivers this information to the next designer (the follower). Some information transfer occurs, but it is not completely cooperative: the leader needs to make assumptions about the (rational) behaviour of the following designer in order to make his or her own design decisions. And the following designer acquires his or her information through the design outcome received from the leader.

In this protocol a concept is defined as a Rational Reaction Set. A Rational Reaction Set is a set of solutions of the other player's design process, which one player constructs in function of his or her own design outcome. In other words, one player tries to predict the (rational) outcome of the other player's design as a consequence of his or her own input. In this protocol the leader has developed a Rational Reaction Set of the follower's design outcome, which means that the leader can predict the follower's reaction to the delivered design outcome of the leader. Based upon this Rational Reaction Set, the leader is able to estimate the necessary information of the other player's design outcome needed for his or her own design process.

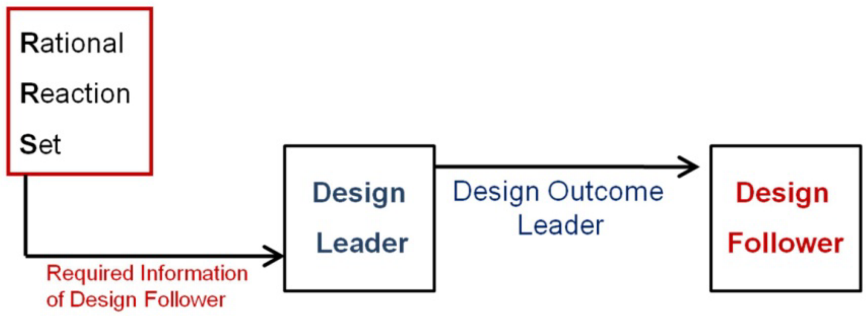


Figure 2-3. Sequential or Staeckelberg leader/follower protocol.

The more accurate the Rational Reaction Set is, the better the design leader can anticipate if the design follower will be able to find an adequate design solution for the proposed design outcome of the leader. An accurate Rational Reaction Set allows for an efficient overall design process.

Research in the architecture, engineering and construction industry (Lottaz et al. 2000; Stouffs 2000) shows that certain design negotiation conflicts arise among the various designers involved when the designers communicate single design solutions instead of a range of design solutions in describing the outcome of their design processes. This can lead to a design process in which no mutually agreed design solution is found even though one exists. The reason for these unnecessary conflicts is that designers make premature design decisions based on insufficient information from the other designers when they narrow down their own design possibilities to one single solution. This single solution is then based on incorrect assumptions about the other's design outcome (because of an inadequate Rational Reaction Set). As a result of these incorrect assumptions, the following designer is then unable to develop an adequate design solution for the proposed design solution of the leading designer. This requires the following designer to alter the proposed single design solution. If all involved designers then continue producing single design solutions based on inadequate information about the other design processes, the complete range of possible solutions might never be overviewed, with the consequent risk that they fail to discover a solution that satisfies all designers involved.

Rudi Stouffs, Claudio Lottaz and Ian Smith propose a collaboration strategy to prevent this kind of conflicts by delaying design decisions until they become essential: delay decision strategy. This is accomplished by producing a range of design solutions as outcomes of a design process instead of a single design solution. This design proposition as a range of solutions is then based only upon the available information of the other design outcomes: ill-informed design decisions are left open. Such a design proposition still contains specific design information and knowledge that then can be applied in the design process of the next design follower involved. This strategy leads to an exchange of design information among the various designers that does not unnecessarily narrow down the design possibilities by requiring each designer to make ill-informed assumptions based on the design outcomes of the others.

2.5 Design communication

The semiotic school of communication theory examines language as a means to communicate meaning. It brings to the fore the importance of a similar interpretation of signs and symbols used in communication to attain a correct understanding of the intended meaning. A meaning (1) that the sender wants to express to the receiver, is to be understood in a system of thoughts (A) that the sender has developed (Figure 2-4). This system of thoughts is a coherent ordering of ideas and opinions in regard to a certain given. The sender will encode this meaning (1) into a message that operates within a system of symbols, externalizing the meaning into a message of symbols. The receiver will then decode this message into a meaning (2) that operates within the receiver's (personal) system of thoughts (B), internalizing the message into a meaning. Sender and receiver are both interpreters of a message. The relationship between meaning and message is determined by the interpreter's knowledge system, culture and emotions. If sender and receiver are to contribute a similar meaning to a message, they need to possess similar coding systems, which are embedded in their knowledge system, culture and even emotions (Fauconnier 1986; Lerdahl 2001; Emmitt & Gorse 2003).

Stephen Emmitt and Christopher Gorse confirm the importance of a mutual knowledge system and culture in communication between architect and engineer. They state that in order for both designers to be successful in their communication of an architectural or structural design topic (i.e. interpret a message into a similar meaning), they need to possess mutual knowledge and experience in regard to this topic (Emmitt & Gorse 2003). Gianfranco Zaccai and Tony Bastick bring it even a step further (Lerdahl 2001): in a successful collaboration for innovative or creative design, there is a need for overlap of expertise among the players of the various disciplinary subsystems.

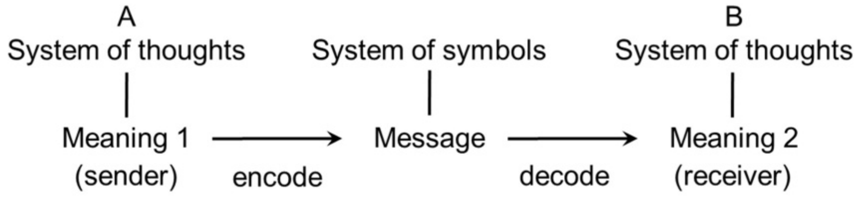


Figure 2-4. Communication scheme of the semiotic school.

A language is not only a tool to communicate meaning; it also affects the construction of our system of thoughts in which this meaning is understood. Within the cognitive linguistics it is shown that a language will influence how we perceive and understand phenomena. Lera Boroditsky states 'that people who speak different languages do indeed think differently and that even flukes of grammar can profoundly affect how we see the world' (Boroditsky 2009). One of the examples she presents is that of an aboriginal community in northern Australia. Here the Kuuk Thaayorre use cardinal-direction terms like 'north', 'south', 'east' and 'west' to define space. This is different from defining space relative to an observer with words like 'right', 'left', 'forward' and 'back' as is the common practice in English. This difference in language leads to a profound difference in navigational ability and spatial knowledge. According to Boroditsky,

> Speakers of languages like Kuuk Thaayorre are much better than English speakers at staying oriented and keeping track of where they are, even in unfamiliar landscapes or inside unfamiliar buildings. What enables them – in fact, forces them – to do this is their language. Having their attention trained in this way equips them to perform navigational feats once thought beyond human capabilities. (Boroditsky 2009)

As language and system of thoughts are closely related, the meaning a designer attributes to a design precedent is dependent on the language he or she uses to describe and understand this precedent. For example, the spatial relations of different rooms in an architectural precedent will find meaning according to the application of cardinal or relative directions by the designer: interpreted with cardinal directions, these rooms will spatially relate to the outside world (e.g. the sun and other buildings), while interpreted with relative directions, their spatial relations will be more focused on adjacent rooms.

And thus the precedent finds meaning in the applied type of interpretation – which is similar to the system of thoughts as described in the semiotic school – and the type of interpretation depends on the language used to describe this meaning (i.e. the message).

Various characteristics and consequences of a discipline-specific interpretation of a design object are investigated in computer-aided design research in the fields of architecture, engineering and construction. This shows that a single, volumetric representation of a built object is insufficient as a tool for interdisciplinary collaboration. Because each discipline has its own concepts and interpretations of a built object, representation of design models should be multiple according to the different disciplinary concepts (Fruchter et al. 1996; Rosenman & Gero 1996; Rosenman et al. 2005). According to Renate Fruchter et al., a volumetric representation of a design object as a medium in which architectural and structural design enter into dialogue should be enriched by information about the architectural and structural function(s) of the design object's constituting elements (i.e. what each is supposed to do) and about the behaviour(s) of each element (i.e. how it reacts). This information should provide for a more profound understanding of the other designer's design proposition, enabling a more creative design collaboration (Fruchter et al. 1996).

Research on the communication between various design teams in the architecture, engineering and construction industry brings to the fore the need to filter the exchanged information. Wim Zeiler and Emile Quanjel propose that design teams present their proposals without overloading the other teams with unnecessary information (Zeiler & Quanjel 2007). This can be achieved by the use of an appropriate level of abstraction during communication. Abstraction is a mapping where certain desirable properties are brought forward and others left in the background in order to reduce complexity and enhance the essence of the message.

Differing levels of abstraction are needed depending on the progress of the design process: as design work becomes more detailed, different information becomes essential in the design process. A level of abstraction represents a specific view of the total information available about a design by determining what is relevant to communicate. It is important to understand the level of abstraction used by others, and to apply the appropriate level in one's own communications (Lerdahl 2001).

According to Paul Laseau (Laseau 2001) graphic communication can play a very important part in the success of teamwork under the condition that it can be rapidly produced and that it is flexible and unrestricting to thinking processes. In this graphic communication there are two basic tendencies: exploratory abstract sketches and definitive concrete sketches. According to Robert McKim, these respond to two types of thinking. ‘The first is fast, crude, holistic, and parallel, while the second is deliberate, attentive, detailed and sequential.’ (McKim 1972, p.127).

Graphic thinking sketches have the advantage to be quickly presentable to the group, remain available for retrieval and manipulation, and in addition help knock down barriers built by professional jargon. They should however be simple and clear to be effective: contain enough information to form a distinct idea but not too much in order to be easily absorbed. The accessibility of these sketches is heavily dependent on associations with familiar objects or experiences. These associations can be accomplished by naming graphic items or by using symbols that are easily recognized as abstractions of familiar objects. (Laseau 2001).

The importance of sketching in design is confirmed through studies by Ammon Salter and David Gann (Salter & Gann 2003). They show that in the renowned engineering office of Arup face-to-face interaction and use of sketching are still the most important elements for developing new ideas and solving problems. Even though Arup is among the highest spenders on ICT tools in the United Kingdom design engineering sector, only 25% of its designers found on-line databases and working with new equipment and software to be important as a source of ideas for design. The most highly cited method for solving problems was face-to-face conversations with other colleagues. Like Kathryn Henderson (Henderson 1999), Salter and Gann discovered that sketching on paper is a widely used technique for solving problems in engineering design, even in environments where there is a high level of CAD-usage. Henderson argues that sketching remains important because it helps engineers develop visual ideas and to communicate these visual representations to others.

3. Development of referential background

This chapter investigates a further articulation of various characteristics and mechanisms of early-stage design collaborations between architects and structural engineers in which the two sides' design processes are mutually informed and lead to the development of a built architectural project. Their individual and collaborative design processes are analysed together with their communication in design collaboration. Diagrams are developed that described their design processes, conceptual design communication and collaboration.

The investigation provides an understanding of essential characteristics and mechanism that contribute to a mutually informed collaboration between architect and structural engineer that starts early in the design process.

Based on the referential background developed in Chapter 2, I analyse my personal experiences as a designer and collaborator with other designers. Various findings on architectural, structural and collaborative design are discussed with architects, architecture students and structural engineers. Through these reflections, I develop the diagrams presented in this chapter, defining the various concepts and describing their interrelations.

This chapter begins with a mutual description of the architectural and structural design process and follows with a closer look at the communication of conceptual design propositions. The findings enable us to establish a protocol for a mutually informed collaboration process. The chapter concludes with a set of proposals to support a mutually informed design collaboration.

3.1 Design process

Chapter 2.2 presents various testimonies by architects and structural engineers, in which they describe their views on design, together with more distant observations by researchers. These descriptions are combined with various theories of design methodology in Chapter 2.3 to establish an understanding of both the architect's and the structural engineer's design processes in accordance with my own design experience. By comparing these processes, I have developed a proposal that describes similar characteristics and mechanisms of both processes. This is described in the following paragraphs and presented in a diagram (Figure 3-1).

Design question within a set of conditions

Since the term 'problem' is strongly associated with the tame kind of problem as defined in Chapter 2.3, I will describe the outset of structural or architectural design as a *design question* for the wicked problem it represents. 'Problem' is furthermore associated with 'problematic', while design is also a matter of creating opportunities without the need for something problematic.

This design question is situated in an existing set of conditions, and thus the design process involves planning and creating a new set of conditions (cf. Chapter 2.2).

In architectural design a design question often originates from a client's brief, and in structural design from an architectural design proposition that requires a structure.

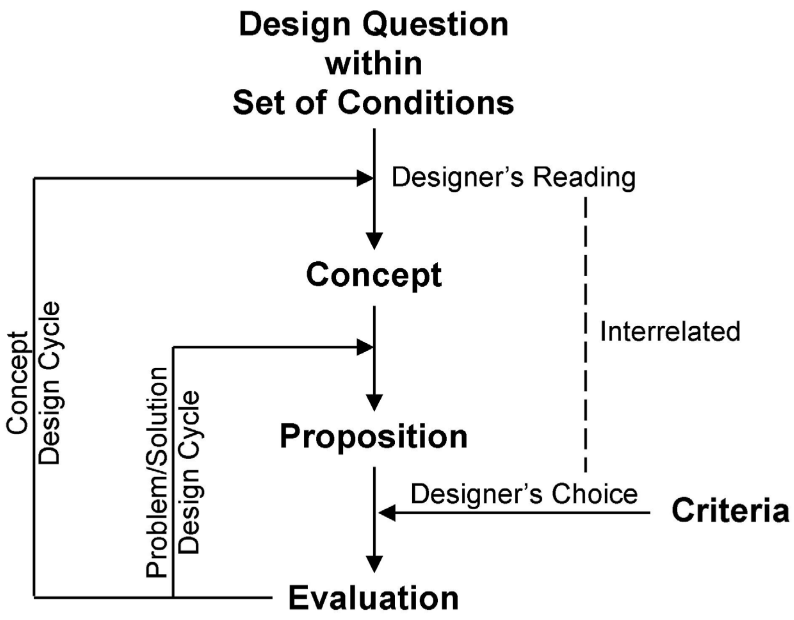


Figure 3-1. Proposed design process diagram.

Concept

In the proposed diagram of Figure 3-1, a *concept* (which relates to the 'apposite concept' of Cross described in Chapter 2.3) brings to the fore those issues of the design question that seem of value for the designer to address (cf. 'primary generator' of Dark and 'framing' of Schön in Chapter 2.3), together with a response (cf. 'conjecture' of Dark and 'make a move' of Schön in Chapter 2.3). This concept is at the heart of a design object, brings forward its essential characteristics and has a conceptual nature, meaning that it groups a wide range of possible design solutions with similar characteristics.

A concept can be considered the result of a designer's translation of the initial design question into a tamer 'problem/solution' format. A concept distils from the question what is essential to a designer in finding a design solution. This framing of the design question contains characteristics of a problem description. At the same time, the concept brings forward an answer to this described problem, albeit not in detail. This process is similar to solving a wicked problem: a problem is defined and understood when a solution is found, or a solution describes how a problem is to be understood. (Both problem and solution find meaning within certain types of interpretation valued by the designer for answering the design question.) A concept will then guide a designer in the further development of this design within the developed 'problem/solutions' format.

In architectural design culture, a concept is considered an important component in design development and evaluation. An architectural concept can take a stance on the architectural design question on many different types of interpretation: urban, social, functional, aesthetic, structural, cultural, economic and so on (cf. Chapter 2.2).

In structural design, the engineer's design concept (normally) provides for a structural design strategy in relation to the given architectural design proposition (cf. Chapter 2.2). Such a concept contains the engineer's design choices that principally determine which loads will be withstood, the possible types and positions of supports to apply, the kind of configurations and structural functions of the structural elements and the type of relations between these elements. It contains the engineer's answer to how horizontal and vertical loads will principally travel through the various structural elements to the supports in order to make the structure strong, stiff and stable. The concept might also involve choices about, for example, aesthetics, sustainability, cost and construction.

Such a concept does not fix the size or position of structural elements, nor their structural form or material. It provides a generic design strategy that guides the engineer in the creation of structural form to meet various design criteria that the engineer finds essential in answering the design question.

Proposition

Through the guiding principles of the chosen concept, a designer develops and externalizes a *proposition* as a concretisation of this concept into form and space. This is accomplished according to the designer's skill and experience and involves making personal choices. Different design propositions can be developed from the same concept (cf. Chapter 2.2).

As a design process evolves, design propositions can become more concrete and detailed: a design proposition can range from very abstract (i.e. a conceptual design proposition that represents a wide range of possible design solutions) to very detailed (i.e. representing only a few possible design solutions).

Whereas in architectural design, propositions can still be rather more abstract than concrete, in structural design they often take such concrete form that they can be used for calculating structural dimensions, thus approximating a designed solution. It is remarkable that engineers do not have a commonly used representational language to develop more abstract conceptual design propositions beyond the rather detailed structural typologies like columns, beams, tie, slabs and so on. (Characteristics of conceptual design propositions of architects and structural engineers are further investigated in Chapter 3.2.)

Evaluation

When a design proposition is developed, its quality can be evaluated by the designer as described by Dark (i.e. ‘analysis of conjecture’) and Schön (i.e. ‘reflective conversation with the situation’) (cf. Chapter 2.3). The designer has a wide range of criteria at hand to evaluate the quality of a design proposition as an answer to a design question. In order to manage such an evaluation, a designer chooses which criteria to take into consideration and how to weigh them (cf. Chapter 2.2).

The design concept developed by the designer is related to this evaluation, since the concept clarifies which design issues are of importance and need to be considered in this assessment. In other words, the issues that a designer considers essential for resolving a design question will also show up in the criteria that the designer finds important for evaluating the quality of a design proposition. Besides evaluation criteria related to the concept, a designer can choose additional criteria in this evaluation.

Some of the criteria used for evaluation are imposed by codes and laws (e.g. insulation standards, urban requirements, structural codes) and others are freely chosen by the designer (e.g. aesthetic, ecological). Certain criteria are objectively measurable (e.g. a maximum building area); others can only be assessed subjectively (e.g. ‘looks like it’s disappearing into the woods’). Some evaluation criteria are part of design negotiations among the various actors involved (e.g. a structure suitable to an architectural proposal).

These criteria can be translated into conditions that must be met (e.g. it has to be waterproof) or into objectives to strive for (e.g. as inexpensive as possible).

Through their education and the culture of architectural critique, architects are generally better trained than structural engineers in articulating and handling subjectively assessable design criteria. Most architects are familiar with providing subjective argumentations (based upon personal opinions and emotions) for their design decisions, while engineers tend to search for objective proof (based on objectively assessable facts) to account for their design decisions, which have a strong focus on the criteria of strength and stiffness (cf. Chapter 2.2).

Cyclic process

Both Dark and Schön describe a cyclic design process, where each evaluation of a design proposition provides for a better understanding of the design under development, which then enables the designer to develop an improved proposition (cf. Chapter 2.3). In the proposed scheme, the evaluation of a proposition can lead to (1) a better adapted concretisation of the design concept into a new design proposition, or to (2) an improved understanding of the design question and the set of conditions it is placed in, and the development of a more adequate design concept. The former cycle maintains the developed 'problem/solution' format provided by the chosen concept; the latter reinvestigates this format by redesigning the concept.

In structural design it seems more customary to improve the design proposition within a given concept than to investigate the design question anew in order to develop a more adapted concept. (The possibility of maintaining a once developed concept is supported by calculation software that enables engineers to design structurally sound solutions for a wide range of possible concepts or conceptual designs.) The culture of architectural design seems to offer more support for reassessing a design question and the design conditions, and for investigating the design more broadly, which enables architects to develop more adequate concepts if necessary (cf. Chapter 2.3).

Not a linear refinement process

The diagram above (Figure 3-1) might incorrectly give the impression that architectural or structural design is a well-ordered step-by-step process. This is often not the case (cf. Chapter 2.2).

The power of this diagram lies in the description of its terms: 'design question', 'concept', 'design proposition', 'evaluation' and 'criteria', and the mechanism between them. During a design process, it is my belief that the mind of a designer switches easily between different stages in this diagram through the mechanisms described: designing a proposition might lead just as quickly to a design concept refinement (after gaining a better understanding of the design question) as to a new design proposition for the refined concept.

Design vocabulary

A type of interpretation (cf. Chapter 2.3) as a system of thoughts (cf. Chapter 2.5) provides terms or characteristics a designer can use not only to give meaning to a design question, but also to describe and create design propositions. For example, such terms allow a designer to attribute meaning to a precedent as a design solution, which in turn can be used as a starting point for design development (cf. Chapter 2.3).

In architectural design, it is possible to develop very conceptual design propositions that represent a wide range of possible design solutions because various types of interpretation generate terms with abstract descriptive abilities. For example, such abstract terms allow architects to develop and describe architectural prototypes (such as Van Berkel's 'design models') that provide conceptual design answers with no physical form (cf. Chapter 2.3).

In structural design, the applied design vocabulary seems unlikely to generate such abstract design propositions as the architectural design vocabulary does. Many structural design terms are related to an interpretation in structural analysis and provide structural typologies as building blocks for design creation. These typologies are closely related to calculation methods that lead to a limited number of individual design solutions. Design propositions constructed with such typologies will consequently not be able to represent a wide range of design solutions.

A possible way to enlarge the engineer's design vocabulary to allow the development of more abstract design propositions could be to provide more abstract terms that pertain to a type of interpretation other than in-depth structural analysis and calculation methods – a terminology suited to a more general structural understanding. Such abstract terms would enable engineers to describe and develop a conceptual design proposition that finds meaning in an interpretation of its structural logic and would allow them to attribute a wide range of possible structural typologies to its composing structural elements.

A more abstract design vocabulary might enable engineers to acquire better skills in developing conceptual designs or even design concepts (cf. cognitive linguistics in Chapter 2.5).

Conclusions on architectural and structural design processes

Based upon Chapters 2.2, 2.3 and the diagram examined above, the following conclusions can be made:

- The proposed diagram (Figure 3-1) identifies characteristics and mechanisms that are similar in both architectural and structural design process. Various terms are defined, such as design question, concept, proposition, evaluation and criteria.
- A concept broadly answers various issues of a design question that a designer identifies as important to address.
- A proposition is a possible concretisation of a design concept into form and space. This proposition is evaluated through various design criteria a designer identifies as important in answering the design question.
- An evaluation of a design proposition can induce an adaptation of the underlying design concept or of the design proposition alone, leading to a cyclic process until a design solution is found.
- A designer gives meaning to a design question and to a design proposition through terms provided by types of interpretations he or she values in creating a design answer. These terms enable a designer to describe and develop design propositions.
- Architect's and structural engineer's design processes contain a subjective part that depends on personal choices a designer makes. These personal choices have an important impact on the design outcome.
- Architects have generally more tradition and skills in developing concepts and conceptual designs than engineers have.
- Architects tend to be more aware of the variety of valuable design possibilities than engineers, who are often trained to seek a design of the 'right' solution.
- Architects tend to be more skilled in developing subjective argumentation for their design decisions than engineers, who incline more towards objective argumentations of proof.
- Compared to architectural design, structural design seems to lack an appropriate language for describing concepts and conceptual designs as a wide range of possible design solutions.

3.2 Design communication

In Chapter 3.1 it is argued that by developing a concept, designers give meaning to a design question through their personal interpretation of it. Within this personal understanding, a designer then develops a design proposition, which in essence consists of various meanings the designer assigns to it within various types of interpretations (or systems of thoughts, cf. Chapter 2.5). And thus to understand a designer's proposition implies understanding the meaning(s) a designer attributes to his or her design proposition.

In the following paragraphs, we take a closer look at the representation of a design proposition in the early phase of a design process as a communication of meaning(s) attributed by a designer to his or her design proposition. (Special attention is given to the early phase of a design process, as it is essential in the collaboration between architect and structural engineer.)

Conceptual design proposition

In the early phase of a design process, a design proposition is mostly conceptual. Such a conceptual design proposition has the characteristics of a 'general idea' as defined by John Locke:

> a general idea is created by abstracting, drawing away, or removing the uncommon characteristic or characteristics from several particular ideas. The remaining common characteristic is that which is similar to all of the different individuals. (Wikipedia contributors 2012a)

One can define the level of abstraction of a design proposition by the number of possible design solutions it represents: a design proposition has a higher level of abstraction than another proposition if it represents a larger number of design solutions. Or one can say that as a design proposition becomes more detailed and defined, its level of abstraction decreases, as more characteristics pertain to it and the number of possible design solutions it represents decreases. A conceptual design proposition contains a high level of abstraction.

In the following paragraphs we investigate conceptual design propositions – first of architects and then of structural engineers – through case studies.

The architectural conceptual design proposition

In order to develop a comprehension of the relation between an architect's understanding of his or her conceptual design proposition and its representation, two design examples are investigated: (1) a holiday lodge in a natural setting and (2) a sun terrace for a home in the city. Both examples are architectural projects drawn from my practice as structural engineer.

(1) The project of the holiday lodge starts out from a **design question** that includes providing a holiday village with several units in natural settings. These accommodations need to possess distinctive characters and provide for a variety of clients. One of these units is presented here: a lodge situated on a lake.

In this project the architects chose to answer the design question with a **concept** that involved siting the lodge on a lake and giving it a distinctive form. In this project sustainability was considered an important issue, leading to the choice of wood as a building material.

The architectural **design proposition** presented to me was still conceptual (Figure 3-2): only a limited number of design decisions had been taken by the architects. For example, the materiality of the building was developed to a certain point (that of expression), but it was as yet not detailed. As the architects explained to me, the roof had a woody expression but was not defined as plywood, straw, shingles or any other possibility. The same can be said about the materiality of the other elements of the building. This architectural conceptual design proposition, therefore, was not a single design solution but rather a range of different possible solutions with common characteristics. One of these common characteristics, for example, was the woody expression of the roof.

In this thesis, the common characteristics of possible design solutions represented by a (structural or architectural) design proposition will be called *design characteristics*.

Figure 3-2. Representation of an architectural conceptual design proposition.

Beside design characteristics of materiality, this proposition as presented also found meaning in other types of interpretation. One of them was an interpretation of form, which is essential in the collaboration between architect and structural engineer, since form is an important communication medium for design negotiation between designers.

The various drawings presented made it possible to define a three-dimensional geometric form for the building design (Figure 3-3). This form consisted of a plate standing on piles in the water. On this plate were some walls and columns supporting an irregular roof.

In this thesis, the term *form model* will be used to indicate a geometrically defined form that can be represented, for example, with computer-aided design software, two- or three-dimensional drawings or even a physical scale model.

Although the form model presented was clearly defined as one geometrical form through the representation provided, the actual design proposition of the architect found meaning – within an interpretation of form – in more than this one single form model: a whole range of different form models could be attributed to this conceptual design proposition. It is possible to grasp this wide range of possible form models through a more profound understanding of the various meanings the architects assigned to their design proposition.

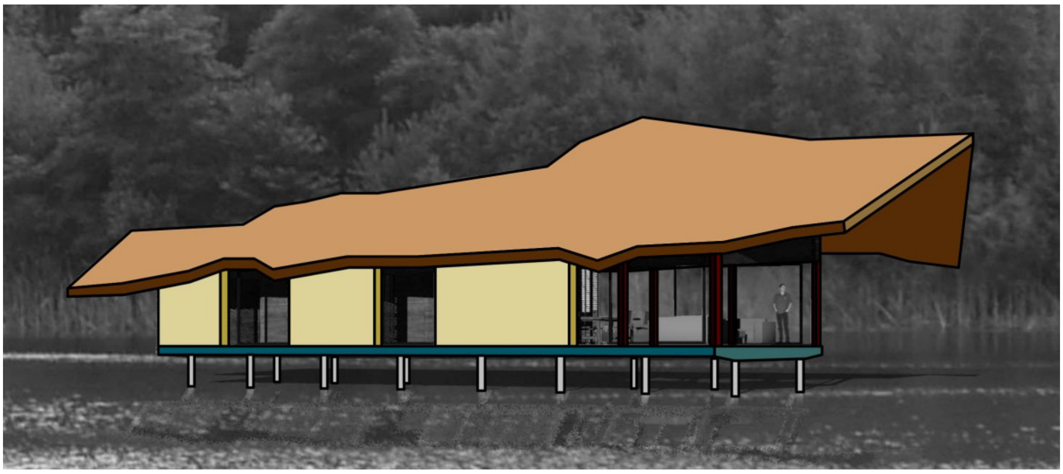


Figure 3-3. The three-dimensional form model of the architectural design.

For example, one of the design characteristics the architects set out for this proposition was that the roof had an irregular shape. The roof in the representation, however, expressed only one possible shape to give form to this design characteristic. In the architects' minds, other roof forms were still possible within the conceptual design proposition they presented (as the white line suggests in Figure 3-4). Within the same conceptual design proposition as understood by the architects, the walls had no fixed positions and could be translated along their axes. Similarly, the columns could be positioned on a grid with no fixed form. (These three design characteristics were in part consequences of the architects' intended expression of the design proposition.)

This leads to the conclusion that the three-dimensional form model as presented in the architectural drawings represented only one solution out of a range of possible form models that would be true to the architectural conceptual design proposition within its interpretation of form understood by the architects. This range of form models can be grasped by a more thorough understanding of the different meanings the architects attributed to their design proposition (Figure 3-4). These meanings were described by design characteristics (e.g. irregular roof) that are to be understood within types of interpretation (e.g. expression) applied by the architects.

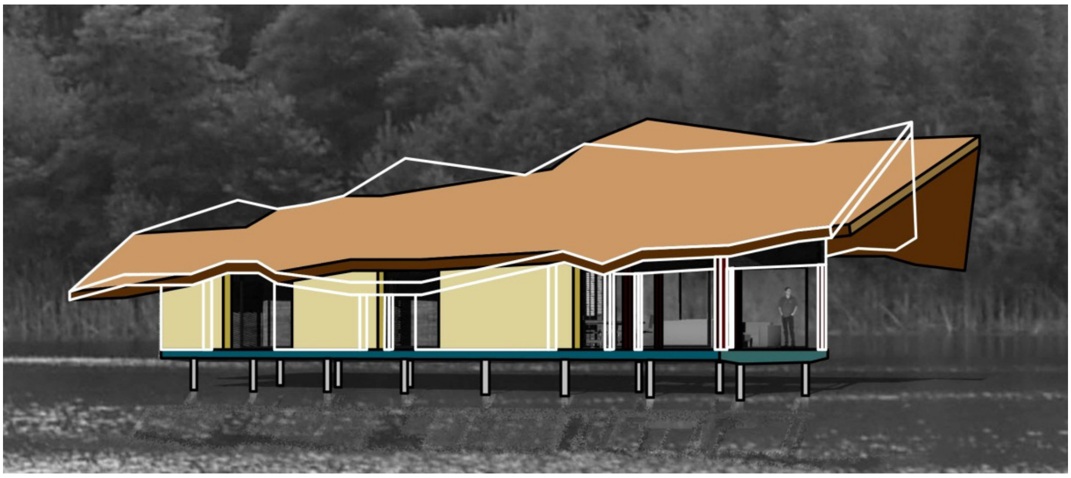


Figure 3-4. The architectural conceptual design as a range of form models.

(2) In order to better understand the design characteristics that pertain to an architect's conceptual design proposition, we examine a second design project: a sun terrace for a home in the city. The conclusion presented here is the result of a discussion and mutually agreed analysis with the involved architects.

In this project, the **design question** included providing a pleasant sun terrace for a small family in an enclosed and small urban garden. The **concept** developed by the architects for this question found meaning in, among other things, an expression of the terrace as a drawer pulled out of an adjacent building. It also entailed catching the sun high above the ground level while providing a theatrical element that afforded a view from above.

The **design proposition** developed by the architects (as a concretisation into form of their design concept) was presented to me as an image of a three-dimensional **form model** and a text with a series of **design characteristics**: it was to be a sun terrace (i.e. exposed to direct sunlight); with the characteristics of a box (i.e. a theatrical element, with a 'view upon'); almost floating in the air; look like a drawer pulled out of a wooden wall; an independent volume; made of wooden materials; built without the use of a crane; and have a transparent railing (Figure 3-5).

Design characteristics:

- Sun terrace: exposed to direct sunlight
- Box: theatrical element, with a view upon
- Almost floating: floating plane, no columns
- Drawer: volume coming out of the wall
- Independent volume
- Wooden materials: wooden surfaces
- Transparent railing: safe and see-through
- Built without crane: everything hand-carried

Figure 3-5. Presentation of conceptual design proposition as image and description.

The conceptual design proposition represented a range of possible design solutions, as many design decisions had yet to be taken: only a limited number of design characteristics (including one geometrical form model) were provided to determine the range of possible architectural design solutions. This also meant that the three-dimensional form model presented was only one of the many possible form models for an interpretation into form the architects attributed to their design proposition.

In conclusion, one can say of both examples that an architect finds meaning(s) in his or her conceptual design proposition through different types of applied interpretations. These interpretations can include form, expression, construction, cost, sustainability, light, comfort, and so on. The meaning attributed by an architect can be expressed by design characteristics that pertain to the applied type of interpretation (cf. system of thoughts in

Chapter 2.5). In a more general sense, one can say that these design characteristics need to be understood within the terminology, logic and culture of the architectural design world (in Belgium). (For example, 'looks like a drawer', as a design characteristic within an expressional interpretation in architectural design, makes little sense within the engineering world.)

Design characteristics are not fixed in time, but relate to a certain design proposition. During the course of a design process, design propositions change: some design characteristics might disappear, while new ones emerge.

There is a hierarchy in these design characteristics: some are more valuable to the architect than others. And as the design process evolves, the architect might give up certain design characteristics in order to maintain others. For example, in the sun terrace project, the expression of the drawer was more important than the idea that it floated, and the structural support was chosen to make it look like a drawer rather than to try to disguise the support and make it appear to float and thus risk losing the drawer expression.

Some of these design characteristics are objectively assessable (e.g. exposed to direct sunlight), others only subjectively (e.g. looks like a drawer). Some are self-imposed by the architect (e.g. expression of a box), others are externally imposed (e.g. built without a crane). And some will be the subject of design negotiations with other design actors (e.g. make it float versus make it strong enough).

Design characteristics express various design criteria the architect takes into account when developing and evaluating an answer to the design question. In a conceptual design proposition, these characteristics are closely related to the architect's design concept, which forms the basis for his or her design answer.

An important type of interpretation of the conceptual design proposition is that of form. In both examples, the wide variety of form models pertaining to the design proposition was expressed by a single form model defined by architectural drawings and accompanied by additional design characteristics. These additional characteristics helped me understand possible changes that could be made to this single form model while staying true to the architects' interpretation of his or her conceptual design proposition as form – for example, whether the terrace could be moved to another location. This location would have to provide the terrace with enough sunlight to maintain the design characteristic of 'sun terrace' in the design proposition.

To conclude, we can state that design characteristics of a conceptual design proposition of an architect are:

- Terms that express the architect's understanding of his or her proposition
- Embedded in the terminology, logic and culture of architecture
- Variable in time
- Hierarchical
- Related to design criteria
- Related to the design concept
- Beneficial for a profound understanding of the proposition as form

The structural conceptual design proposition

In order to have a better comprehension of a structural engineer's understanding of his or her conceptual design propositions and their representation, we now examine an example from my practice as a structural engineer.

The structural design proposition to be investigated (Figure 3-6) was developed for the architectural design proposition mentioned above for a lodge on a lake (Figure 3-2). In this project, the structural **design question** involved proposing a structure to maintain the desired architectural form of the architects' conceptual design proposition. The architects also requested I take into consideration the goal of sustainability and a thereto suitable choice of materials, preferably wood.

A structural **concept** was developed to apply A-trusses in the roof and the already given (architectural) columns with rigid bending supports. For the long cantilevered roof, a system of inclined truss-girders with reinforced free edges was set out. Glulam was chosen for the structure where the sizes could be accommodated by the architectural design and steel where smaller dimensions were required. The combination of both materials also enabled easy construction details. The (visible) tension members of the A-truss were chosen to be cables to express a refinement in structural design.

A conceptual design **proposition** was developed as a concretisation into form and space of the chosen structural design concept. It was presented to the architects as a wire-frame model (Figure 3-6) together with a verbal explanation of various **design characteristics**: an identification of structural elements as typologies like columns and trusses, hints of structural order and logic under horizontal and vertical loads, and indications of structural materials and dimensions. These design characteristics gave a (limited) expression of various meanings I found in this design proposition: flow of forces, functions of elements and their connections, expression, form, construction, cost and so on.

This was a conceptual design proposition as it represented a range of structural design solutions, with various design decisions still left open and only a limited number of design characteristics decided. (The exact position and size of elements, materials and dimensions, detailed connections and so on were not as yet decided.)

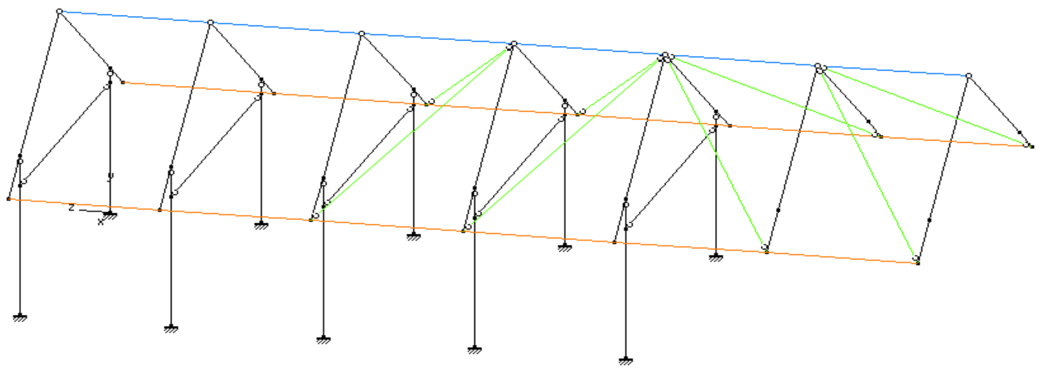


Figure 3-6. Representation of a structural conceptual design proposition.

An important interpretation of the structural proposition in this architectural project was that of form, as it provided a direct relation with the architectural design proposition. The three-dimensional wire-frame (Figure 3-6) gave expression to only one (general) structural **form model** (Figure 3-7, left upper form model) out of the range of form models that could be attributed to my structural proposition. By understanding additional design characteristics, it would be possible to grasp this wide range of possible form models.

For example, in this case the structure of the roof consisted of a series of independent A-shaped trusses. This A-shaped truss as a structural typology was one of the design characteristics of the structural design proposition. This characteristic (within an interpretation of structural logic) implies, for example, that the configuration of the various structural elements of such a truss is A-shaped, but not that a specific height is to be maintained. The presented form model of the wire-frame could thus be altered within the structural logic of this A-truss characteristic. This means that within the presented structural design proposition, the architectural design characteristic of an irregular roof could be obtained by attributing changing heights to the different A-trusses while maintaining the A-shaped configuration (Figure 3-7, right upper form model).

Within the same structural conceptual design proposition, more alterations of the presented structural form model could be developed through an understanding of the proposition's design characteristics. For example, the distance between the A-trusses could be changed (Figure 3-7, left lower form model) or certain A-trusses could be translated perpendicular to the main axis of the form model (Figure 3-7, right lower form model). These form model changes remain true to the design characteristics of the structural design proposition. In other words, the various form models presented in Figure 3-7 have the same common structural characteristics (e.g. order and functions of the various elements) that pertain to my understanding as structural designer of my conceptual design proposition.

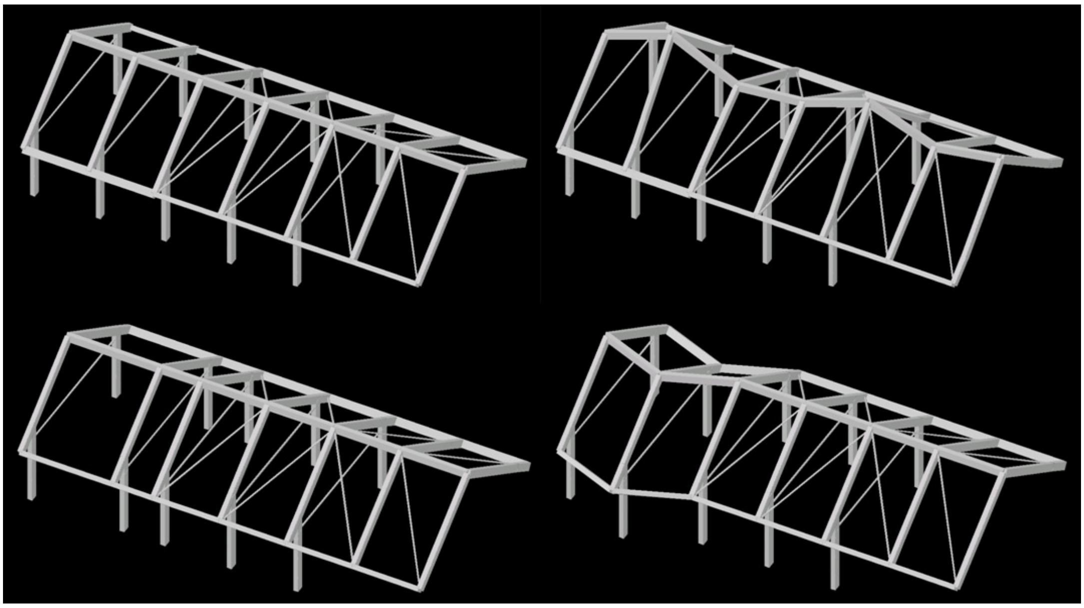


Figure 3-7. Four possible form models of the presented design proposition.

In conclusion, one can state that a structural conceptual design proposition often finds meaning as a configuration of structural elements (e.g. beams, columns, ties and slabs), and the way these elements are connected to one another and to their supports (e.g. bending stiff or rotation free). It is a translation into form of a structural strategy developed by the engineer, to transfer loads to the supports while keeping the structure strong, stiff and stable: the engineer has made general design decisions to identify loads, supports, structural elements, the structural order of these elements and their individual structural functions. In a conceptual design proposition structural elements are not completely designed yet: their materiality and dimensions are mostly undecided, although by the structural functions they are to perform, a rough idea is already formed. As such, a conceptual design proposition represents a range of structural design solutions with certain common characteristics.

Such a common characteristic or design characteristic finds meaning within a type of interpretation or system of thoughts by the structural designer. These types of interpretation can vary from general stability to in-depth structural analysis, and can include structural aesthetics, construction, sustainability, structural form and so on. In a more general sense, one can state that structural design characteristics are to be understood within the terminology, logic and culture of structural engineering.

There is a hierarchy in these design characteristics: certain characteristics can be more important than others (e.g. maintaining the A-type truss might be more important than making it all in the same structural material).

As the design evolves, the characteristics of the different design propositions can vary in time: the hierarchy of importance can vary, new design characteristics can emerge and old ones disappear.

Through calculations, certain design characteristics can precisely and objectively be assessed (e.g. the structural function of an element); others can only be subjectively assessed by the engineer designer (e.g. expression of structural logic in the configuration of the elements). Some are self-imposed by the engineer (e.g. tie as a cable); others are externally imposed (e.g. limit of transportation length of elements). And some will be the subject of design negotiations (e.g. structural form enclosed within architectural form).

As with architectural design propositions, design characteristics express various design criteria the engineer takes into account when developing and evaluating an answer to the design question. In a conceptual design proposition, these characteristics are closely related to the engineer's design concept, which forms the basis for the design answer.

The construct of performing alterations on a given structural form model through an understanding of additional design characteristics is similar to that performed on a given architectural form model. One difference is that important structural design characteristics that find meaning in an interpretation within structural analysis operate within a more general, objective (structural) logic to develop and asses form model alterations, whereas many architectural design characteristics operate more within the personal, subjective logic of the architect designer.

Still, in structural design there are also design characteristics with a more subjective nature that do not allow the application of an objective structural logic. For example, in the above proposition all elements under tension are assumed to be cables as a way to express design refinement. And thus changing a tie in this form model into a more massive element – which would not affect its structural function – is not part of the given proposition (such a subjective design characteristic would, however, be negotiable).

To conclude we can state that design characteristics of a structural conceptual design proposition are:

- Terms that express the engineer's understanding of his or her proposition
- Embedded in the terminology, logic and culture of structural engineering
- Variable in time
- Hierarchical
- Related to design criteria
- Related to the design concept
- Beneficial for a profound understanding of the proposition as form

Representation of conceptual design propositions

To understand a conceptual design proposition is to understand the various meanings a designer attributes to his or her proposition. In the above, special attention is given to the interpretation of the form of a conceptual design proposition, since form is an important medium in which architectural and structural design meet. A conceptual design proposition is often understood by a designer as a range of possible form models but not necessarily presented as such: it is not unusual in design communication that only one possible form model is put forward in the various drawings or images (cf. design examples in the above).

However, grasping the implied range of possible form models provides a collaborating designer with more possibilities to develop a creative response. For example, the engineer Cecil Balmond shows in his project of the villa in Bordeaux how he interprets the initial conceptual design proposition of architect Rem Koolhaas in a variety of possible form models (Figure 3-8) that give him the freedom to be creative in structural design without developing a response outside the architect's intended design proposition (Balmond 2002).

The ability to grasp the implied range of possible form models requires a more profound understanding than one presented form model alone provides. In this thesis I argue that this profound understanding can be enabled through expressing and apprehending design characteristics other than the given form model. These design characteristics describe various meanings a designer attributes to his or her proposition as shown in the above. (Research in the fields of architecture, engineering and construction has already shown the need for complementing the form model with additional disciplinary information in order to promote creative design collaboration between different professions (cf. Chapter 2.5).) Understanding these additional design characteristics then not only provides a logic to change the one presented form model into the implied range of possible form models, it also provides a more profound understanding of the different meanings a designer attributes to his or her design proposition. And thus a representation of a conceptual design proposition should not only express one form model, but also additional design characteristics (Figure 3-9).

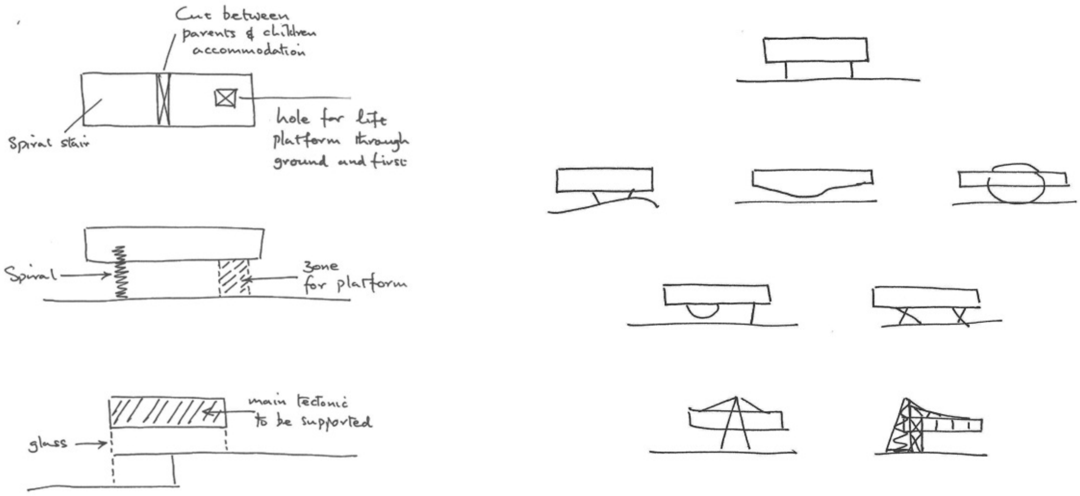


Figure 3-8. Koolhaas' conceptual design; Balmond's variety of form models.

Design characteristics find meaning in the first place in the designer's own system of thoughts, but are generally to be understood within the paradigm of the discipline: they are embedded in the terminology, logic and culture of that discipline. This means that for an engineer to properly understand the design characteristics of an architect's proposition, the engineer must be sufficiently acquainted with the design paradigm of the architectural discipline. In the same way, an architect needs to sufficiently understand the terminology, logic and culture of the structural design paradigm in order to grasp structural design characteristics. In other words, the success of a communication of conceptual design propositions depends on the various designers involved sharing a common knowledge system and similar culture and experiences, leading to similar systems of thought in regard to the conveyed meaning (cf. Chapter 2.5). This interdisciplinary communication is a balance between sufficiently expressing the essence of a discipline-related message and limiting the use of discipline-specific knowledge.

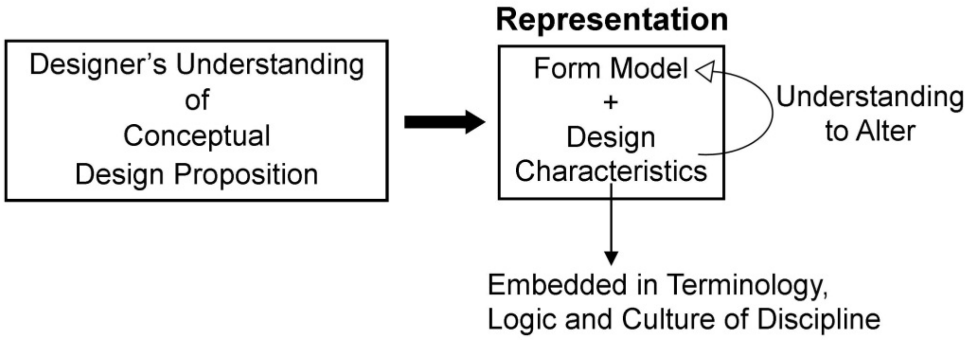


Figure 3-9. Communication of conceptual design proposition.

When conceptual design propositions are communicated between designers, attention should be given to filter the total available information of such a design proposition (cf. Chapter 2.5). Presenting a conceptual design proposition not only as a form model but also through an articulation of its defining design characteristics is already one way of bringing attention to what the designer finds essential in the design proposition while leaving out non-essential information. (A representation of a single form model alone can risk calling attention to elements that are not of relevance to the designer.)

Still, it is possible that certain design characteristics of a design proposition contain information that is superfluous for the other designer. Therefore a selection should be made that filters out design characteristics that do not affect the design process of the other player. This is on the level of the disciplines (e.g. the architectural preference for a colour does not normally play a role in structural design), but also on the personal level of the designers (i.e. based on the designer's experience in designing and the established collaboration experience between the two specific designers). For example, some architects prefer to show the structural story, while others prefer to hide it. Such a difference requires a different information exchange between designers (Luyten 2009b).

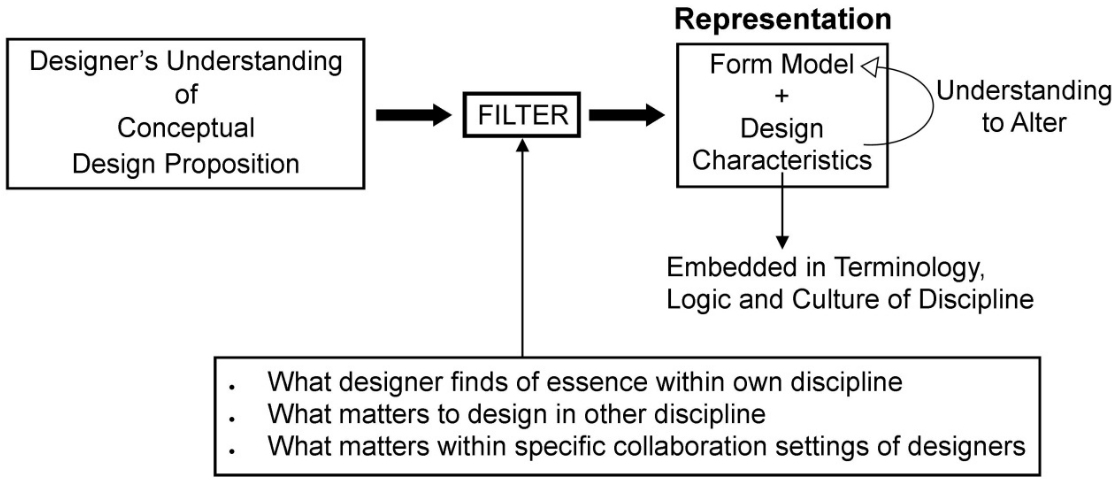


Figure 3-10. Filtered communication of conceptual design proposition.

Design communication in face-to-face meetings

From a communication perspective, the face-to-face meeting as an instrument for collaboration has many benefits. Face-to-face communication enables feedback on the information given, which reduces the chance of miscommunication. Furthermore, in this collaboration between architect and engineer, quick responses to questions keep the stream of design thoughts going (e.g. quick structural responses from an engineer in an architectural design process is an important element in a successful collaboration between architect and engineer (Lawson 2004, p.22)). Face-to-face meetings thus provide an interesting communication setting for design negotiations between architects and structural engineers.

Representations created during face-to-face meetings as a tool for communication and collaboration should be unambiguously interpretable, easy and quickly produced and unrestricting to thinking processes, which indicates the importance of (qualitative) sketching during design meetings (cf. Chapter 2.5).

The design processes of both architects and structural engineers involve an important subjective aspect in which the designer influences the design outcome through his or her personal choices (e.g. in concept design and in design evaluation; cf. Chapter 2). In design negotiations, architects and structural engineers mainly address this subjective aspect of their design, since it is negotiable. (Objective, procedural design processes are not negotiable as they always deliver the same outcome for a certain input independent of the operator.)

This means that conceptual design negotiations generally involve the use of subjective argumentations and not of objective proof. Architects are more acquainted with a handling of subjective argumentations than engineers, requiring of the engineer extra effort and attention during design negotiations (Ahearn 2000).

Subjective argumentations in design communication often make use of metaphors as a powerful tool to communicate ideas, concepts and nuances. Balmond, for example, describes the beginning of his design collaboration with architect Daniel Libeskind as ‘we exchanged metaphors’ (Balmond 2002). A study by Paloma Ubeda Mansilla shows that architects often use metaphors to explain essential aspects of their design to clients and to fellow architects, but use far fewer metaphors in their design communication with engineers (Ubeda Mansilla 2003). This seems to indicate that architects tend to leave out essential aspects of their design proposition in their communication with engineers, or at least give a different nuance in their storytelling. Architects should give attention to a sufficient communication of architectural design characteristics with the structural engineer to convey their essential understanding of their design proposition.

Conclusions on conceptual design communication

Conceptual design propositions represent a wide range of possible design solutions with common design characteristics.

Understanding a conceptual design proposition implies understanding the various meanings a designer attributes to his or her own proposition.

Design characteristics give expression to these meanings. A meaning and the design characteristics that describe it are to be understood within a type of interpretation (e.g. expression, form and cost) applied by the designer.

The representation of a conceptual design object as form requires additional communication of design characteristics to sufficiently convey a designer’s understanding of his or her conceptual design proposition.

Design form is an important medium for design collaboration between architect and structural engineer. In order to grasp a designer’s translation into form of his or her conceptual design proposition as a range of possible (geometrically defined) form models, a communication of one possible form model needs to be complimented with additional design characteristics.

The design characteristics of a conceptual design proposition reveal what a designer values in his or her design, and are therefore closely related to the design concept and the various evaluation criteria the designer considers important.

Design characteristics are embedded in the terminology, logic and culture of a design discipline and consequently require sufficient disciplinary knowledge to understand.

A designer may value one design characteristic over another in his or her design proposition, and as propositions evolve so also do design characteristics.

Face-to-face meetings combined with qualitative sketching are recommended for a communication of conceptual design propositions, where attention needs to be given to an appropriate filtering of design information.

3.3 Design collaboration

In order to describe multi-disciplinary design collaborations in which designers of different disciplines are dependent on each other's design decisions to optimize their own design, three types of protocol have been developed in game theory (cf. Chapter 2.4).

One of these protocols is the sequential or Staeckelberg leader/follower protocol (cf. Figure 2-3). It follows a linear process in which the leader first finalizes his or her design before delivering this information to the next designer (i.e. the follower), who is then able to optimize his or her own design. In this protocol the leader establishes a Rational Reaction Set to predict what information is required from the follower's design outcome to optimize his or her own design.

This linear leader/follower protocol can be applied to certain collaborations between architects and engineers in which the architect is the design leader and the engineer the design follower. In the following paragraphs, this protocol is further developed to investigate and describe a design collaboration in which the architect doesn't just inform the structural engineer unilaterally, but both designers mutually inform each other of their design process. This development is accomplished by enhancing the leader/follower protocol with a delay decision strategy (cf. Chapter 2.4) and the developed understanding of conceptual design propositions as form model and additional design characteristics of Chapter 3.2.

Development of a protocol for a mutually informed design collaboration

In certain architectural design projects, the architect designs a detailed architectural proposition in which the architectural form is decided without the involvement of a structural engineer. This architectural proposition is then presented to a structural engineer, who designs an adequate structure for it. In such a collaboration, the Staeckelberg leader/follower protocol identifies the architect as design leader and the engineer as design follower.

The first steps in structural design are thus taken by the architect. (It is possible, for example, that the architect has foreseen a system of beams and columns – as formal elements – in the architectural design proposition, which the structural design must then accommodate.) These first steps in structural design are based on the architect's knowledge and expectations for the outcome of the structural engineer's design process. In the Staeckelberg leader/follower protocol, this knowledge is represented by the Rational Reaction Set of the structural engineer's design outcome: it is what can be expected as the outcome of the structural engineer's design process in relation to the input of the architect's design.

With an adequate Rational Reaction Set of the engineer's design, the architect is able to produce a design proposition that determines the architectural form but allows the engineer to design an appropriate structural design solution without creating a design conflict. In such a case, the engineer designs a structure that fits the given architectural form model without compromises (i.e. the structural design does not affect the architectural design).

It is not unusual, however, that the engineer is not able to design a structure that will not affect the given form model of a detailed architectural design proposition. In such a case, the engineer can become the design leader by deciding to alter the given architectural form model in such a way that an adequate structure can be designed to fit this altered form model (i.e. [Form Model'] in Figure 3-11). It is then the engineer's Rational Reaction Set of the architect's design that will help the engineer in making architectural alterations that the architect is likely to accept (or to be more precise, to develop a structure that will lead to an architectural design solution). In such a case the architect – now as design follower – is presented with a structural design proposition that affects the initial architectural form model as it was presented to the engineer.

If the architect is not able to design a qualitative design solution for the given structure, the architect will then design a different architectural form model he or she hopes will lead to an adequate structural design solution from the engineer. Again, the architect's Rational Reaction Set of the engineer's design will help the architect in deciding which different form model might be successful. And so a cyclic process can develop in which the architect and the engineer adjust the total design until they arrive at a design solution both find sufficient within their own disciplinary design (Figure 3-11).

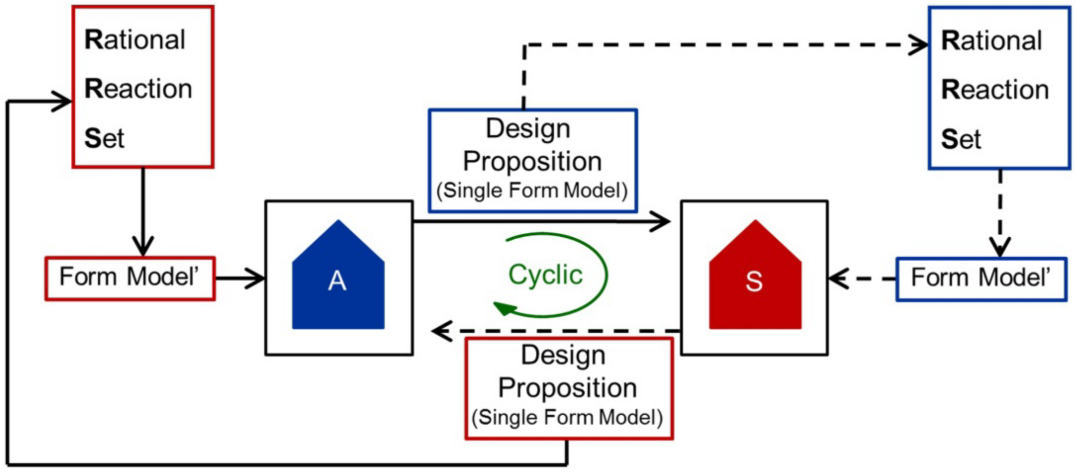


Figure 3-11. Developed cyclic protocol for architect (A) and structural engineer (S) with single form model communication.

The Rational Reaction Set is established through general disciplinary knowledge, but also through experiential knowledge of the collaboration with a specific designer: for example, certain types of structural solution may be preferred by some engineers more than others.

A cyclic process of presenting design propositions to each other helps designers improve their Rational Reaction Set: each player's design proposition is a direct response to the other's proposition and is as such an addition to the Rational Reaction Set specific to this project. In other words, each design response to a proposition helps the designer better predict the design outcome for the next design proposition he or she will make (at least when these design outcomes are related to the same specific project).

The diagram of cyclic design collaboration between architect and structural engineer shown in Figure 3-11 presumes a communication of design propositions in which form is decided, and thus a conveyed proposition only represents one single form model as a design solution. Research in the architecture, engineering and construction industry has shown the importance of communicating a range of design solutions instead of a single design solution to establish a delay decision strategy. This delay decision strategy prevents unnecessary design conflicts caused by ill-informed design decisions (cf. Chapter 2.4). This requires the architect to communicate only those architectural design decisions that are well informed by presenting an architectural design proposition as a range of possible design solutions. And in return the engineer presents only well informed structural design decisions in his or her proposition to the architect through a range of possible design solutions.

A conceptual design proposition represents such a range of design solutions in which design decisions are still left open and form is still under investigation. As described in Chapter 3.2, a conceptual design proposition can be understood as a form model and design characteristics in which sufficiently comprehending these characteristics is essential to grasping the range of solutions for which the following designer can choose to develop an adequate design. Understanding these design characteristics improves the accuracy of the Rational Reaction Set, since it enables the designer to change a presented form model within the designer's understanding of his or her design proposition as form.

Through a communication of conceptual design propositions as form model and design characteristics, a cyclic collaboration process can develop in which both designers inform the other of their well-informed design decisions while delaying design decisions until they are sufficiently informed by the other designer. This enables a collaboration process in which architectural design is structurally informed and structural design is architecturally informed from early in the design process (Figure 3-12).

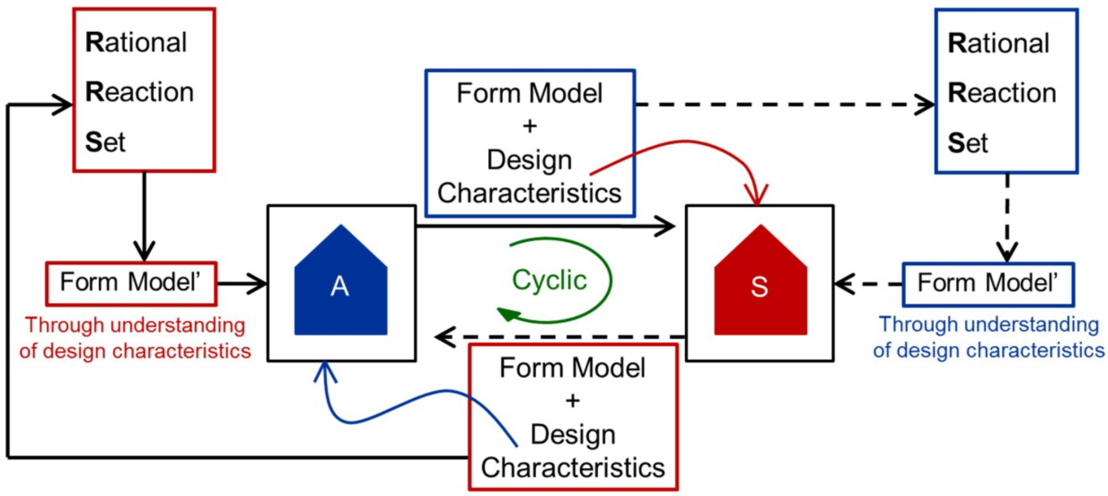


Figure 3-12. Developed protocol for mutually informed design collaboration.

Besides enabling a delay decision strategy, communicating design propositions as a form model and additional design characteristics provides more benefits. In order to resolve conflicting design propositions (e.g. on the level of their form), it is essential that each designer understands the range of possible design solutions implied by a proposition. This understanding can be engendered through a comprehension of the various design characteristics of the proposition (cf. Chapter 3.2). Instead of addressing possible design solutions in design negotiations, it is more efficient to directly address the underlying design characteristics that define the various implied design solutions. Design negotiation then involves bringing the divergent design characteristics of the two propositions into congruence.

The design characteristics of conceptual design propositions are closely related to the underlying design concept, and reveal which criteria each designer values for his or her design evaluation (cf. Chapter 3.2). Having the design characteristics of both propositions in harmony allows both designers to evolve their designs towards a common goal. This common goal is essential for both designers to work as a design team towards synergy and not as independent designers interested only in the quality of their own design outcome instead of the quality of the overall project (cf. Chapter 2.4).

Another interesting aspect of making design characteristics explicit in design communication is that a design characteristic can become part of the other's design process: what one designer values in his or her design (i.e. design characteristics) can become a design aim for the other designer. Incorporating such extra-disciplinary design characteristics in one's own design process can sometimes lead to novel approaches to design and to creative output within one's own discipline. This output is then a product of knowledge from two design disciplines that would not have been developed within one design discipline alone (i.e. multi-disciplinary design creativity, cf. Chapter 1.2).

For example, in the Bordeaux villa by Rem Koolhaas, one of the several design characteristics of the architect's conceptual design proposition is that the building should fly (Figure 3-13). This characteristic then becomes a design aim for the structural engineer, Balmond, as he tries to develop a structure that expresses this characteristic: here structural design partly develops along an architectural design path. It requires the engineer to approach structural design in an unusual way, and leads to a creative solution – not only exceptional to the engineer but also to the architect.

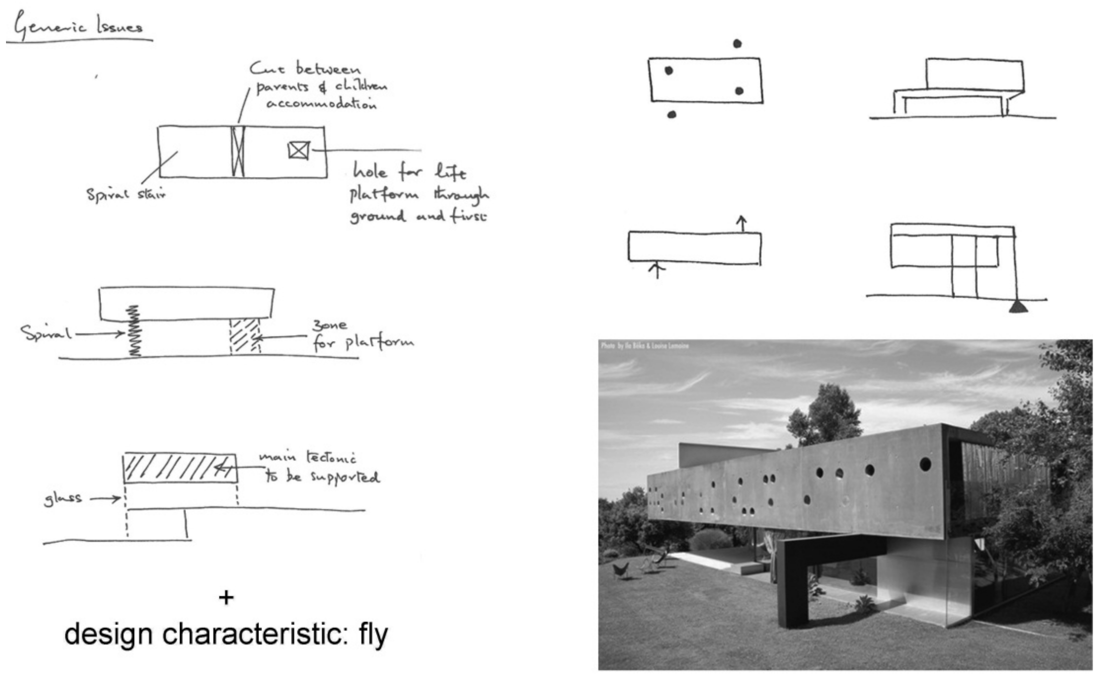


Figure 3-13. Proposition architect; structural concept and built solution.

The protocol developed here for a collaborative design process might give the impression that such a collaboration between architect and engineer consists of a cyclic process in which design is only a process of refinement as each cycle better informs each designer in order to make more well-informed decisions. Although such a process might occur, it is also possible to have important design shifts when, for example, within one discipline the design concept itself undergoes a major change. This protocol does not preclude such design shifts in the process; it merely brings to the fore certain mechanisms involved in a multi-disciplinary design collaboration.

Implementing the developed protocol on an example

In order to clarify the various terms and mechanisms of the protocol described above, we now apply this protocol to the collaboration project of the canopy roof introduced in Chapter 1.1.

When the involved architect presents me with her design proposition for the first time, it still is very conceptual: materials, details and even certain aspects of the general form still need to be decided. As such, her conceptual design proposition represents a **range of design solutions** rather than one single design solution.

This conceptual design proposition is conveyed as a **form model and design characteristics**. The form model is presented as a floating slab positioned between a series of boxes, and the main design characteristics of the proposition are that the roof is floating, connecting the various objects on the site, and – in the beginning of the collaboration – disappearing into the surrounding woods by having as few supporting columns as possible.

The architectural form model thus presented does not allow for a structure without changing its form. This requires that I alter the form model as presented so that an appropriate structure can be designed. This alteration of the architectural form model, however, will need to be approved by the architect in order to come to a design solution. More precisely, the structure I develop for this altered form model will need to enable the architect to develop a satisfying architectural design solution.

It is my understanding of architectural design, and in particular of the desires of this architect in her design choices in general and in this specific case, that helps me in making a successful alteration of the presented architectural from model. This knowledge forms the basis of my **Rational Reaction Set**. It gives me an idea of what the consequences in architectural design will be of my structural design decisions. It tells me, for example, that putting too many visible columns in the structure in order to reduce the structural cost will result in an architectural form that conflicts with the architect's design desires. The Rational Reaction Set helps me in making structural design decisions that will affect the architectural design.

In this particular case, my Rational Reaction Set becomes more accurate through the architect's communication of her design proposition as form model and design characteristics. These design characteristics give an enhanced understanding of what the architect values in her proposition that the form model alone cannot provide (e.g. disappear into the surrounding woods). They (partly) give expression to the design concept and the different evaluation criteria the architect chooses as important. Throughout the collaboration, special attention must be given to externalizing these design characteristics rather than merely relying on a limited implicit communication using only images of the design object.

Before the face-to-face meeting, there was sufficient information for me to design a structural solution (with few columns) for the presented proposition. In this project, several different design solutions are possible, so designing a specific, detailed structure means that I leave out certain architectural design solutions that would contain equally valid structural solutions. My choice of a structural design solution, however, might not be sufficiently informed by architectural design, as certain of the solutions I left out might have led to better architectural design solutions. Therefore we choose to communicate *conceptual design propositions* instead of *single design solutions* in order to leave ill-informed design decisions open while still communicating well-informed decisions. This **delay decision strategy** enables the architect to direct me toward the structural design solution that provides the most qualitative architectural design, and allows me to guide the architect in her design towards a sound structure.

In this project I sensed a contradiction in the two design characteristics of ‘having as few columns as possible’ and the canopy roof as a ‘connecting element’ between the various boxes and the dormitories: the first design characteristic would divide the roof into two types of structures, while the second design characteristic seemed to require one element. During the workshop these partly **conflicting design characteristics** are **negotiated** and a new set of design characteristics is decided upon: the canopy roof becomes an ‘independent connecting element’ and the number of columns is no longer a design characteristic, as long as the columns become part of the surrounding woods. This negotiation of having the different disciplinary design characteristics in **congruence** is an important element to make sure that both designers are heading in the same design direction so a synergistic collaboration can occur.

At the end of the workshop, I explain to the architect the structural logic of the structural system that will be applied for the canopy roof. This is also a communication of a form model and design characteristics. The form model is the structural configuration of the various elements (although these elements are still conceptual and represented by simple lines). The design characteristics are the identification of the structural elements, their load and supports, the path the load follows through the structure, the way the different elements work structurally (i.e. structural functions like bending or compression) and the way they are connected. This understanding helps the Rational Reaction Set of the architect to eventually **alter my structural form model** within my conceptual design proposition by placing the columns in every possible direction. Because these alterations remain true to the structural design characteristics that I have set, I can finalise my design process and dimension the structure with no problem. As these design characteristics are taken into consideration when making changes to the structural form model, one can say that the architect is **sufficiently informed** about the structural design to make her own design decisions without causing negotiation conflicts.

In this project, this **cycle** of the two sides communicating design propositions to each other and each designing further within his or her own discipline occurs several times before a solution is found. These cycles become even more intense during a face-to-face meeting in which each designer gains information from the other in a very short time and each designer is actively designing during the meeting. In this meeting, various possibilities are investigated by **each designer incorporating the other's design characteristics** into his or her own design process. For example, the desire of the architect to have a flat roof leads my structural design process to a search for structural details in which no structural elements are sticking out. In this manner I am being creative not only within the field of engineering but also of architectural design, which in my view can be defined as **multi-disciplinary creativity**. In the same way, the architect designs the configuration of the structural system by taking into account my structural design characteristics and her architectural design aims. The result is a design emerging from a multi-disciplinary creativity.

Conclusion on a mutually informed design collaboration

The protocol presented in Figure 3-12 for a mutually informed design collaboration between architect and structural engineer provides for a delay decision strategy through a cyclic process of information exchange. This information exchange is formed through a communication of conceptual design propositions as a range of design solutions, where ill-informed design decisions are left open and well-informed design decisions are established and communicated.

In this protocol, conceptual design propositions are communicated as form model and design characteristics. These design characteristics give expression to the designer's essential understanding of his or her proposition.

Understanding the design characteristics of the given design proposition improves the Rational Reaction Set. This Rational Reaction Set helps each designer predict the consequences of his or her own design decisions for the other's design. An accurate Rational Reaction Set provides for an efficient design collaboration.

Design negotiations involve establishing congruence between the different design characteristics of the two design propositions. This leads to the development of a common design goal for both designers, which is essential for collaboration synergy.

3.4 Proposals for a mutually informed design collaboration

Based on the understanding of the architect's and the engineer's design processes developed here (cf. Chapter 3.1), their conceptual design communication (cf. Chapter 3.2) and mutually informed design collaboration (cf. Chapter 3.3), a set of collaboration proposals can be formulated to support a mutually informed design collaboration:

- Attention should be given to an explicit communication of design characteristics of a conceptual design proposition in addition to a presented form model.
- Design information should be filtered in order to bring to the fore the essence of a conceptual design proposition, and should be tailored to the receiver's design discipline and design preferences.
- The different design characteristics of both conceptual design propositions should be developed towards congruence.
- A cyclic information exchange should be employed, with conceptual design propositions presented as a range of design solutions and design decisions delayed until sufficient information is obtained.
- Face-to-face communication should be provided where information exchange is supported by sketching.

These collaboration proposals are applied and investigated in various cases that are described in the second half of this thesis. A series of conclusions is then formulated in Chapter 9.

4. Exploratory and explanatory research through case studies

This chapter presents the applied research approach in a number of case studies. This approach is derived from participatory action research and case study research. Both types of research enable an investigation of phenomena within their natural settings, as these phenomena are hard to distinguish from their context.

First, various characteristics of participatory action research and case study research are described in their relation to the applied research approach, followed by different applied methods of data retrieval in the different cases.

4.1 Participatory action research

Because of the important influence of the designer on the design process, I have chosen a research approach that focuses more on understanding human behaviour and the mechanisms that influence such behaviour instead of an empirical registrations of facts: the focus is more on 'why' and 'how' than on 'what', 'when' and 'where'.

This brings the applied research approach within the scope of qualitative research methods. According to Norman Denzin and Yvonna Lincoln, 'Qualitative research is a situated activity that locates the observer in the world. ... This means that qualitative researchers study things in their natural settings, attempting to make sense of, or interpret, phenomena in terms of the meaning people bring to them' (Denzin & Lincoln 2003, p.3). Both state that qualitative investigators think they can get closer to the actor's perspective than quantitative researchers because the latter rely on more remote, inferential empirical materials.

Concerning quantitative and qualitative research, Robert Stake states that

> the distinction is not directly related to the difference between quantitative and qualitative data, but a difference in searching for causes versus searching for happenings. Quantitative researchers have pressed for explanation and control; qualitative researchers have pressed for understanding the complex relationships among all that exists. (Stake 1995, p.37)

One possible approach in research is for the investigator to try to understand these complex relationships by taking part in the events. In this case it means that the researcher is actively involved in the design processes under investigation as a structural engineer. This position enables the researcher to experience and analyse the dynamics between architect and structural engineer as a participant, but also to have a close look at the mental mechanisms involved in a structural design process through reflections on his own action.

In this doctoral research, the participating researcher can rely on more than fifteen years of experience as a structural engineer collaborating with different architects, and as a teacher giving structural consultation to architecture students in their design studios. This experience is an asset to establishing design conditions close to their natural settings when investigated. (No additional training is required for the researcher to be able to play his part in these events.) What's more, the researcher's structural design and collaboration experience can act as a benchmark when analysing the investigated events. On top of this experience, the researcher is educated as an architect, enabling him to relate to the mechanism involved in the architect's design thinking when analysing research data.

As a practicing engineer and teacher, a wide range of qualitative events are available for investigation. These events are various collaborations between architects and a structural engineer, and structural consultations between a teacher and architecture students. These opportunities are used to pursue a research approach in which changes are implemented in on-going events in order to investigate their effect and establish a better understanding of the mechanisms involved. This is an effective approach for exploratory research because of the complexity of these mechanisms.

The research approach developed starts with implementing change(s) with a broad impact (e.g. having architect and engineer work together very early in the design process) on an event (e.g. a design collaboration), and analysing its/their effect(s) in order to develop a better understanding of various mechanisms involved. This understanding allows the implementation of the approach on following occasions to be more directed and the scope of the analysis to be more focused on specific effects (e.g. structural communication through the newly developed language and its effect on the architect's ability to design with the given structural information). This research approach enables an exploratory research that leads to a better understanding of the investigative mechanisms in order to develop improvements to these mechanisms.

This research approach is related to Participatory Action Research, sometimes called simply Action Research, which engages in a cyclic problem solving process of planning, acting and reflecting in which the researcher participates in the practice that is being investigated in action. Kurt Lewin introduces the term 'action research' as 'a comparative research on the conditions and effects of various forms of social action and research leading to social action' by applying 'a spiral of steps, each of which is composed of a circle of planning, action, and fact finding about the result of the action' (Lewin 1946). The problems or issues that participatory action research addresses lie in the practices of people working in teams. To improve such practices, new courses of action are proposed, implemented and evaluated. In this process of 'learning by doing', new proposed courses of action are guided by previous evaluations.

The role of the researcher is not only to be submerged in the action as an active participant, but also at the same time to supervise and evaluate the course of action. This triple assignment puts the researcher in a challenging position. William Torbert calls it 'consciousness in the midst of action' (Torbert 1991, p.221).

According to Ernest Stringer, action research is 'based on the proposition that generalized solutions may not fit particular contexts or groups of people and that the purpose of inquiry is to find an appropriate solution for the particular dynamics at work in a local situation' (Stringer 2007, p.5). But besides solving particular problems and issues within a local situation, action research also strives to developed knowledge that overcomes the local situation and furthers disciplinary knowledge.

Stringer states that action research in it most effective forms is phenomenological (it focuses on people's actual lived reality), it is interpretive (it focuses on their interpretation of acts and activities), and it is hermeneutic (it incorporates the meaning people make of events in their lives). This kind of research provides the means by which the involved stakeholders explore their experience, gain greater understanding of events and activities, and use that extended understanding to construct effective solutions to the problems under investigation. Action research takes into account the deeply seated social and cultural forces of the community setting (Stringer 2007, p.20) and tailors the found improvements for the investigated issues to the specific practice. Special attention is required to translate such tailored improvements to other practices.

One way of presenting action research is by the spiral of its cyclic research activities: 'planning a change, acting and observing the process and consequences of the change, reflecting on these consequences, and then re-planning, acting and observing, reflecting, and so on' (Kemmis & McTaggart 2000, p.595). There are several variations on this action research cycle. Two of them will be presented here.

(1) According to Stringer, research activities can be described in three major groups: look, think and act (Stringer 2007, p.8). Look stands for the activities through which relevant information is gathered and the situation is defined and described. Think is the activity of exploring and analysing the situation in order to interpret and explain how or why things are as they are. Act is the activity of planning the next course of action, and implementing and evaluating it.

A Basic Action Research Routine

Look	• Gather relevant information (Gather data) • Build a picture: Describe the situation (Define and describe)
Think	• Explore and analyse: What is happening here? (Analyse) • Interpret and explain: How/why are things as they are? (Theorize)
Act	• Plan (Report) • Implement • Evaluate

Table 4-1**.** A Basic Action Research Routine (Stringer 2007, p.8)

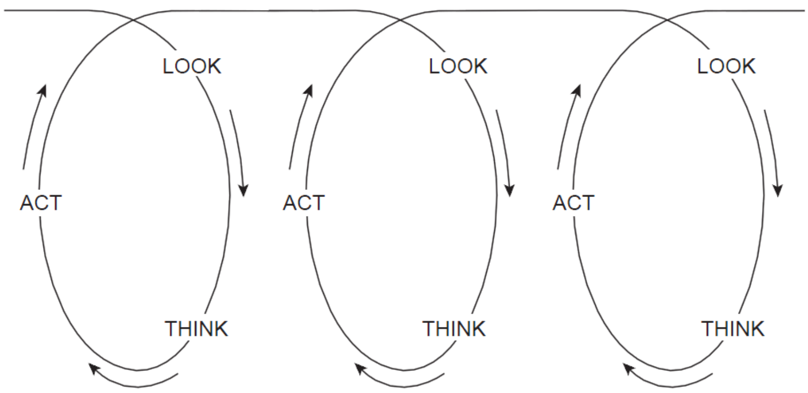


Figure 4-1. Action Research Interacting Spiral.

In the doctoral research presented, the first action research spirals involve a more general, explorative investigation into the mechanisms of structurally informed architectural design, while in later spirals more specific, explanatory investigations take place. Each spiral provides a better understanding of the mechanisms involved, which makes it possible to develop a more directed and precise investigation in the following spiral.

Although this diagram gives the impression that action research is a neat and orderly activity in which participants proceed step-by-step to the end of the process, in reality it is not. ‘People will find themselves working backward through the routines, repeating processes, revising procedures, rethinking interpretations, leapfrogging steps or stages, and sometimes making radical changes in direction’ (Stringer 2007, p.9).

(2) An attempt at a diagram that better expresses the messy real world of practice in action research is provided by Morwenna Griffiths (Griffiths 1990, p.43). Here feedback is going in many directions at once. Griffiths's diagram contains an extra inner loop that is related to the reflection in action of Schön (Schön 1983), and an extra outer loop that is related to the critical community and to long-term reflection.

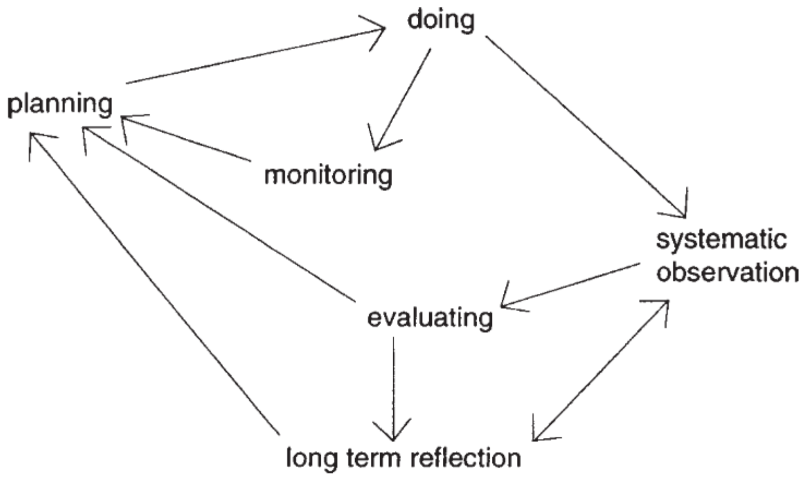


Figure 4-2. Action Research Spiral.

In the doctoral research presented, a variety of different spirals, ranging from inner to outer loop in Griffiths's scheme, occur with varying frequency as they are related to different aspects of the issues being investigated. At times these spirals are driven by insights gained by the researcher, or by opportunities to take a research action (e.g. a design workshop with an architect early in the design process presents itself). The research process is not a clear sequence of spirals related to one comprehensive problem investigation for which actions are performed at discrete moments in time. However, during the course of the research presented certain discrete actions have been used for specific investigations. These actions can be examined within the theory of Case Study Research.

4.2 Case study research

> In general, case studies are the preferred strategy when 'how' and 'why' questions are being posed, when the investigator has little control over events, and when the focus is on a contemporary phenomenon within some real-life context. (Yin 2003, p.1)

A case study tries to bring to the fore why certain decisions are taken, how they are implemented and what their effects are. It deals with research in which the boundaries between the phenomenon being investigated and context are hard to distinguish. This is in contrast to an experiment in which the phenomenon is clearly separated from its context so that only a few variables need to be focused on during research (Yin 2003). Case study research strives to illuminate causal mechanisms, revealing the causal pathway from input X to output Y, while large-N cross-case studies try to reveal causal effect, which only deals with the likelihood and precision of output Y for an input X (Gerring 2007, pp.43–44). In large-N cross-case studies, statistical generalisation is used to extrapolate research findings from the investigated cases into a larger population. In case study research, the findings are also generalizable, but in this case to theoretical propositions instead of populations, as is the case with experiments: the purpose is to expand and generalize theories through analytical generalisation (Yin 2003, p.10).

As each action (e.g. an investigated collaboration between architect and engineer) in the spiral of Action Research can be considered as a case within Case Study Research, it requires five components of Research Design:

1. **A study's question:** 'how' and 'why' question that needs to be investigated.
2. **Its possible propositions:** they state which phenomena might be of importance in answering the study's question. It points towards possible evidence to be investigated.
3. **Its unit(s) of analysis:** what is the case under investigation?
4. **The logic that links the data with these propositions:** how can the retrieved data provide information on the propositions being investigated?
5. **Criteria for interpreting the data:** how can the retrieved data be evaluated to make a value statement on the propositions (i.e. to what degree can the data refute or support a proposition)?

When the study of a case is more explorative because it is unclear what kind of findings can be expected, these five components are difficult to provide. Nevertheless, in such an exploratory case study one should be able to define what needs to be explored in the case and what the purpose of this exploration is, and to provide criteria that define when such a case study research can be considered successful (Yin 2003).

The case studies conducted in the beginning of this doctoral work contain a strong exploratory component, while the ones at the end have a stronger explanatory component that allows these five components to be better formulated. For example, one of the first case studies was set up to understand which problems would arise when an architect and a structural engineer collaborate very early in the design process. Its purpose was to identify phenomena that might be responsible for obstructing a structurally informed architectural design process. Identifying these problems is then the criterion for the success of this case study. For this case study it is not possible to provide those five components of Research Design prior to the execution of the action event.

In one of the last case studies, when the importance of communication between designers had become apparent and a new language had been developed to improve their communication, those five components could be developed. (1) How can communication and collaboration between designers be improved during their early collaboration? (2) The communication and design possibilities improve for an architect when the structural information of an engineer's design proposition is provided on the level of structural order, function, dimensions and possible structural design solutions. The newly developed language provides a communication with these different layers. (3) The case is an early collaboration between architect and structural engineer. (4) The engineer's communication with the architect on paper and reflexive note keeping shows if the engineer is able to express the essence of his conceptual proposition with this new language. The responses of the architect during the collaboration show if he or she understands the engineer's proposition. Questionnaires provide a measure of various parameters (e.g. did the architect think he or she was able to understand the engineer's message? Did the language help in the architectural design process?). (5) The value of the improvement is mainly measured through benchmarking against what the architect and engineer are used to experiencing during collaboration.

In Case Study Research, three principles of data collection are suggested: (1) the use of multiple sources of evidence, (2) the creation of a case study database and (3) establishing a chain of evidence.

(1) Because the data collected in Case Study Research is seldom precisely and objectively measured (in contrast to scientific experiments), using multiple sources of evidence can provide a better argumentation for the relevance of the data retrieved. This can be provided through converging lines of inquiry through which several different sources of information follow a corroboratory mode (Figure 4-3). When the events or facts in the case study are supported by more than one source of evidence, the data has been triangulated. This provides for a better construct validity (cf. Chapter 4.3) of the case study, as the same phenomenon is essentially measured through different sources of evidence (Yin 2003).

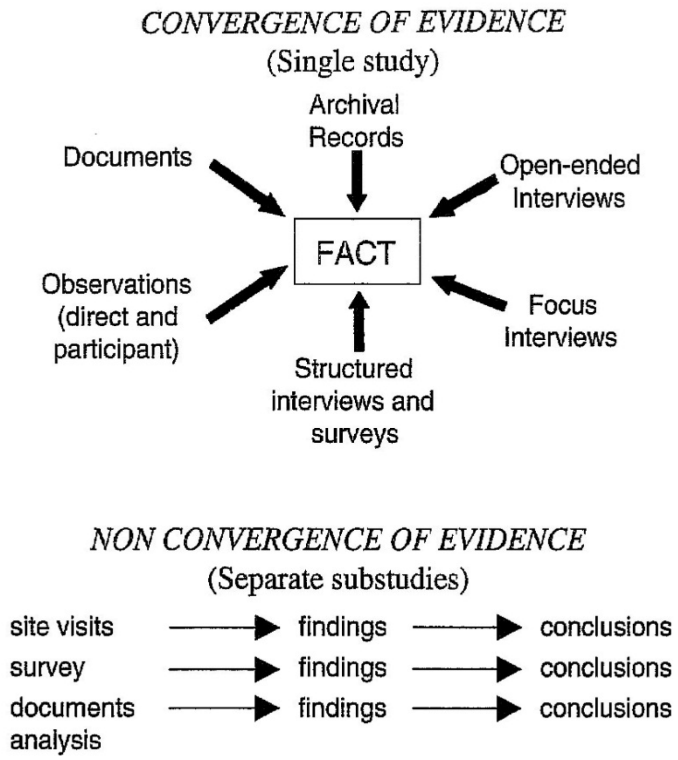


Figure 4-3. Convergence and Nonconvergence of Multiple Sources of Evidence.

In the doctoral work presented, various sources of evidence are provided that investigate the same phenomenon. For example, a number of activities were undertaken to evaluate whether architecture students were able to understand the newly developed language: documents were investigated in which the students used the language to express a structural concept, students were tested to determine if they could correctly interpret a structural concept using the language, questionnaires investigated whether students believed they had mastered the language, and group discussions with the students were held to evaluate the language.

(2) Another principle of data collection in Case Study Research is that the raw data that leads to the research conclusions can be reviewed independently by other investigators. This requires a separation of this raw data and the case study report. Therefore every case study project should strive to produce a formal, presentable database (Yin 2003).

In this doctoral work, all data has been bundled for each case study and stored digitally (e.g. video recordings, descriptions of seminar exercise, students' reports and communication documents) or stored on paper (e.g. workshop sketches and questionnaire responses).

(3) Reliability of the information derived from a case study can be further increased by maintaining a chain of evidence. This is achieved by allowing an

external observer to follow the derivation of any evidence from the initial study question to the final case study conclusions, and to trace the steps back in this chain of evidence (Figure 4-4) (Yin 2003).

The following chapter will present the chain of evidence established in this thesis.

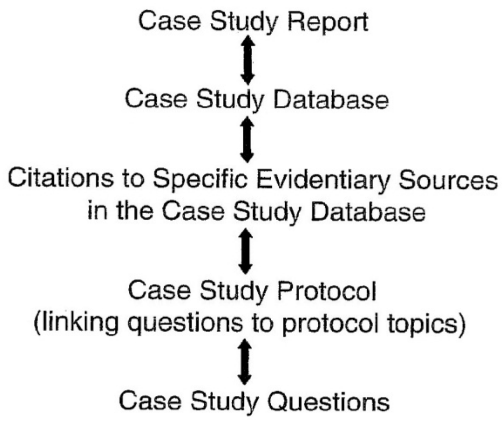


Figure 4-4. Maintaining a Chain of Evidence.

4.3 Applied data retrieval in cases

In this thesis, data from various case studies is retrieved under different forms: documents, field notes, interviews, questionnaires, reflexive journals, participant observations, video recordings and transcriptions are the most important ones. These different forms of data retrieval are chosen and at times developed according to the need of the research at a given moment. Howard Becker describes the qualitative researcher as a 'bricoleur' who will use whatever strategies, methods and empirical materials are at hand (Becker 1998, p.2). If necessary the qualitative researcher will invent new tools or techniques in the course of his research according to the given setting at that time (Denzin & Lincoln 2003, p.4).

Most of investigated cases consist of a design collaboration in which the researcher is engaged as the structural engineer on a design team. Such a collaboration consists of face-to-face meetings in which architect and engineer design together. These meetings are all video recorded and later selectively transcribed according to their value to the research project.

This transcription follows a procedure developed by the author to distance himself from his participation in the face-to-face meeting to the more objective position of the observer-researcher. This is achieved by first describing the meeting activities in chunks of approximately two minutes time, then describing the internal thoughts and motivations as an engineer during the workshop, and finally by analysing these descriptions as an observer and coming to certain research conclusions.

Besides making video recordings of these face-to-face meetings, notes are also taken. In these notes research insights are recorded as they manifest themselves during the author's observation of the meetings. These insights often occur during events that relate to the points of interest of the research at that moment (e.g. during the development of a new language, such an event can occur when an architect misinterprets a newly developed symbol, or the engineer is unable to express a structural proposition with the symbols at hand). At the end of each meeting a mental overview is made of the collaboration process and additional remarks or insights are noted.

During face-to-face meetings, architects or architecture students are at times asked for their opinion on the on-going design process or other elements of interest to the research project. For example, during the development of the language, their opinion on the symbols used or how they experience the collaboration are inquired. These kinds of questionings are informal and intended to provide direct feedback on the points of interest at hand, but also to explore issues that are not premeditatedly investigated at that time.

Most of the interviews conducted during the doctoral research can be described as 'informal conversational interviews' and as 'general interviews guide approach' as Daniel Turner (Turner 2010) defines them, and are summarised by Meredith Gall et al. (Gall et al. 2003). The 'informal conversational interview' has many of the characteristics of an everyday conversation. There are no predetermined questions and the researcher relies on the interaction with the participant(s) to guide the interview process. On the other hand, more structure is involved with the 'general interview guide approach'. Here questions are directed towards predetermined general areas of inquiry, but there is still a degree of freedom and adaptability in getting information from the interviewee.

Most interviews are limited in time, very informal and unannounced as they often occur in addition to a previously arranged meeting. This puts the interviewee in a rather relaxed situation. Often the interviewer and interviewee are already acquainted, which makes it easier for the interviewer to contextualise personal responses. On the other hand, this kind of interview runs the risk of producing responses that are biased due to the established personal relationship. These interviews are often used for exploring and guiding research and less for obtaining research data for an analytic generalization of case studies.

Compared to intensively organized and processed interviews, these types of interviews can be arranged on very short notice whenever the need occurs during research. For example, while working on the concept of design characteristics in architectural design, the opinions of several architects with whom the author was well acquainted, are inquired. This ability to check research findings externally in the world on very short notice makes it possible to proceed swiftly in research. This kind of feedback-interview is conducted with architects and engineers on matters concerning professional practice, and with students and teachers on matters concerning educational practice.

In order to obtain responses that are less likely to be biased by a desire to please the interviewer, anonymous questionnaires are applied. In the beginning of the doctoral research, these questionnaires contain open-ended questions because the research is more explorative, but by the end, as the required information becomes more specific, the questionnaires contain close-ended questions, often asking respondents to rate a statement on a sliding scale of appreciation. This latter kind of questionnaire is appropriate for investigating precisely formulated propositions and has mostly been used when implementing a newly developed language for structural communication. Much attention is given to these close-ended questionnaires by carefully wording the questions according to the guidelines provided by Janet Ruane (Ruane 2005, p.127). These guidelines include: (1) questions should be put in a good sequence with a logical flow; (2) if close-ended questions are used, all possible answers ought to be included; (3) limit the number of questions to a thirty-minute survey; (4) avoid the induction of a response set by deliberately mixing the directions of the answers.

Similar and dissimilar measures are included in the questionnaires to establish construct validity. Construct validity refers to the degree to which inferences can legitimately be made from what you measure in a survey to what you refer to in your theoretical construct (e.g. how much does the questionnaire truly investigate whether students understand the newly developed language rather than something else?). This construct validity can be developed through convergent and discriminant validity. Convergent validity implies that ‘measures of constructs that theoretically should be related to each other are, in fact, observed to be related to each other’. Discriminant validity, on the other hand, implies that ‘measures of constructs that theoretically should NOT be related to each other are, in fact, observed to NOT be related to each other’. A typical way of estimating whether or not two measures are related to each other is by defining their correlation coefficient. When the correlation is ‘high’, the two measures are similar, and when the correlation is ‘low’, the measures are dissimilar. And thus it is important to include similar and dissimilar measures in a survey to establish construct validity (Trochim 2006).

Because of the statistically low number of samples, the results are not intended to be extrapolated to larger groups of students than the one sampled (i.e. the external validity is low). Questionnaires are used in the testing phase of the new language to give a more objectively acquired quantitative account of the participants' viewpoints on the inquired subject.

The selection of data varies from case to case based on the current points of interest in the research. In the beginning, when the research has a strong explorative component, these points of interest are broad, such as 'communication' and 'design collaboration' in general. But as more theoretical propositions develop and the research becomes more explanatory, the focus narrows to, for example, 'the use of the developed language' or 'the expression of design characteristics'. In this process of investigating cases based upon findings from previous case studies, study case propositions become more accurate. Accurate propositions make it possible to establish a more directed focus on desired data, which can propel the investigation process in an articulated direction.

An important technique in recognizing the value of data for this thesis, is by comparing events in new cases to the body of knowledge of previous cases as experienced by the participants (the researcher has more than fifteen years of experience in educational and professional practice). Phenomena that occur in a case are brought to attention when they are not in line with what is to be expected from previous cases. For example, in a case of design collaboration in which the researcher is participating as a structural engineer, an event is recognised by the researcher as valuable for research when it is dissimilar to what he expects to occur based on his experience as a structural engineer in previous collaborations.

Besides the experience of the researcher/engineer, the design experience of architects and students is also used as a benchmark to bring forward valuable data for research. For example, evaluating the quality of the new language is partly based upon comparison with structural languages with which the participating students are already acquainted. Data on the new language is then brought forward in comparison with the student's experience. This technique of valuing data through this (subjective) comparison is applied because most of the phenomena investigated cannot be absolutely measured through objective standards.

Another way of illuminating valuable data is statistical analysis. Case studies with architecture students often contain multiple cases to which more quantitative research methods can be applied. And in the last investigated cases with students, when theoretical propositions are formulated more precisely, extensive questionnaires are applied to statistically process the extract-ed data. This makes it possible to quantify and more objectively evaluate the desired information from the cases.

In Case Study Research, four tests are provided to establish the quality of the research design: (1) construct validity, (2) internal validity, (3) external validity and (4) reliability (Yin 2003).

(1) Construct validity tests if correct operational measures are established for the concepts under study. In the case studies for this thesis, construct validity is increased through the use of multiple sources of evidence with convergent lines of inquiry by providing a chain of evidence, and by having the research findings reviewed by key informants (e.g. the conclusions on the design characteristics of an architectural design proposition are presented and reviewed by different architects).

(2) Internal validity tests if causal relationships are established, where certain conditions are shown to lead to other conditions. This validity only concerns explanatory case studies and not exploratory ones. In this thesis, this is mainly achieved through explanation building by developing theoretical propositions that are then evaluated in cases, sometimes specially designed for this purpose.

(3) External validity tests to which domain the findings of a case study can be generalised. Because the findings of a case study rely on an analytical generalisation (and not a statistical generalisation as with survey research), this generalisation domain in this doctoral work depends on the theory developed and the set of cases used for explanatory research.

(4) Reliability evaluates to what degree the operations of a study (e.g. the procedure for data collection) can be repeated with the same results. In the research presented here, attention is given to document the procedures followed in each case study and to establish case study databases.

Action Research provides additional validation tests for the findings of the research (McNiff et al. 1996, pp.108–109). In this thesis, the quality of many of the findings is assessed mainly through **self-validation** (i.e. the responsible researcher can vouch as a practitioner for the claimed improvements in practice and present a systematic enquiry to accomplish this), partially through **peer validation** (i.e. the researcher's colleague architects, architecture students, structure teachers and structural engineers can attest to having gained genuine knowledge and that the claimed improvements work effectively), and partially through **academic validation** (i.e. the academic community agrees that the researcher's work has contributed to a recognized body of knowledge) through academic papers, conference contributions and seminar presentations.

The cases investigated here can be divided into two categories: (1) cases in professional practice and (2) cases in educational practice. (1) The former category contains cases in which collaboration between architect and structural engineer occurs as part of a professional architectural building project. These cases are derived from the researcher's professional practice as a structural engineer. (In these cases, the researcher plays the role of structural engineer as well as observer). Cases are chosen for investigation as the opportunity arises and under the condition that they involve collaboration early in the design process in which architectural form still needs to be designed and structural input is welcomed. These cases are not planned in advance, since they depend on external factors of the building industry. It is mainly key to recognise a project as an interesting case to be studied.

In these professional cases, the architects are hardly informed about the purpose of investigating the collaboration, and they are not given any instructions on how to proceed within this collaboration: these architects are expected to play no role other than their customary one as architects.

(2) The other type of case is developed within the researcher's practice of educating architecture and interior architecture students. Here some cases involve design collaborations in design studios between the teacher as structural consultant and the student, and some cases are constructed as testing grounds for research findings and development (certain cases contain collaboration and testing components at the same time). In these education cases, the researcher is able to determine and direct certain conditions for collaboration and testing, enabling him to focus the research towards certain points of interest. For example, in the early stages of the doctoral work, design studios are set up in which students have to design together with the structural consultant from the very start of their design process. Imposing this condition enables the
researcher to discover and investigate certain mechanisms involved in such an early collaboration in contrast to the usual practice of waiting to collaborate until later in the design process.

In these educational practice cases, students are also asked at times to play the role of researcher. For example, during collaboration they are required to keep a log of their own design process in order to make them aware of their own actions, so that later they can evaluate and report their own design process. (These logs provide additional data that can be analysed in the doctoral research project.)

There are often many cases to investigate within one educational practice case study because many students take part in each. This makes it possible to introduce quantifiable measuring in these cases because they all occur within similar conditions. In professional practice, however, cases always occur as single events with unique conditions, making them less preferable for quantifiable measurement.

In the cases that involve collaboration, the researcher is always part of this collaboration as a structural engineer or as a structural consultant. This enables him to have a close look at and get a feel for the various mechanisms involved, and to recognize events dissimilar to his experience as an engineer or teacher. This is especially true when it comes to developing possible improvements for collaboration: having a direct personal experience of the implications of a certain possible improvement is an important advantage. For example, while developing a new language, the researcher can directly experience whether or not he is able to tell a clear story during collaboration with this language, and determine which parts of the language are valuable.

There are also disadvantages of an observer taking part in the action. One of them is that observations lose quality, as participation in the action requires time and energy of the researcher. This is partly countered by video filming all collaboration cases and later transcribing the important ones through a protocol that induces observation distance. Another method of reducing data loss through direct participant observation is using different sources of data retrieval (e.g. document analysis, questionnaires and interviews).

Another disadvantage involves biased responses from architects and students as they might want to provide socially preferred reactions (i.e. most architects and students have a relationship with the researcher outside the research and might want to please or displease the researcher through their answers). When many cases are involved within one case study, anonymous questionnaires are developed to obtain answers that are as unbiased as possible. Personal appreciation answers are handled with caution and other sources of evidence from the cases are used to back them up if possible.

As this research did not start out with a clearly defined research question, the first part of the research needed to be very explorative before case study research could be applied. This exploration contains a retrospective analysis of the researcher's past design projects with architects. Its main purpose is to identify characteristics that might be of importance in a collaboration process in which architectural design is structurally informed. When such characteristics can be defined, points of interest in research can be set for the case study research. The start of the following chapter provides an insight into these explorative first steps of the research.

Research Findings through Case Studies

5. A research focus on collaboration and communication

5.1 First investigations in structurally informed architectural design

In order to get a better understanding of the mechanisms involved in an architectural design process that is structurally informed, some of my past structural engineering projects are analysed. These projects are chosen because they involve a close collaboration between architect and structural engineer, one in which some design decisions are made based simultaneously on structural and architectural considerations. Three projects are broadly analysed on the level of social relationship, collaboration conditions, design attitude of the architect, characteristics of the architectural project, collaboration process, structural design process, structural input, communication and timeline. Various events of each project are gathered and logged: e-mails, faxes, phone meetings, face-to-face meetings, my paper notes and calculations. These three projects are compared with my other less structurally informed projects to identify dissimilarities and similarities. This leads to an array of questions about architectural design, culture of architects and the role of structural design in architectural design. These questions, along with some conclusions of the analysis, are put to the various architects involved for further evaluation during some open and informal interviews. This leads to a paper that reports the findings. This paper is presented to the architects involved for comments and their (few) comments are then incorporated into the final paper. This paper is then further discussed with various academic tutors.

One of the conclusions of this investigation is that in these projects there is a cyclic process of architect and engineer informing each other as the design proceeds: the architect makes a first proposition, the engineer gives his structural vision for this design, the architect adapts his or her design based on this information, and so on.

The architects interviewed regret that some structural engineers are not interested in such a cyclic process. These engineers see their job as providing a single, dimensioned and calculated, structural solution rather than searching for various structural alternatives, as these architects would prefer.

One architect considers the role of an engineer in this process to be providing architectural guidelines based on structural logic. These guidelines make a frame within which an architect operates with a maximum of architectural freedom. In these projects, this frame is mostly provided by presenting an array of possible structural design solutions from which the architect can choose (e.g. by providing alternative structural concepts or different possible dimensions and materials for a single structural element). This architect's proposition leads to an interesting research question of how to convey the common characteristics of this array of possible structural design solutions: what are these design characteristics and how can they be explained to and understood by an architect who is not an engineering expert?

An important part in this cyclic process of designers informing each other is for the structural engineer to understand in the first place the architect's design proposition together with the architect's (possibly implicit) desire for a certain structural solution. This helps the engineer to develop an appropriate structural design, and if necessary to alter the architect's proposition for a better structural design outcome. It often requires insight into architectural design for the engineer to grasp the broad spectrum of an architect's proposition and desired structure (just as it requires structural insight for the architect to understand the potential in an engineer's proposition). I have the impression that my education as an architect gives me an advantage compared to most classically trained engineers in understanding the architect's design proposition and desires. This ability is much appreciated by the architects with whom I work. In Belgium, several successful structural engineers who are renowned and appreciated by architects also have an architectural education. And thus the question arises as to whether it is advantageous for an engineer to have a degree in architecture when collaborating with architects, and more specifically whether there is an advantage in communication and how this advantage can be described. For example, is it easier to grasp the design intention of the architect, and which elements in design communication provide for this better understanding? This investigation can lead to communication improvements during the collaboration through improved collaboration procedures or even through educational adjustments (e.g. getting engineering students acquainted with architectural design).

Another conclusion of the investigation is that collaboration and communication is influenced by the combination of architect and engineer. As each architect has a different approach to architectural design and the role of structure in it, the structural design needs to be adjusted to the individual architect. For example, some architects want structure to be clearly visible in their designs, while others don't. This requires different kinds of structural solutions. Also the architect's experience in architectural and structural design will determine the way that I collaborate with them. For example, more attention is given to the consequences of a structural solution when it is uncertain if an architect is sufficiently aware of them due to inexperience. Even the collaboration experience between architect and engineer determines the collaboration. For example, certain structural solutions are presented before others because similar solutions have already been approved in previous cases with the same architect. This means that the communication between designers is adjusted to the experience of the design team and to the experience of the other designer.

There is also an important interpersonal link between architect and structural engineer that influences their collaboration because the way people relate to each other will drive their group dynamics. However, such aspects of collaboration are not further investigated in this doctoral work.

Figure 5-1. Three analysed structural design projects.

One of the architects interviewed believes that his initial architectural concept gets replaced by a poorer hybrid concept when following the road of a structurally sound concept. This raises the question if there are ways to get architectural and structural concepts in tune from the start so that a pure architectural concept does not have to give in to the structural concept and lose quality later on.

The investigation also shows that major parts of the structural concept are already decided by the architect before consulting an engineer. (Often an architect has already decided to some degree where to put some columns, slabs and beams, or what the desired architectural form is and where the structure will need to fit in.) My advice as an engineer is only demanded early on in the process for inquiries on foundation or critical structural elements (i.e. to check if the size of an element still fits within an architectural design). The reasons given by the interviewed architects for not seeking structural advice earlier are the extra cost of having an engineer involved early on and that architects feel comfortable enough to develop these first steps in structural design on their own in these smaller projects. In such a case, however, the architects may limit their own design possibilities due to their limited knowledge of structural design. Only in larger projects with a more complex structure do these architects feel the need to involve a structural engineer from the start because of their lack of structural knowledge. So the question is, what value can a structural engineer as an expert in structural design add to an architect's design process in the conceptual phase, even for smaller projects?

All the architects I interviewed would like to know more about structural design so that they could design structures more by themselves. One architect suggests developing a software program that would immediately put structural sizes on architectural form. This would enable him to develop form that is structurally viable by trial and error. Another suggestion this architect makes is to have a structural engineer as part of his architectural design team – always available during the design process and accustomed to the specific needs and desires of the architectural design team.

This longing for structural knowledge is not shared by all architects, however. Other architects with whom I have worked as an engineer have expressed a preference for not knowing anything about structural design, as it would hinder them in their architectural creativity. In my projects with such architects, structure and architecture get in tune mostly after many cycles of negotiation between architect and engineer.

This investigation brings forward two focal points for research that might lead to an architectural design process that is better informed structurally: (1) improve architects' ability to design structurally realistic objects in the conceptual phase, and (2) improve the collaboration and communication in the conceptual design phase between architects and structural engineers as experts in their own design fields. Once architectural form is conceptually sound for both architectural and structural design, both experts can then further refine their designs within their own discipline.

5.2 Enabling architects to develop structure early in design

One way of enabling architects to get structural input in their architectural design in the early stages is by providing adequate software tools. It is not the aim of this research to make architects into structural engineers or experts in structural design. The software should enable architects to request specific structural information for their design.

A lot of structural engineering software is already available that can precisely calculate any required dimension of a structural element. But this software requires specific engineering knowledge to operate correctly. Because the required structural information process does not need to be as precise as this software requires for an architect early in a design, it should be possible to have some pre-dimensioning through elementary input by the architect.

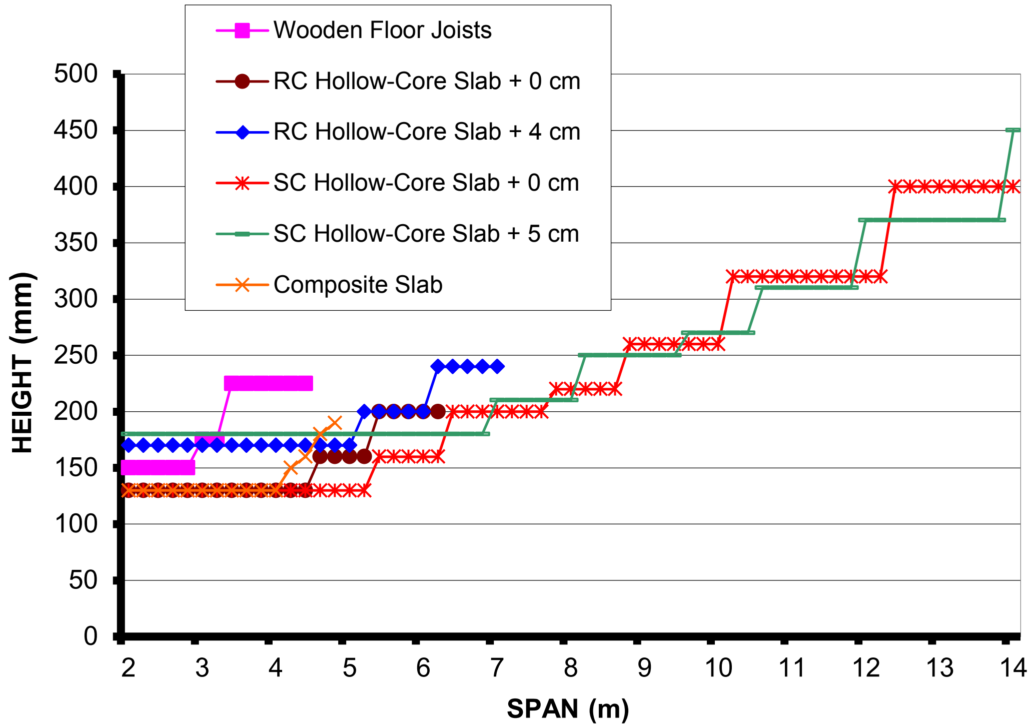


Figure 5-2. Undeveloped tool: floor height versus span for a load of 3.5 kN/m^2.

In order to understand what inputs are required and what outputs can be expected of such pre-dimensioning software, an explorative investigation is developed. Data is produced that links the span of a floor and its material and form with its height. The intention is that an architect would design a floor, and by choosing the span and type of floor get an estimate of the thickness of the structural slab. To enable this, certain structural variables need to be chosen and fixed in advance, such as the structural quality of the materials, the fire resistance of the floor and the load. One of the problems that occur in establishing this structural data is determining these fixed variables. For example, in Belgium buildings with wooden floor joists are typically finished with lightweight wooden surfaces, while concrete slabs can have a heavier finish such as ceramic tile flooring. And thus in general the wooden floor system needs to withstand a much lighter load than the concrete slab unless a finish of ceramic tiles is required on the wooden floor, which would increase the load considerably. And thus such a pre-dimensioned database would need to make a distinction between wood-framed floor systems with different finishes. Translating such engineering variables (e.g. load) into architectural variable (e.g. finish) risks overloading a designing architect with a lot of choices. This would contradict the intention of providing easily accessible structural information.

Although a database was produced in this investigation that gives interesting information on the thickness of floors, it also shows that there are many decisions involved that guide structural design. These decisions are not only on the level of finish and its implication for the structure, but also on the direction of a span and its consequences on the rest of the design, the need for fire resistance and its possible implications for the structure, the possibility of integrating steel beams into a concrete floor plate to reduce its height, the combination of certain materials during construction, the insight to suspend a load from a structure above instead of resting it on a structure below, and so on. When I design a structure as an engineer, dimensioning is only one aspect that guides me in developing a structural concept; my field of knowledge and experience is much wider and more complex. It does not seem likely that software tools will be able to replace the multi-level expertise and creative abilities of a structural designer, which enable creative or innovative design. Addis describes this human factor of structural design:

> The model of a universal building built up by the human mind is far too subtle to feed into any computer, and the workings of this mental image are far too fast to see. An engineer simply knows, feels – the nature of the relationship between floor span and depth, between the shape of a structural section and its deflection, between the rise of an arch and its stability and outward thrust. In a way which is half visual, half feeling, an engineer can imagine all the different consequences of changing column spacing, floor structure, a material, or the relative dimensions of members. The impression is of an imaginary object that is almost alive... Much of this type of engineering knowledge cannot be written down and cannot be learnt quickly; it has to be built up gradually and through direct personal experience. (Addis 1994, p.16)

Therefore this effort to improve structural input in the architectural design process by providing the architect with structural software tools is abandoned. An important part of creative structural design lies in the human factor of the engineer. Leaving out the structural designer in an architectural design process will likely limit the range of creative design possibilities.

Studies have also shown the importance of face-to-face meetings with co-designers and the use of sketching to solve problems in engineering design, while online databases and software are only beneficial to a limited percentage of engineers as a source of ideas for design (cf. Chapter 2.3). It is likely that architectural design that takes into account structural design will similarly benefit from a collaboration between architect and structural engineer in face-to-face meetings and through the use of sketching. Therefore this doctoral investigation will focus on such collaborations between architect and structural engineer as a team of creative design experts.

5.3 Investigation of collaborations early in the design process

In order to have a better understanding of the mechanisms involved in design collaboration between architects and engineers early in the design process, a design studio is set up with architecture students in the final year of a master's program. In this design studio, students are required to work together with a structural engineer from the very start of their design process. Students are asked to keep a log of their design process in order to make them aware of their design decisions and to create a design process report at the end of the studio. This report is then analysed by me. All weekly collaboration moments between the students and the structural engineer are recorded on video and some of these recordings are later transcribed.

In this studio I play the role of structural engineer. During the collaboration meetings I take notes of interesting events that occur. (Interesting events are mainly recognized when they are dissimilar to my experience of previous consultations in design studios.)

The focus of this investigation is on collaboration and communication during the face-to-face design collaboration meetings. As the students have little experience in structural design, they are more dependent than experienced architects on the structural input from an engineer. This makes the collaboration intense and the communication richly informative. Such rich communication brings essential characteristics of the information exchange more clearly to the fore for research.

At the end of the studio, students are asked for their opinions of the collaboration and their design process through open-ended questions. This (informal) inquiry and the general findings of this research project were recorded in a paper (Luyten 2009a) and presented for comment at a conference on construction education.

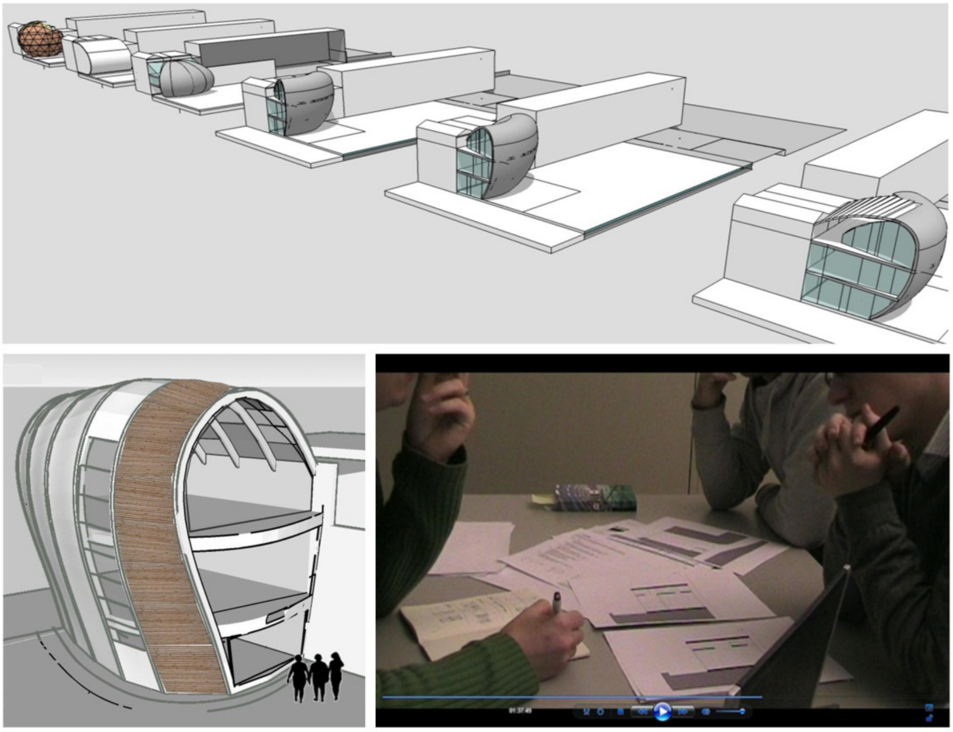


Figure 5-3. Research Seminar 2008: student project and videotaped meeting.

This investigation shows that it is difficult to provide structural input when the architectural design proposition is still so conceptual that many different structural design propositions can be designed for it. With the currently available structural vocabulary, each structural input needs to be rather detailed (i.e. consist of structural typologies like columns, beams, trusses and so on). As many structural propositions composed with these structural typologies are still possible in the early stages, this vocabulary would require the designer to present many different stories, which would take a lot of effort and time. This leads to the question, can a more conceptual language be developed that more easily describes the common characteristics of these structural possibilities in a single story instead of the many that are required now?

The investigation also shows that the discourse in concepts between architecture students and structural engineer requires specific knowledge of both disciplines and cultures for the two to understand each other. For example, a load-bearing column is not considered a column by architects when it is so slender that it fits into a window frame, although to engineers it remains a structural column. The question here is, can communication be directed so that it only requires a little knowledge pertaining exclusively to one discipline to understand it, while still containing the essence of a design message? More specifically, what is the essence of an architectural or structural concept, and how can it be conveyed so that the other designer can easily understand it?

In the communication of an architectural design proposition, architecture students often use examples of built architecture to show their design intentions. For example, with some pictures of Philip Johnson's Glass House, students can express how they would like to have transparency implemented in their architectural design. As this is a common communication tool in architectural design, the question arises if such built examples can be used to communicate structural design intentions between architects and engineers. This would not only lead to a communication of structural design but also of architectural design, since these examples can consist of built structures incorporated into architectural design.

Setting up face-to-face meetings for design collaboration between architecture students and a structural engineer seems to be a natural way of collaborating in the early stages of the design process. Since there is no need for thorough calculations that require time, all structural input can be given on the spot. These meetings are a fast way to proceed in the design process, because this type of direct communication enables quick responses and immediate feedback to check if the message is well understood. This feedback is certainly important in the conceptual phase, when the design description depends on terms that can be interpreted in many ways, making miscommunication likely. The question here is, can techniques like paraphrasing the received message or sketching benefit the collaboration process or will it mainly just slow the process down?

6. Cases for explorative research

6.1 Research Seminar 2009

One of the main conceptual design characteristics of a structural proposition that an engineer should be able to convey in an early design collaboration is, in my opinion, its structural logic. The currently available structural language of internal forces and stresses conveys this structural logic poorly, and is also too specific for this more conceptual communication. Therefore I have developed a new language that explains the structural logic of an engineer's conceptual design proposition. This language does not present a structural proposition in the common manner as a configuration of structural typologies (e.g. columns, beams and slabs), which are importantly characterized by the type of internal forces that occur in their structural elements. Instead, the new language focuses on the structural function and consequential implication on dimensions that a conceptual element (e.g. line or surface) needs to perform to transfer a load to the supports. The configuration and order of all elements and their structural function(s) then explain how the structure works as a system.

The language under development needs to be used during face-to-face meetings in design collaborations between architects and structural engineers, because such meetings create favourable conditions for design collaboration. Therefore one focus for development is creating symbols for sketching that are easy to draw by hand and intuitive to understand (cf. Chapter 2.5). Since this language is created for practical application, professional practice helps create it through trial and error: the language is developed to some degree prior to its application, but is mainly optimized for practice by applying it in practice, analysing its use and adjusting it accordingly.

In order to further develop this language and experience its ability to convey conceptual design propositions of structures, another design studio is arranged to bring together architecture students and a structural engineer. One of the purposes for this setup is to understand if a new language can provide a more conceptual communication of structural design that can be understood by architecture students: can a structural engineer convey a wider range of design solutions more easily than he or she would normally do using the currently available language? And is a student able to grasp this wide range without having to acquire additional structural knowledge? In other words, is it possible to structurally inform an architecture student early in the design process?

An architectural design studio is set up with architecture students in their last year of a master's program. As the supports provided for their project require large spans, structural design is an important component of their design process. As in Research Seminar 2008, they are asked to work together with me as a structural engineer from the start of the design process. Collaboration only occurs during seven face-to-face meetings for each of the nine design teams of two students. These meetings are videotaped, and I write down my experiences of the application of this new language as it happens during these collaborations. More informal interviews are held with the students during these meetings to see if they are able to understand this language: for example, are the symbols comprehensible? Do the students use the language outside the collaboration meetings? Do they understand the structural proposition? This feedback from students and from me applying this language is then used to adjust the language and its use. Because there are several design meetings, it is possible to change the language and test the changes during the course of this one research seminar.

The evaluation of the language occurs through these informal interviews and through benchmarking against my fifteen years of experience in design communication with students in design studios. The language is further evaluated at the end of the seminar through anonymous questionnaires for the students with open-ended questions, and by analysing the students' seminar reports containing their design outcome and logs of their design process.

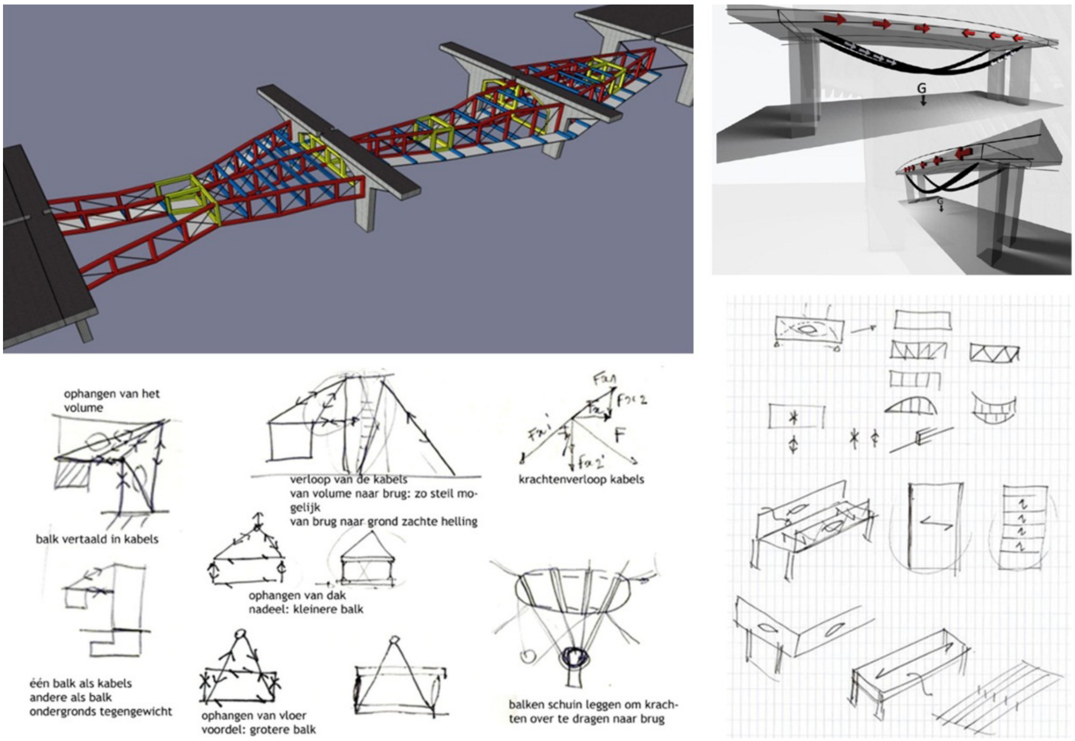


Figure 6-1. Research Seminar 2009: design presentations and workshop sketches.

This seminar shows that it is possible for me to express a wider range of design solutions with less effort using this new language than my previous vocabulary would allow. The drawings produced with the language express the essence of structural behaviour applied to conceptual (architectural) elements rather than to more concrete structural typologies like columns and beams. With this more conceptual language, I am able to quickly compare and discuss with the students major choices in the conceptual design of a structure. There are moments when I notice that through this language I am able to find creative solutions that my experience suggests I would not have found using a more refined language of typologies. This seems to be due to the fact that it is easier to draw in three dimensions and to maintain an overview using the new language, and easier to reflect on the design as a whole instead of focusing directly on one aspect of it (as two-dimensional drawings of structural typologies tend to do). I can maintain a distance to my design proposition and let the drawing ‘talk back’. The language itself mainly shows the basic structural behaviour of a proposition, which leads to a conceptual investigation of the structural design rather than a detailed one that would risk eliminating certain design paths prematurely. With a language based on more detailed structural typologies, my investigation normally would not have been so conceptual.

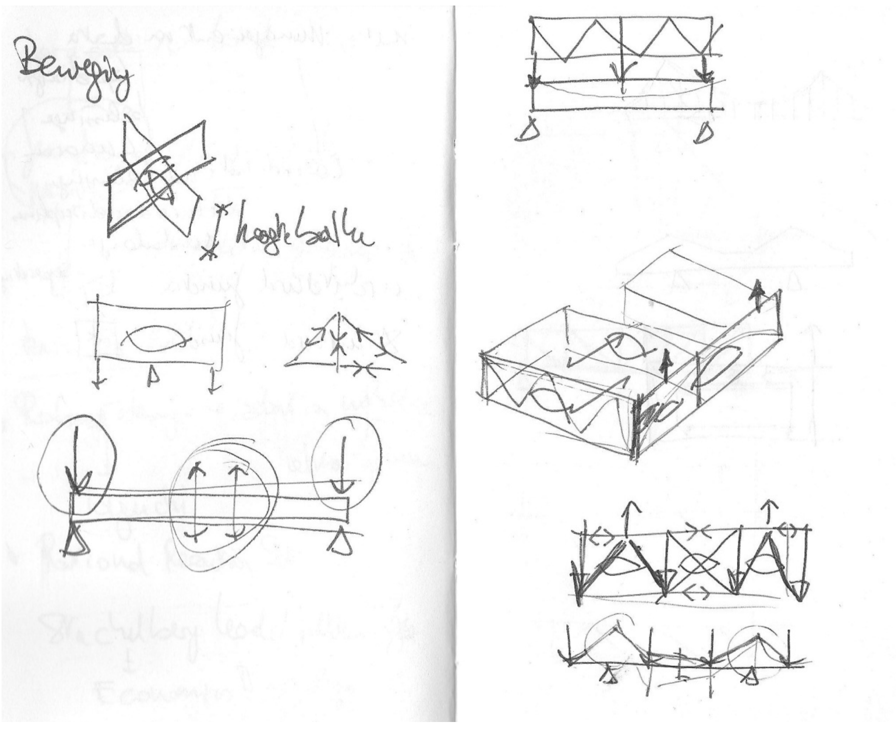


Figure 6-2. Example of note taking with initial symbol for bending.

The symbol developed to express the function of bending poses problems during the collaboration: it is not applicable for cantilever and it is has no upper/lower orientation. Its use is therefore too specific and its capacity to inform too limited. During the workshop, certain students indicate that they do not understand this symbol from the start. They tell me that they understand the language when I use it to explain a structural proposition, but that they sometimes forget what the symbol of bending means when they get home and look again at the sketches from the meetings. The symbol used to represent a compression and tension bow is not an image that students relate to immediately, and therefore it seems difficult for them to remember what it means. (Students were not given an extra course on the language or provided with a manual of the language.)

The symbols that express the functions of normal forces of compression and tension do not seem to be confusing since students are very easily acquainted with these symbols.

This seminar also shows that three-dimensional overviews of a structural proposition help in understanding its overall structural behaviour, but risk overloading a drawing with information. One way of dealing with this overload is to reduce information to the level of two-dimensional plans and sections. The symbol for bending, however, has an orientation that does not allow a view from above, which makes it inapplicable for slabs under bending on floor plans. Together with the previous remarks on the symbol of bending, this leads to a redesign of this symbol.

The questionnaires filled in by the students at the end of this seminar show that:

- Most students understand the symbols and the structural explanation given.
- For some students, more attention is needed to learn the new language (no introduction lesson was provided).
- For a few students the symbol for bending moment is a bit harder to learn (This symbol is further developed).
- A few students understand the schematic sketches of the structural proposition during the consultation but not when they get home.
- Most students appreciate the way structural insight and structural possibilities are presented during this collaboration.
- Some students have problems refining the more conceptual structural elements into a real structural solution.
- Some students prefer the graphic style of the language, which is seen as quick and to the point, over a spoken explanation of structural behaviour.

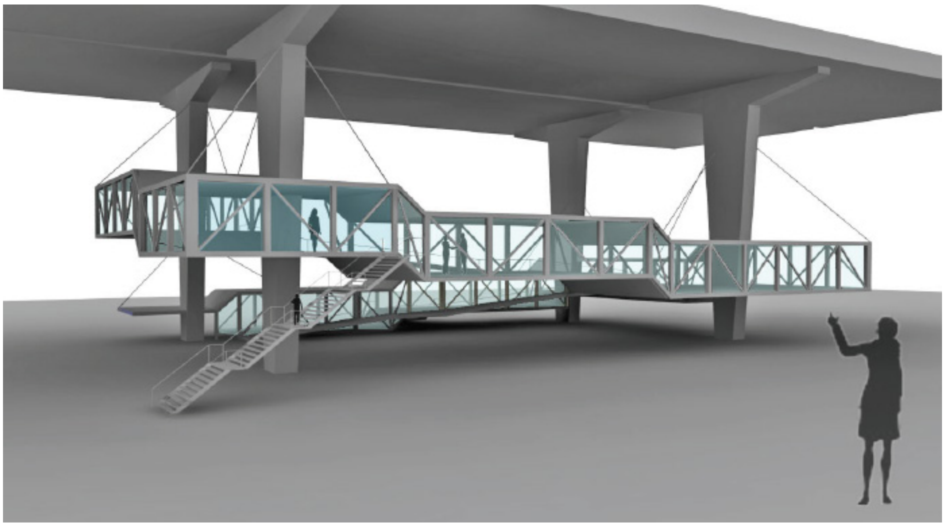


Figure 6-3. Example of a final design.

This seminar is also used to explore an early collaboration between an architect and a structural engineer in which the two designers inform each other of the design characteristics of their conceptual design propositions. Students are asked to develop decision matrices that bring to the fore which criteria they use to evaluate various design possibilities in the course of the process. The purpose is to make the students more aware of their design process, and better able to articulate the design characteristics they find essential in their design proposition as presented to the engineer. They are specifically asked to express these design characteristics during the meetings in which they present their design propositions.

Throughout the collaboration, students present their design propositions as form models and design characteristics. Sometimes a form model is presented in two-dimensional drawings, sometimes in three-dimensional sketches. Students often express design characteristics verbally, but at times they have a hard time expressing them. It seems that they are not so well trained in recognizing the essence of their own design proposition.

Certain design characteristics are partly concealed in their drawings. It is my impression that my architectural education and experience helps me to reveal these design characteristics. When I think I recognize a design characteristic, I present it to the students to check if they agree.

The process of expressing design characteristics, helps both students and engineer to understand in which direction the design needs to develop (i.e. architecturally and structurally). These design characteristics also reveal what is of importance to the students and what they want to achieve with their design. (As the design process evolves, so do these design characteristics.)

The questionnaires presented to the students also reveal that:

- Most students appreciate an early collaboration and call it inspiring when structural design guides the architectural design.
- Most students express a wish to have more of this type of collaboration in design studios.
- One student remarks that in this design studio structural design is rather dominant over the architectural design process, and that it should be more in balance.

This seminar shows through the design results that it is possible to have creative architectural design solutions when an architecture student is structurally informed from the start. As a design outcome depends on a lot of different factors, it is hard to attribute the architectural quality achieved to the use of this new language or the method of collaboration. Getting students excited about what they are doing or giving them a lot of attention from a structural consultant might be reason enough to generate more qualitative results.

But the seminar at least shows that this applied approach leads to qualitative design outcomes and that it helps students design architecture that is structurally informed from the start. The design results also show that structure and architecture are integrated and not in conflict. Some students may have paid too much attention to this structural input, perhaps because they were not pushed specifically to defend architectural quality in their designs. In the next design studio, architectural quality will be emphasized by involving a teacher who is concerned only with that aspect of the students' projects.

6.2 Project Jo & Karolien

This is a project taken from my professional practice that is selected for research because the architects wanted to be structurally informed when shaping the architectural form. The project was built in 2011 according to the result of this collaboration.

This project is used to investigate (1) how an architectural design proposition can be described in a form model and design characteristics, (2) whether these design characteristics are part of negotiation within a design team and (3) whether a technique of paraphrasing each other's design communication improves the collaboration between two designers. Throughout this project special attention is given to the communication between the architects and the structural engineer.

In this project, written communication is logged and the only face-to-face meeting is recorded on video and transcribed through a technique designed to give the participating researcher more distance. The research findings are discussed with the architects, written down in a paper (Luyten 2010) and then presented to them for critique. This paper is presented at an international conference and to peer professionals and academics.

Figure 6-4. Project Jo and Karolien: initial presentation, meeting and transcription.

I am introduced to this project through an email from one of the architects. In this email the project is presented through a long descriptive text and two three-dimensional renderings of the design. In this text one of the two architects describes what their conceptual design is (e.g. a sun terrace) and what it should be in the end (e.g. look like a theatre box). In my view, this design proposition is presented with a list of design characteristics that the representation of the three-dimensional form model alone might not sufficiently convey. As an exercise, I transform the long text into a list of what I see as various design characteristics of the architectural proposition. This list is presented to the architects at the start of the face-to-face meeting as my interpretation of what their design consists of. After some reflection the architects agree on my interpretation. Later on, there is a more profound discussion with one of the architects on the nature of design characteristics. The result of this process is already described in the above chapter on conceptual designs (Chapter 3.2).

In this project, two architects are involved, and in the beginning of the meeting a discussion starts between them as I present my list of design characteristics. One of these characteristics is the expressional movement of the stair. To one of the architects this element is not important, while for the other one it is essential. In this discussion a path is set for the further development of the design as both architects further refine what they find important in their design and come to an agreement on the stair as an element that accentuates the expression of a box. This negotiation of design characteristics not only gets the architects moving in the same design direction, it also informs me more precisely what their design proposition entails. This more precise understanding helps me in designing an appropriate structure, since in this case the structure of the stair will be an important part of the architectural expression.

In essence I investigate different possible architectural forms based upon how I understand the given architectural design proposition: I strive for structurally sound design propositions that would alter the presented architectural form model according to my understanding of the architectural design characteristics (i.e. develop a structural form that would be approved by the architects). (Here my Rational Reaction Set is at work, trying to predict what the design reaction of the architects will be to my design outcome. This prediction is based upon my understanding of architectural design and my collaboration experience with these architects, but here even more on my understanding of this particular architectural design proposition – presented as form model and design characteristics.)

Later on in the design workshop there is a discussion between one of the architects and myself on the use of one of the walls. Within the architectural concept, the design should not touch that wall as it stands detached from it, but from a structural perspective this wall can be a very useful support. This discussion leads to an agreement of structurally using the wall but striving for a detachment in expression of the design object. This negotiation of structural and architectural design characteristics helps to arrive at a design process in which all designers involved are working within their own disciplinary design process towards a common goal defined by these converging design characteristics.

A clear set of agreed design characteristics also serves as a guide for further refinement of the design proposition.

In this design workshop, paraphrasing is used on several occasions. One of the most explicit ones is my interpretation of the architectural design proposition in design characteristics. Repeating a received message to the sender is a method of checking if the message is correctly understood. During conceptual design, design characteristics are not always very precisely conveyable, as they are sometimes related to a personal understanding such as ‘looks like a box’. Paraphrasing in such a case diminishes the risk of miscommunication. (In a later interview, one of the architects in this case emphasises the importance of paraphrasing in this kind of collaboration of different professions.)

But besides being a communication tool, paraphrasing can also be a design tool with which to distance oneself from one’s own message (or in this case, design proposition) and allow another team member to rephrase (or ‘talk back’) one’s design message. Hearing one’s own message in another’s words helps a designer evaluate his or her own design proposition (i.e. instead of having a conversation with the drawing as Schön describes it (Schön 1983), it is a conversation with one’s own design proposition through an external description). This process occurred when I expressed my interpretation of the architectural proposition and the architects read their own design anew through my understanding, which led to a discussion of the essence of the stairs.

Analysis of the meeting through a transcription of its video recording reveals that as I follow a certain path of structural design solution into detail, it takes mental effort to leave this path behind and return to a more abstract design level to look for other design solution paths. After the architects leave a certain design path we’ve all been investigating together, it takes me quite some time before I can follow them in this new investigation.

This phenomenon is also described by Rowe (Rowe 1987 cited in Lawson 2005), who calls it a ‘tenacity with which designers will cling to major design ideas and themes in the face of what, at times, might seem insurmountable odds’, and by Balmond (in his design for the villa in Bordeaux), who talks about ‘the insanity of design “rightness” that makes one stick to stubborn judgements’ (Balmond 2002, p.39).

Therefore it seems important to me to spend enough time to investigate on a more abstract level before going into a deeper investigation and risking getting stuck. (This is also a matter of efficiently using mental energy. For example, a structure calculated in detail requires quite some energy, with little return to design when a completely different structural concept is pursued. This might be a reason why some engineers are not keen on investigating different structural design possibilities as they – unnecessarily – calculate every possible solution in detail.)

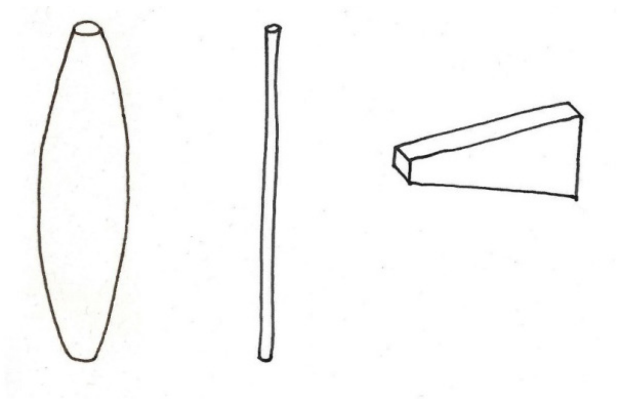


Figure 6-5. Example of volumetric language: strut, tie and cantilever beam.

In this workshop, the newly developed language of symbols is only used scarcely because the project is already quite detailed in its elements. (The language is developed to structurally inform more conceptual elements.) But the symbols are only one way to express structural logic; another way of expressing this logic is applied in this workshop. Instead of expressing the structural function of each element with a symbol, it is also possible to express this through an adequate dimensioning of the structure in an imaginary material (Figure 6-5). This imaginary material is isotropic and able to equally withstand tension and compression. Structural logic is then expressed through a structural shape that is formed through an engineering logic of minimal use of material (comparable to a structure made out of concrete using the least possible material without limitations of formwork). This volumetric language requires more effort in drawing than the symbols, and is therefore less appropriate for complex structures and quick responses.

In this project, however, only a few elements need to be structurally informed. One of them is a strut and another a combination of column and cantilever beam. By giving these elements structural form (Figure 6-6), the architects get inspired by these drawings and develop conceptual design characteristics for the support of the platform: the support elements are part of a machinery that is put into place once the drawer-platform is brought to its full extension.

This event shows the potential for expressing structural logic through form instead of symbols. In my view, this is because architectural design focuses heavily on form and these kinds of structural drawings use the architectural vocabulary of form. This volumetric language brings a structural concept one step closer to a built reality. In the further development of the language, attention is given to linking the language of symbols to the built reality in the realm of architectural form.

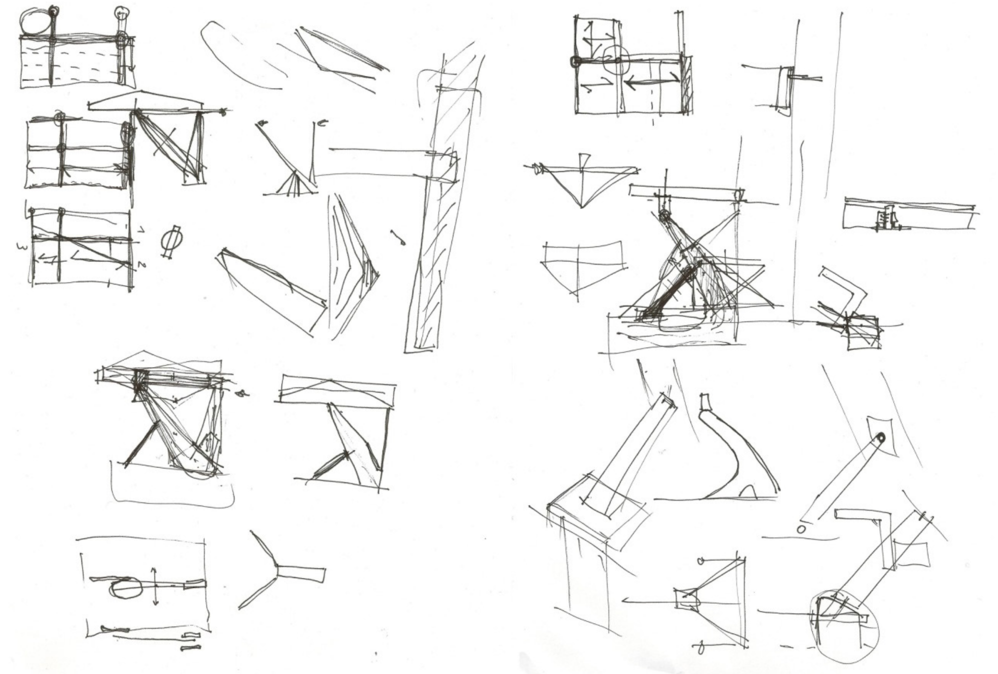


Figure 6-6. Workshop sketches of structural study through volumetric language.

Figure 6-7. Built design.

6.3 Project Tomas

This case consists of one design workshop in which I collaborate as structural engineer with an experienced architect. The architectural project is developed by the architect within his work on his doctoral thesis as a professional design project in which the structural engineer is involved early in the design process. This opportunity is used (1) to apply the further developed language (with an improved symbol for bending) in a professional practice, and (2) to test the paraphrasing of each designer's design proposition as a communication and collaboration tool. As this collaboration takes place early in the architectural design process, the new language should enable a negotiation of architectural and structural concepts without narrowing the design possibilities by relying on structural typologies. As the architect has never encountered the new structural language, this workshop is also a test of whether it is intuitively comprehensible by architects.

During our one face-to-face meeting, the architect demonstrates through paraphrasing and explicit confirmation that he understands the applied structural language. Later, the architect confirms this in an informal inquiry and even describes the structural drawings as inspiring for his architectural design. He later reiterates this confirmation publicly at a conference.

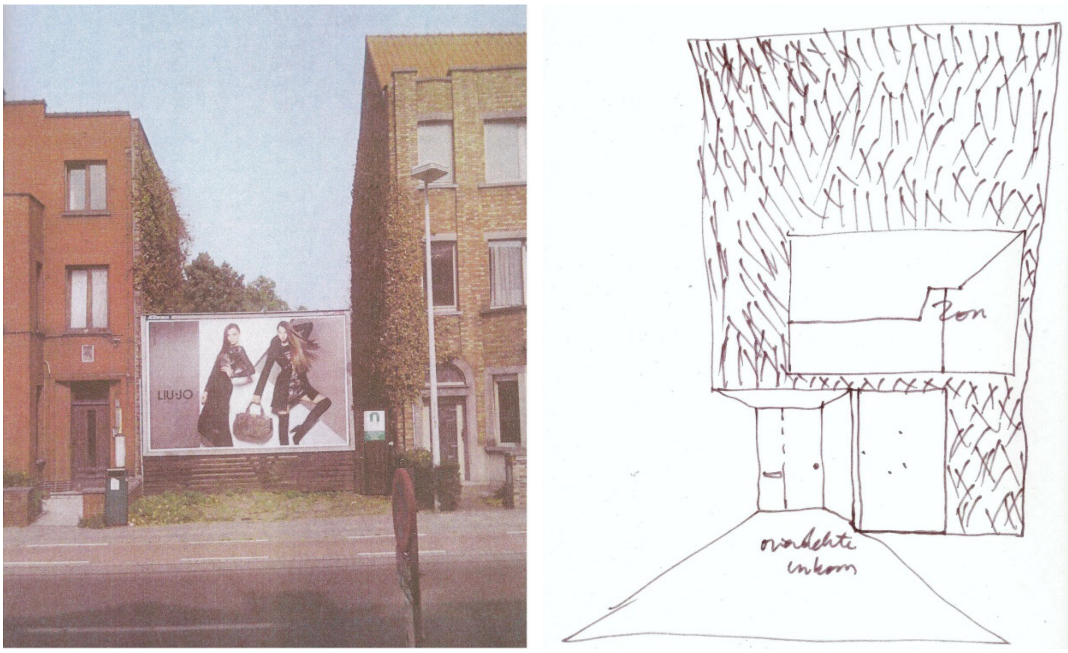


Figure 6-8. Building site and designed façade.

At the beginning of the workshop, the architect presents his conceptual design through a bundle of sketches and a verbal explanation. I write down my interpretation of the design characteristics of his proposal and present them to him. The architect agrees on my interpretation. Although I am not used to applying this paraphrasing, it seems to benefit our communication and collaboration, as I have never worked with this architect before and within a short span of time we are able to develop a qualitative structural answer for the proposed architectural question.

For the architect's design proposition, I design two different structural conceptual design propositions that differ only on the upper floor. These propositions are presented to the architect through three-dimensional drawings using the new structural language. As I draw the various symbols, I explain the meaning of each to the architect by relating it to structural typologies like beams and columns.

The main difference for me with more conventional structural advice in such a situation is that my structural proposition is much more conceptual and does not include structural typologies. With only two drawings I can present both conceptual design propositions, while many more drawings would be required to show the different possibilities of these two propositions using structural typologies. In the structural drawings developed in this meeting, each of the conceptual elements represents an array of design possibilities of structural typologies, and through various combinations of these elements the range of structural possibilities grows much wider still.

Another advantage of using this language in this phase of the design collaboration is the ability to present my advice through three-dimensional drawings that give an overview of the structure. (In conventional collaborations two-dimensional ground floor plans would mainly be used indicating plates, beams and columns.) This overview not only expresses the spatial qualities of the structural concept, it also enables me to have an 'overlooking' conversation with the structural proposition and find three-dimensional alternative solutions instead of just two-dimensional ones.

During this meeting, I notice I am able to design while drawing the propositions, as this language lets me record an idea on paper and thus allow other ideas to enter my design thinking. The conceptual language keeps my design attention on a conceptual level, encouraging me to search first in breadth without getting distracted by details prematurely and losing my concentration. Using a language of typologies would seem to require more effort, since one is forced to return from detail to a more conceptual level each time a different kind of structural proposition is explored. (Finding satisfaction in a first adequate solution might even eliminate the incentive to explore other solutions.)

The technique of going through different structural solutions for each conceptual element provides me with an organized range of design solutions.

In my experience, this wide range would not be attained by going immediately into more detailed design propositions through a language of typologies.

The spatial qualities of the structural propositions in this meeting relate directly to architectural design, since the two propositions organize space on the upper floor in different ways. This forms a part in the negotiation between architect and structural engineer to further the design.

In order not to overload the drawing with information, only the structural story of the vertical loads is presented. (In this case the horizontal load is not particularly determinate of the structural form.) Through the new language the structural behaviour of the propositions is explained to the architect so that he can manipulate the given form models according to structural logic.

Also some of the conceptual elements are further refined to show the architect the range of possible solutions entailed by the conceptual design proposition. The architect demonstrates his understanding of the range of possible structural solutions I present, but this advantage for architectural design is not put to the test because the architect decides not to further develop the project. (The architect does not proceed with his doctoral work.) At the end of this workshop, the architect expresses a clear understanding of my language and my conceptual propositions, and says he has received sufficient structural input to further develop his design. He is very pleased with the outcome of this meeting for his design process.

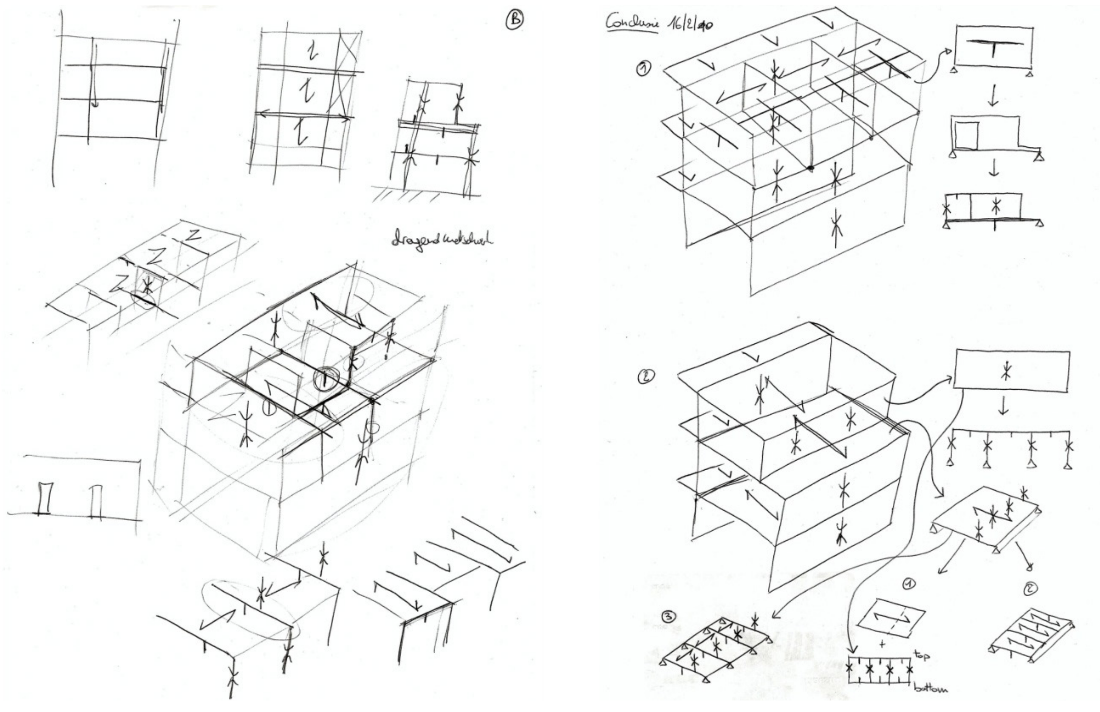


Figure 6-9. Sketches of the workshop; redrawn structural propositions.

In this workshop only two A4-sized pages are required to communicate the structural input. As an exercise, I redraw the conceptual design propositions in a more careful manner (Figure 6-9) in order to check if the language can provide a rich image without being overloaded. (On this drawing I also express some of the possible refinements of certain conceptual elements.)

This exercise tells me that rich pictures are possible, but that the symbol of bending applied to a conceptual line is still confusing to interpret. (This leads to a further development of the language by using a different pencil for the functions than for the wire-frame model.) It also shows me that a different symbol is applied in the language for bending in a surface than in a line. The two symbols bring out different aspects of the structural characteristics of the element: the bending requirement and the load path. This insight leads to the introduction of an extra 'load path' layer in the language as a way to express the course followed by the load through the structure to its supports, and as a way to show the interdependency of the various structural elements.

7. A structural language for conceptual design

7.1 Purpose of a new structural language

Cognitive linguistics shows that a language is not merely a tool to communicate meaning, but that it also affects the way we perceive and understand phenomena (cf. Chapter 2.5). Because of these repercussions in language application, I believe that one way of supporting collaboration between architects and engineers lies in choosing an appropriate language for their communication. Such an appropriate language is not just a means to tell a structural story; more importantly, it frames how we perceive and give meaning to structural design through the language-specific descriptions it provides. And thus the structural language proposed in this research is not only developed as a vehicle to communicate design characteristics of a conceptual design, but also to provide for a type of interpretation that gives meaning to structural knowledge in a designerly way (i.e. going from conceptual to specific and expressing essential aspects of structural design logic).

By giving meaning to a structural design proposition through this new language, specific characteristics pertaining to conceptual design will be brought to the fore while others will be filtered out. This provides for an articulation of conceptual design that enables a designer to distance him- or herself from the proposition and let it talk back in order to further develop and explore conceptual design possibilities (as Schön and Lawson have described it, cf. Chapter 2.3). (As the proposed language is intended to be understood by architects and structural engineers, both designers should be able to reflect-in-action when using this language in design collaboration.)

The proposed language brings to the fore various (personal) choices a designer makes during the conceptual design of a structure. These choices already determine the range of possible design solutions before any structural calculations are performed, and involve identifying various loads, supports, and structural elements, and the structural order and function of these elements. Articulating these important design decisions brings them up for design negotiation between the architect and the structural engineer: do both designers agree on the choices presented that delineate the structural form and influence the architectural design?

The proposed language allows a structural engineer to express the structural logic of a conceptual design proposition as an important design characteristic. In this language, structural logic is expressed through the primary structural functions of the elements that form the structural system, and through their inner order when transferring loads to the supports. (Structural functions are considered secondary when they have no influence on the dimensions of elements that are determined by the primary functions. Secondary functions are considered redundant in the main structural story.)

Understanding the underlying (objective) structural logic of a structural proposition provides an ability to alter the given structural form model while keeping it structurally sound. It enables an insight into the range of design possibilities that a proposition entails, and in how the engineer understands his or her design proposition. According to Addis, when imagining or looking at structures, engineers broadly see ‘patterns of loads which the structure must withstand’; ‘and they see load paths which conduct these loads through the structure to the foundations and the earth’; and they see the behaviour of each element, among many other aspects of structural design (Addis 1994, p.12).

One of the purposes of the proposed language is to filter the variety of structural information an engineer can provide while still expressing structural logic.

The new language is also developed to provide for a more abstract type of interpretation of structural design as an alternative to more in-depth structural analysis and calculation methods. This new interpretation leads to the development of some building blocks of design that are more conceptual than the usual structural typologies (as described in Chapter 2.3). It even enables us to develop and express structural prototypes that can serve as starting points for structural design in the way architectural prototypes can initiate architectural design (cf. Chapter 2.3).

In a creative collaboration between an architect and a structural engineer, face-to-face interaction and the use of sketching is very important (cf. Chapters 2.5, 3.2 and 5.2). In the development of this language much attention is given to symbols that can be drawn quickly and easily and comprehended intuitively.

This language is to be applied during interpersonal design processes (e.g. during collaboration meetings between the architect and the structural engineer) and during personal design processes (e.g. to provide proposition drawings as described by Lawson (Lawson 2004, pp.45–49)). In both cases the language addresses a subjective aspect of structural design that sometimes requires a personal expression of a structural story. The language does not contain strict rules for expressing a structural story, but rather guidelines that leave a certain application freedom to allow for a degree of poetic content.

Each conceptual element described with the proposed language represents a range of possible design solutions with common characteristics (as described by the language). The language thus provides for a taxonomy of design solutions through the conceptual design characteristics it can express.

7.2 Existing languages versus the new language

The engineering sciences already provide several terms for expressing the structural behaviour or logic of a specific structure. One set of terms is based on the notion of internal forces. These terms are *normal forces*, *shear forces* (in two directions), *bending moment* (in two directions) and *torsion moment*. These six terms provide numerical variables that describe the structural requirements each element of the construction must meet in order for it to withstand the forces applied on it. At the same time, these requirements express the structural behaviour of the construction under load.

Another available term is the *deformation* of the construction in three dimensions under load, and related to it the *rotation* of elements. Both terms are related to our visual experiences and thereby provide for a more experiential understanding of structural behaviour, even though in the reality of built structures these deformations are often barely noticeable.

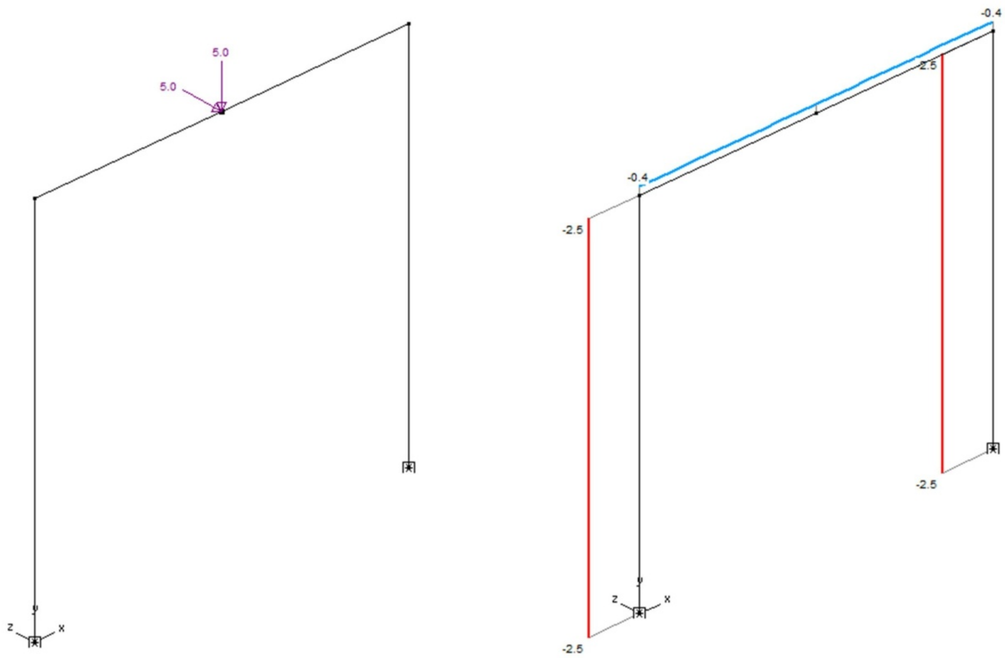


Figure 7-1. Example of expressing structural behaviour in coloured diagrams. (Double loaded frame and diagram of normal forces in kN)

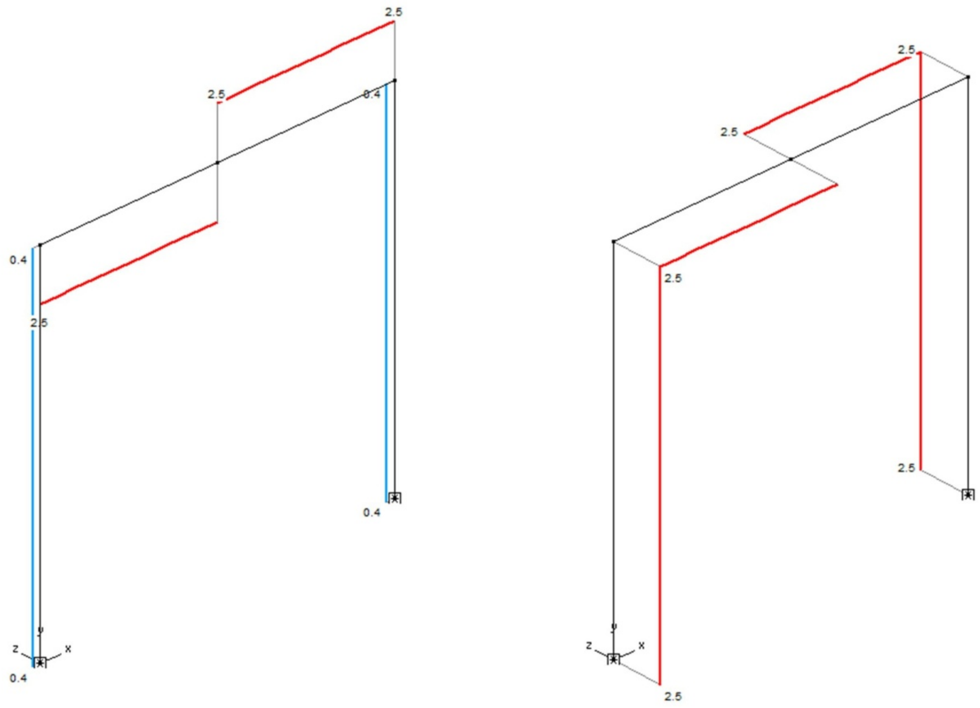


Figure 7-2. Example of expressing structural behaviour in coloured diagrams. (Diagram of y-shear forces in kN and diagram of z-shear forces in kN)

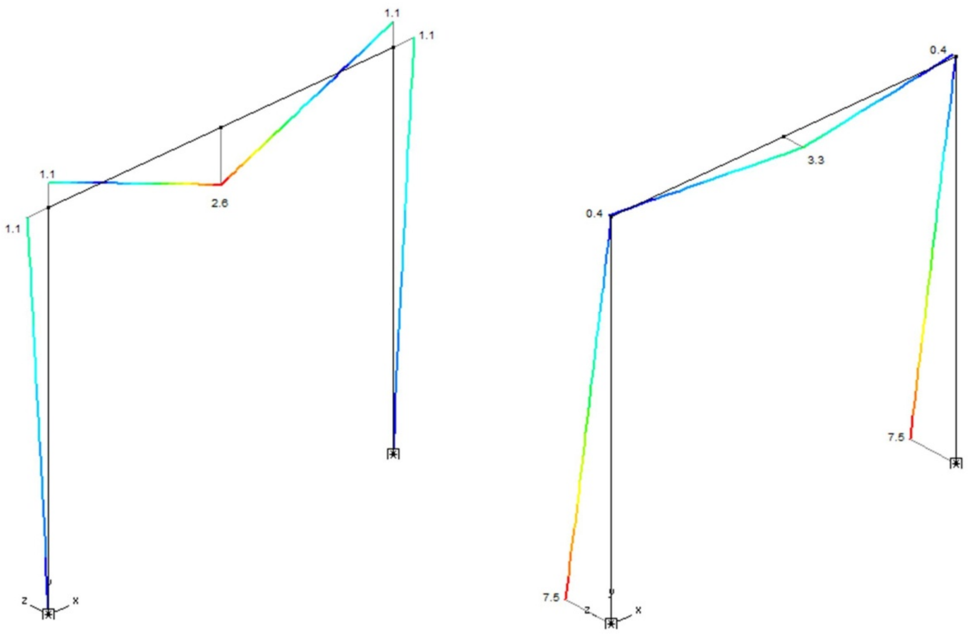


Figure 7-3. Example of expressing structural behaviour in coloured diagrams. (Diagram of z-bending moments and diagram of y-bending moments in kNm)

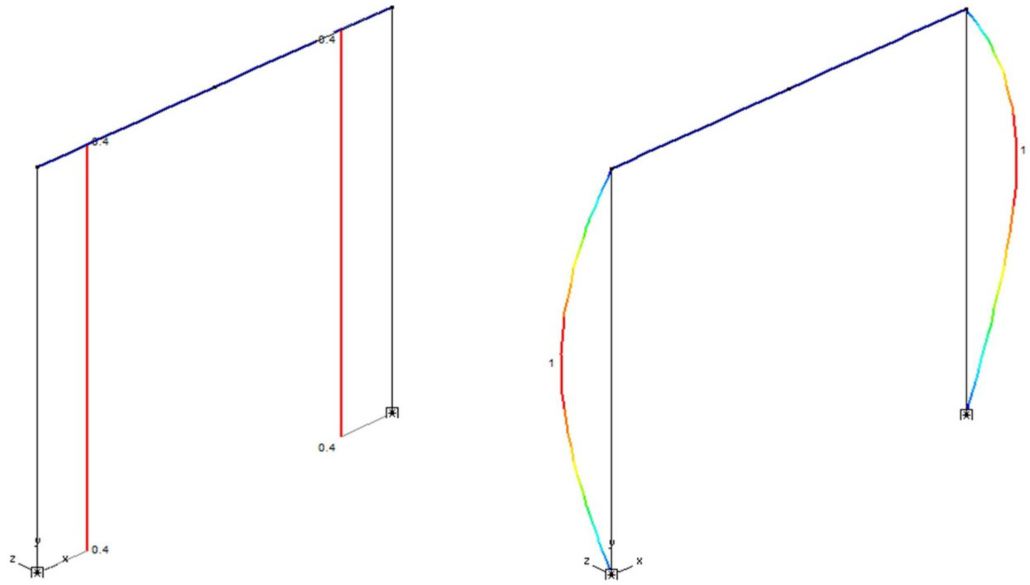


Figure 7-4. Example of expressing structural behaviour in coloured diagrams. (Diagram of torsion moments in kNm and diagram of x-deformation in mm)

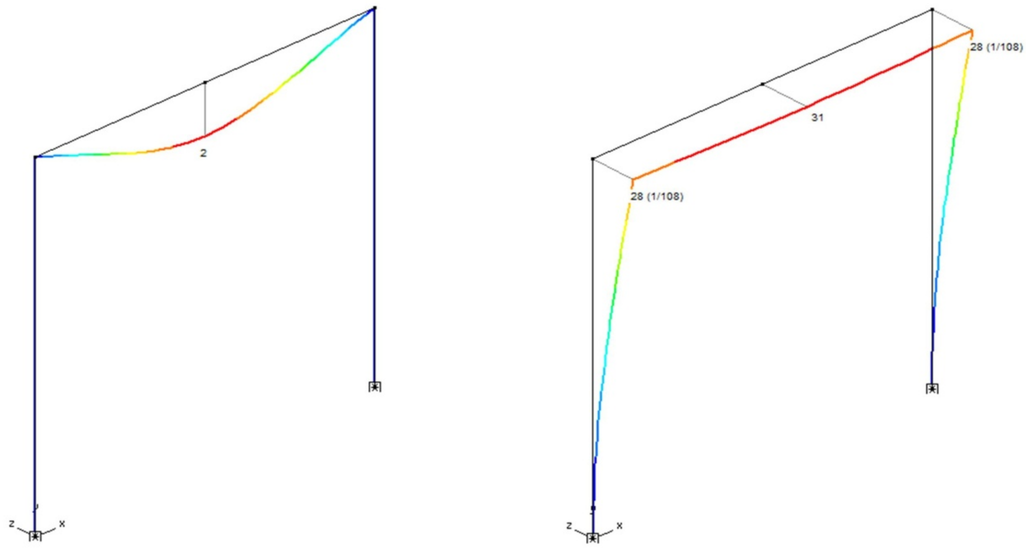


Figure 7-5. Example of expressing structural behaviour in coloured diagrams. (Diagram of y-deformation in mm and diagram of z-deformation in mm)

On a more detailed level, another set of available terms is the internal stresses in the material of the construction. They consist of three *normal stresses* and three *shear stresses*. As with the internal forces, they are oriented according to chosen orthogonal axes. Because these axes are sometimes chosen uniformly, more interesting information may lie in other directions: they are expressed through *principal stresses.*

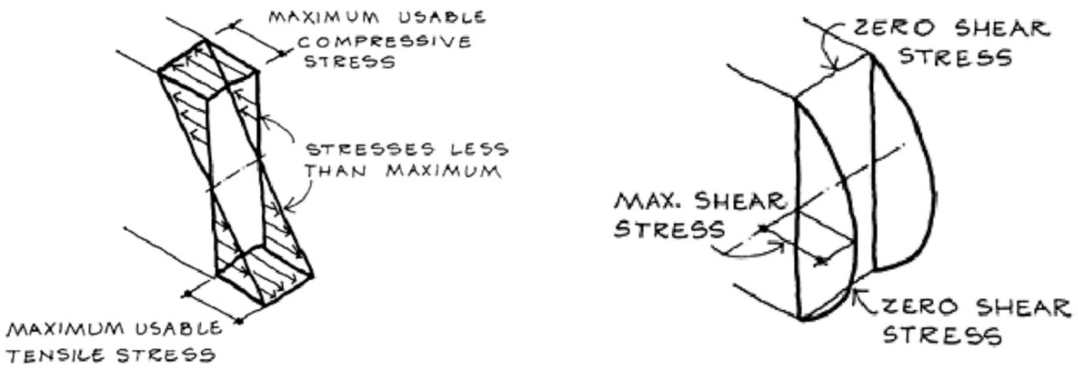


Figure 7-6. Expressing structural behaviour through internal stresses.
(Single-span beam: diagram of normal stresses and diagram of shear stresses)

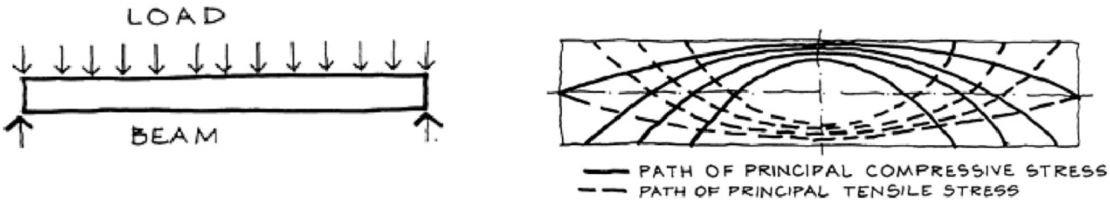


Figure 7-7. Expressing structural behaviour through principal stresses.
(Single-span beam: load condition and principal stresses)

On the level of structural system, there is one more interesting term applicable: the *load path* or *flow of forces*. (This concept is more commonly used in architecture education than in engineering.) This path shows which elements of a structural system are loaded (and which ones are not) and how an implemented force flows through the construction until it arrives at its supports.

All the terms presented above have proven their importance over the years, and enable us to express structural logic and behaviour precisely. However, most require that the reader of these images have sufficient knowledge of structural engineering – and not only on the level of understanding the different terms but even interpreting the relative values of the different terms. Not all terms are equally important in telling the story of the main structural behaviour. (In many books (e.g. Millais 2005) one can find a structure explained by only a few carefully selected terms. Structures are even categorised based on which terms best explain their structural behaviour (cf. Engel 2009).)

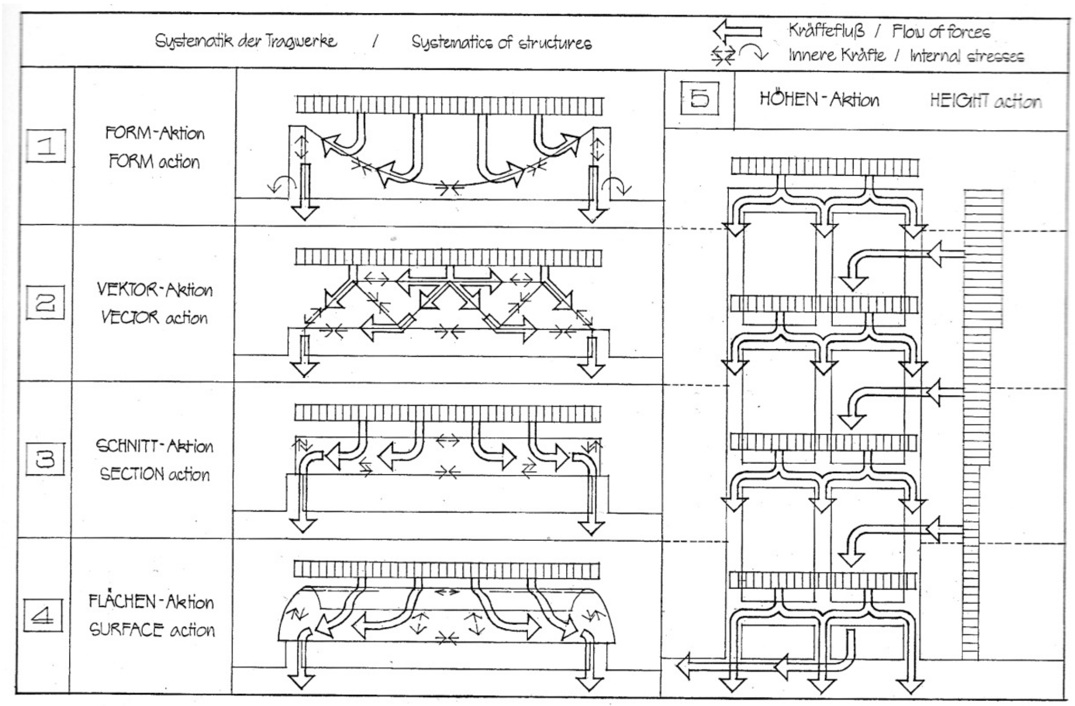


Figure 7-8. Expressing structural behaviour through flow of forces.

The early phase of a design process often does not require the detailed precision that can be expressed with these engineering science terms.
A general structural understanding of the structural proposition is most often sufficient to communicate during collaboration. Being too precise would slow down the design process, not only because of the time needed to produce and convey the various diagrams, but also because of the overload of information. In my view, a structural engineer needs to filter out all secondary information and focus on the main story of structural behaviour when communicating the essential design characteristics of a conceptual design proposition.

In contrast to the currently prevalent engineering sciences language, the proposed new language tries to filter out all secondary information by focusing on the main structural story, and tries to be more intuitively understandable by requiring of the reader less engineering-specific knowledge. For application during face-to-face meetings, the language also strives to be easier and quicker draw by hand than the various mathematical diagrams of internal forces and deformation.

In a structural conceptual design proposition, in my view, the focus for understanding its structural logic must be on its structural system (i.e. how different structural elements work together) rather than on isolated elements. Therefore the new language tries to establish this focus on the whole by presenting structural systems in three-dimensional overviews, using as few images as possible and preferably capturing each system in a single image.

The generative idea behind the development of the language is to load an architectural three-dimensional image or physical model with structural information by encoding its architectural elements with this language. This language basically consists of four different layers: structural order, structural function, structural dimensions and structural design possibilities. Each layer brings forward a specific element of structural understanding involved in a collaborative design process between architect and structural engineer. Although each layer is autonomous, they are also related to one another. In combination they can bring to the fore specific characteristics of structural understanding that transcend the sum of each individual layer. These layers will be presented in the following paragraphs.

7.3 Structural order

One of the main functions of a structure is to direct loads towards its supports. Engel has described this as load reception, load transfer and load discharge (Engel 2009, p.25). This concept introduces a direction of load, going from where the load is received to where the load is discharged at the supports: a flow of forces, or load path (Millais 2005, pp.30–36). Engel calls this ‘the basic conceptual image for the design of a structure’ (Engel 2009, p.25). Thus tracing this flow of forces or load path is a principle element in understanding a structure. It identifies the structural elements for a specific load case and introduces order in these elements as one element relies on the next element to bring the load to the supports.

Structural order could be defined by the dynamic propulsion of stresses in a structural system due to the introduction of a load. The flow of this stress propulsion then determines the order of the different structural elements. (In certain cases this stress propulsion can come from both sides of a structural element, giving it contra-directional flows of forces. As reception and discharge are then on the same side of the element, no unidirectional load path can be defined. This limits the use of this layer.)

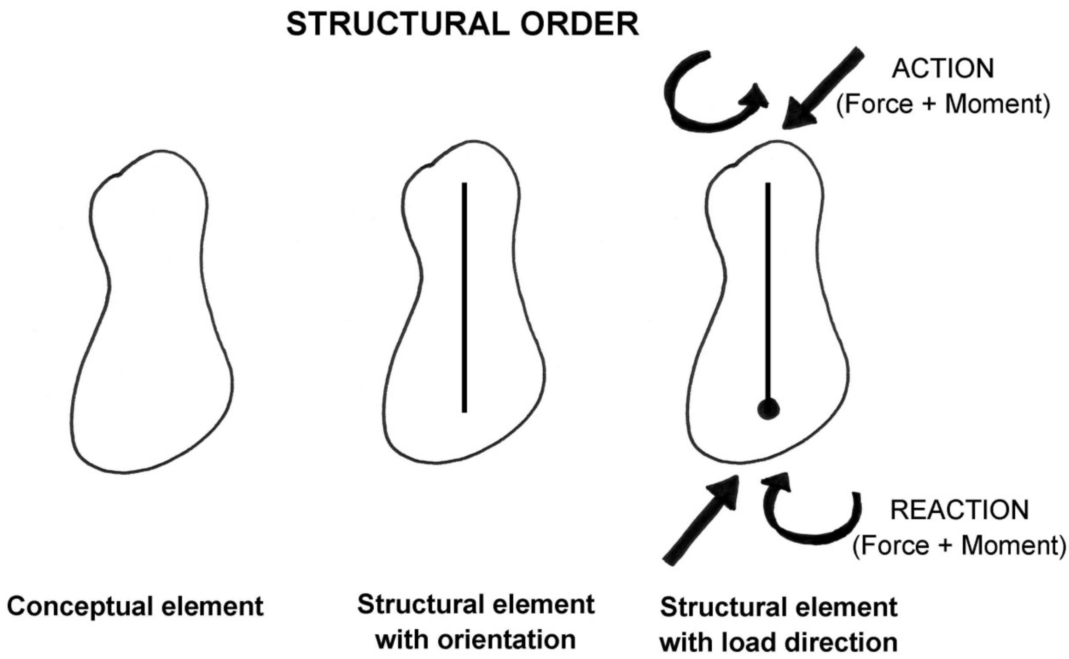


Figure 7-9. Recognizing an element as structural and defining its load direction.

The layer of structural order first recognizes a conceptual (architectural) element as a structural element with a specific orientation. This structural axis is indicated with a line. By using the symbol ● towards one side of an element, the direction of the flow is expressed: it indicates which side of the element discharges the load, or where the reaction is to be understood. The connection with the other elements then makes clear which element will receive the load next (as action). In this manner, the path of the load can be traced throughout the different elements and their structural order becomes apparent.

Although structural order can be defined by structural engineering science, the flow of forces is not so commonly used in structural engineering. When the dimensions of a structural element are calculated, all the forces that affect this element must be considered. There is no distinction in these calculations between whether such a force is to be considered an action or a reaction. (Switching action and reaction forces will lead to the same structural dimensions for an element.) Thus the concept 'flow of forces' has no meaning for dimensioning calculations.

Still, structural order can express which elements an engineer considers part of his or her designed proposition and in what order the elements function to transfer the load to its support. This order makes the interdependency of the different elements explicit: which other elements does each element rely on? In other words, which elements are affected when one element is omitted?

Developing a structural order is an essential part of structural design that involves personal design decisions by an engineer. It requires the engineer to identify the loads, supports, structural elements and their interdependency. For example, in Balmond's structural design for the villa in Bordeaux, one of his most creative contributions are his choices in structural order: he brings certain loads to the top (instead of the bottom) of the building before transferring them to the supports, and he chooses to locate supports outside the building footprint (Balmond 2002).

In architectural design this flow of forces seems to be more commonly used. (When I ask architecture students to explain how a structure works, they will often draw flow of forces on the structural system.) The concepts of order and hierarchy are part of the architectural design vocabulary. Expressing the structural order of a design proposition enables this order to then become part of the architect's design process.

As a structural system gets defined through its elements with an orientation (i.e. its axis) and a direction of load, it provides for an organization of space and a rhythm that relates to architectural design.

According to Karl-Gunnar Olsson et al., revealing a load path of a structural system provides for a common language for architect and structural engineer during the design of architectural form and structure (Olsson et al. 2008).

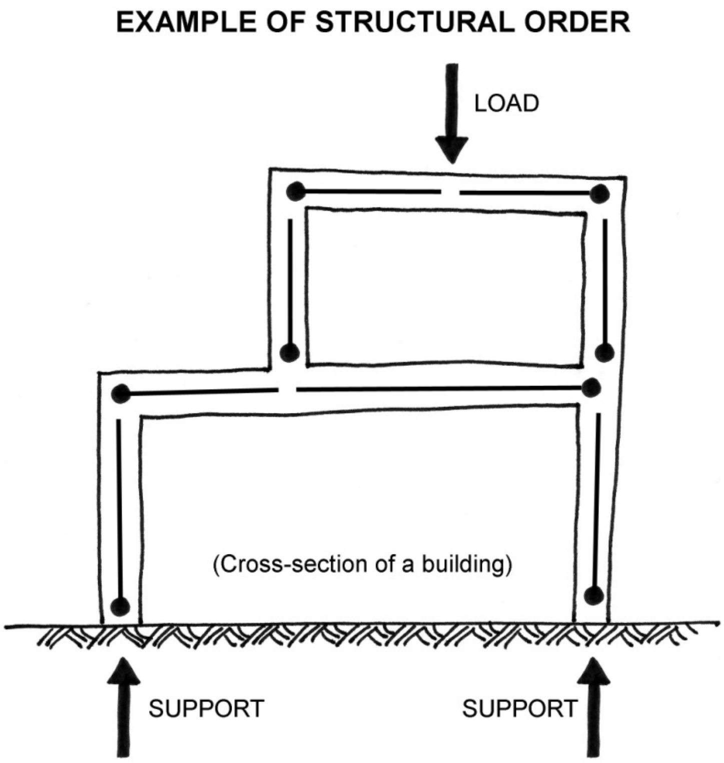


Figure 7-10. Expression of structural order in a cross-section of a building.

Structural order provides for a (sequential) narrative of a structural story. This layer of the structural language expresses which elements an engineer considers to be part of his or her design proposition and how they relate to one another. Understanding this structural order of a proposition is essential to foreseeing the consequences of changing a structural form model. This layer expresses an important design characteristic of a structural proposition that often lies at the basis for design negotiation.

Since a flow of forces is not always presentable as unidirectional flows (e.g. in a truss-girder) as described above, there is a limit to its applicability.

7.4 Structural function

As mentioned in Chapter 2.5, according to Renate Fruchter et al., communicating information about the structural and architectural functions of the various elements of a form model provides each collaborative partner with a more profound understanding of the other's design proposition, which enables a more creative design collaboration than without this information (Fruchter et al. 1996).

The main structural function of an element is to transfer one or more loads or actions to its supports or reactions. This structural function can be described through two times two types: axial and parallel transfer of force, and axial and parallel transfer of moment.

When the load is a single force, a structural element can transfer the load along its axis or parallel to its axis. When the load is a moment or a couple of forces, a structural element can transfer the load along the axis of the moment or parallel to it. This transfer of load is what a structural element is required to do: it is its structural function as designed by the engineer. (In the case of parallel transfer of forces, an extra stabilizing moment is required to keep the element in static balance. This moment, however, is not part of the structural function the element has to perform, but considered a consequence of its function and therefore omitted in this layer).

From an engineering point of view, this function relates to the internal forces an element has to withstand in order to bring the load to the support: an element that is able to perform a function is required to withstand the internal forces caused by the forces and moments applied on that element. In performing this function there is no difference in action and reaction, and thus the structural function of an element has no direction, since action and reaction can be switched.

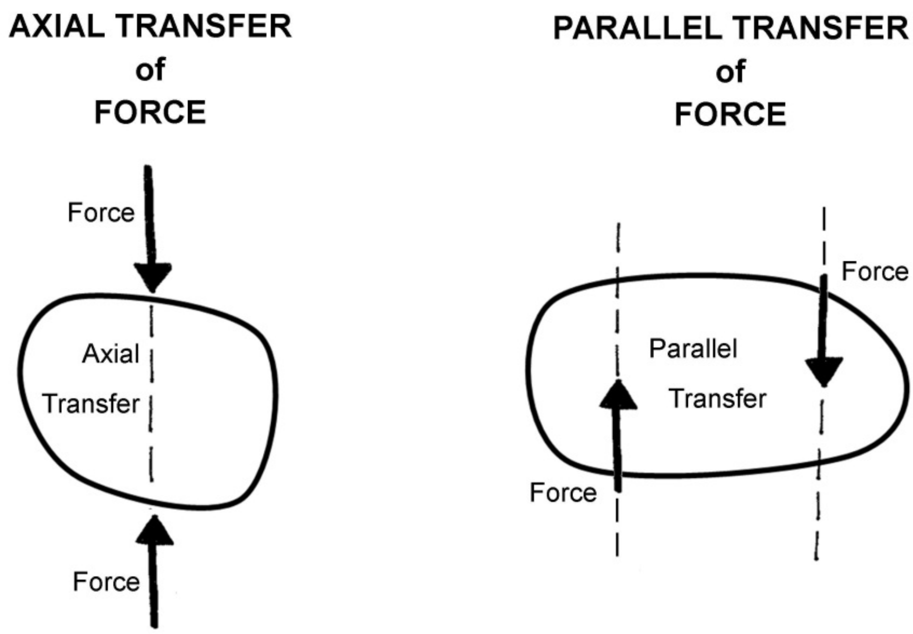


Figure 7-11. Structural function: axial and parallel transfer of force.

In the engineering sciences, because internal forces are directly related to the structural function(s) of an element, these internal forces describe the function of an element: the structural function is what the element is required to do and the internal forces are the consequences of this requirement. (The structure not only has to withstand the forces by being strong enough, but also by being stiff enough. This means that the consequences of a structural function for an element are not just that it withstand the internal forces, but also that it limit its deformation.)

In the field of structural design, however, the structural function of an element is what a structural designer requires this element to provide. This is part of the design characteristics of a structural proposition.

This rhetoric of a structural engineer requiring a designed structure to function in a specific manner is sometimes suppressed in engineering culture by the idea that structural calculations decide how a structure functions. These calculations, however, actually express the behaviour of an element due to its required function: requirement and consequences seem to be mixed up. This layer brings to the fore the intention of the structural designer in the design proposition.

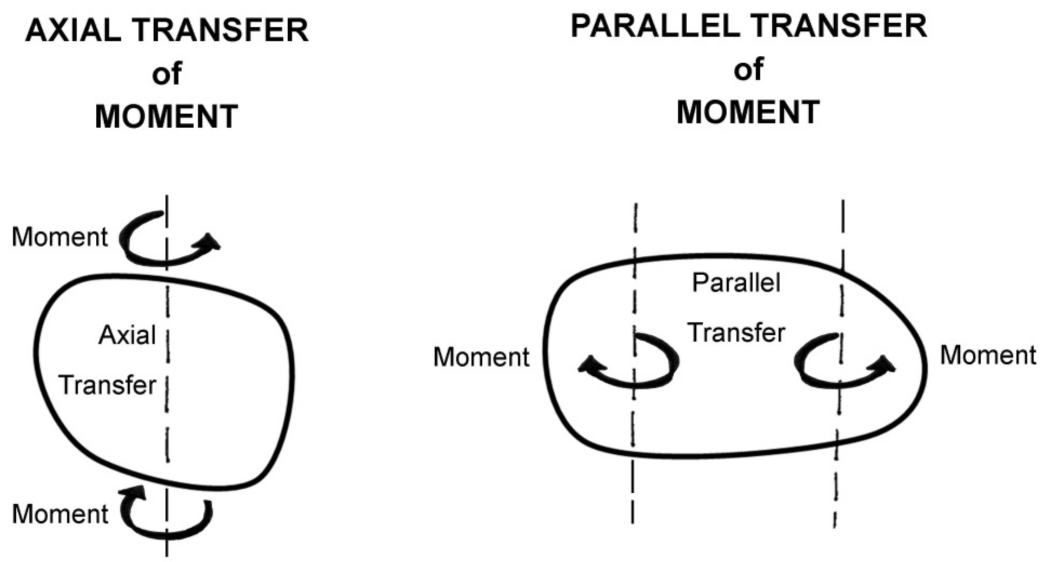


Figure 7-12. Structural function: axial and parallel transfer of moment.

In the field of architectural design, this structural function seems to be a very abstract notion on the level of structural understanding. But it relates to the structural order by describing how the forces and moments are transferred through a structural element.

In a collaboration between architect and structural engineer, the main function of this layer is to call attention to the engineer's intention – as a designer rather than a calculator – for what each structural element is required to perform in his or her design proposition as part of the design characteristics.

7.5 Structural dimensions

The layer of structural dimensions brings to the fore the consequences of structural function on the structural form of an element. In structural engineering, these consequences are determined by the internal forces of the element: for a given structural material the required structural dimensions of an element can be calculated from the values of the internal forces.

These structural dimensions are determined by the most demanding structural functions and thus imply a filtering of functions: only those functions responsible for the final dimensions are to be brought to the fore.

This relation between function and form can be turned around: a structural form (in a specific material) is capable of performing certain structural functions (sometimes more than the one for which it is designed). Structural form then determines its possible functions.

There are five major types of structural dimensions to be considered:

- Tension through axial transfer of force
- Compression through axial transfer of force
- Bending through parallel transfer of force
- Torsion through axial transfer of moment
- Bending through parallel transfer of moment

The characteristics of structural dimensions are directly derived from the characteristics of structural functions, except for axial transfer of force, which is divided into tension and compression. A distinction is made between tension and compression because structural dimensions can be smaller for tension (e.g. a cable) than for compression (e.g. a column) for the same load, since tensile members do not have to withstand buckling.

The symbol used for compression is two arrows pointing at each other. In order to express tension, two arrows pointing away from each other are used. (In the lower figures, the conceptual element on which the layer is applied is that of a flat surface.)

The symbol used for bending through parallel transfer of force is | , indicated at one end of the structural axis. (This structural function is performed by a cantilever beam.) The symbol | indicates the position of maximum bending moment, where the material form requires the most height (if width is kept constant). It is drawn on the side of the structural axis where tension due to bending occurs. A distinction is made between tension in the upper side (| on top of the axis) and the lower side (| under the axis), because of the relation with the material form: the part of an element in tension has no buckling problems and can be slender compared to the part in compression.

In order to achieve a static balance for an element performing a parallel transfer of force, a 'stabilizing' moment or couple of forces is required. This couple of forces is placed at the side of the element where maximum bending moment occurs, as indicated with the symbol | . These stabilizing forces then respond to the maximum bending moment.

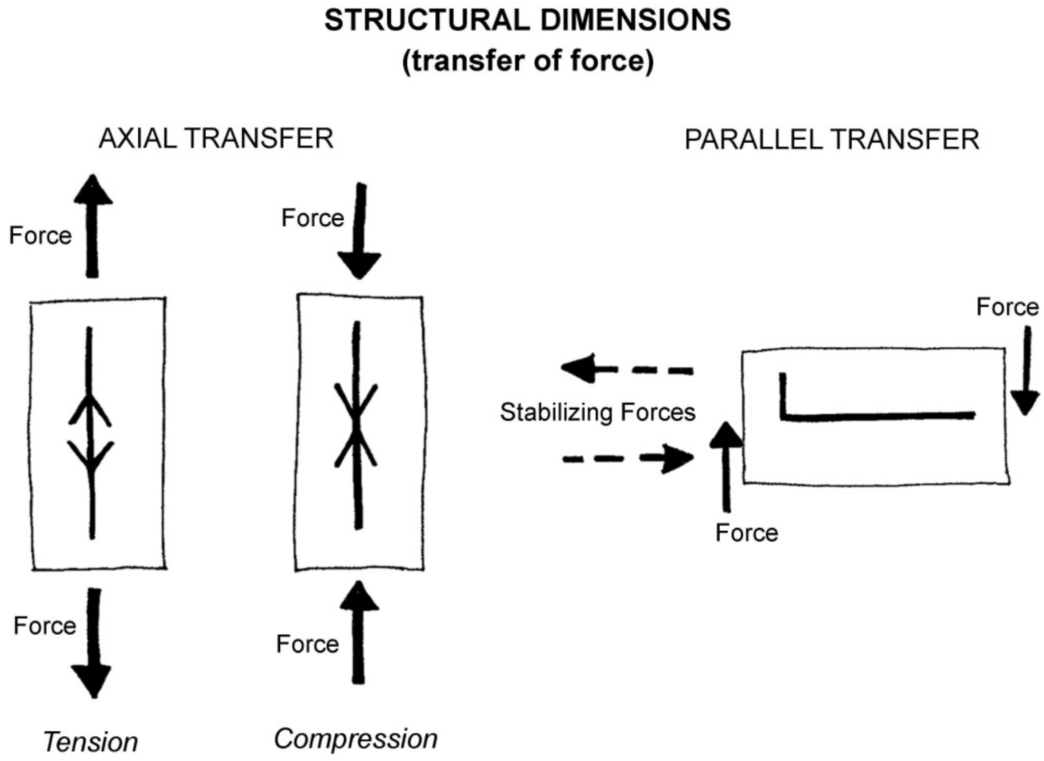


Figure 7-13. Axial (tension/compression) and parallel (bending) transfer of force.

The symbol used for axial transfer of moment is a spiral. It indicates tension stresses that occur in the element due to the internal torsion along the axis of the element.

When a parallel transfer of moment occurs in a structural element, it is described in engineering sciences through a constant value for bending moment along the axis of the element. The symbols used here are two I on both ends of the structural axis. The symbols are placed on the side of the axis where tension through bending occurs. It indicates a continuous bending moment that the element has to withstand over its full length, and also the constant height of the material form.

The symbol used for axial transfer of moment is a spiral. It indicates tensile stresses that occur in the element due to the internal torsion along the axis of the element.

When a parallel transfer of moment occurs in a structural element, it is described in engineering science by a constant value for bending moment along the axis of the element. The symbols used here are two I 's on both ends of the structural axis. The symbols are placed on the side of the axis where tension through bending occurs. This indicates a continuous bending moment that the element has to withstand over its full length, and also the constant height of the material form.

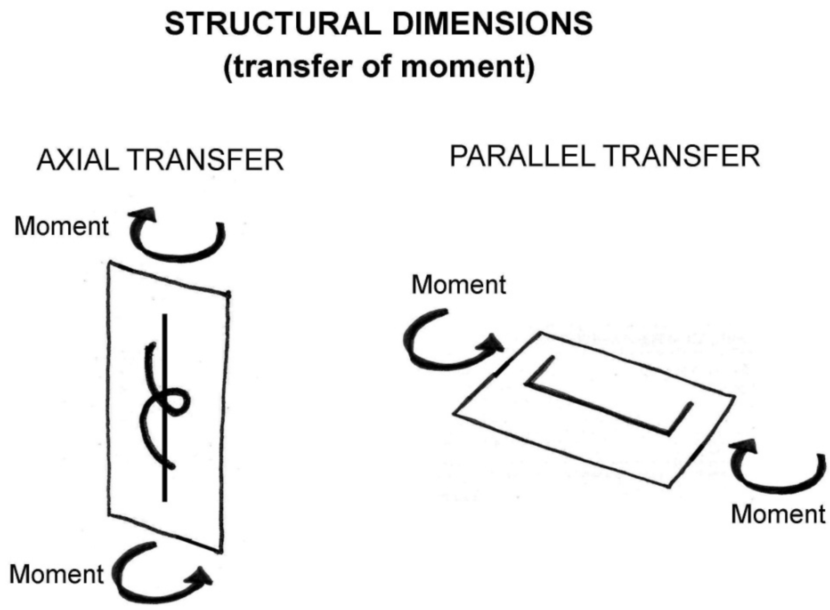


Figure 7-14. Axial (torsion) and parallel (constant bending) transfer of moment.

This layer of structural dimensions relates within the engineering sciences to the calculated dimensions a structural element is required to possess (for a specific material) in order to perform certain structural functions. These calculations are performed using knowledge of the internal forces, which in turn relates to the layer of structural function.

The layer of structural dimensions only gives an indication (and not precise values) of the consequences of these structural functions on structural form, and is not related to any structural material. Through structural insight alone (i.e. without calculations), an engineer filters out redundant structural functions and brings to the fore those functions that are vital to the structural dimensions of his or her design proposal. (Most engineers are trained in this filtering procedure of taking into account only the most important elements in an investigation.)

The rougher, more abstract structural information of this layer allows us to proceed more swiftly during design meetings, since time is not lost on extensive calculations.

This layer that brings to the fore dimensions of structural elements, relating closely to architectural design, as form is key in architecture. Through the layer's filtering of structural information, the consequences of a structural design proposal on structural form are made explicit to architects. This filtering of information, however, might at times be achieved at the cost of a more transparent structural story.

The layer of structural dimensions provides a link between a more intuitive understanding of structural behaviour through form, and a more theoretical understanding through internal forces. The former understanding is fed through everyday experiential encounters with structural forms; the latter is developed in engineering science.

In collaboration, the structural dimensions layer enables an engineer to express the design characteristics of his or her design proposal through the consequences for structural dimensions. This provides a more intuitive understanding of the structural behaviour of his or her design proposition than is afforded by the structural function layer (though the two layers are closely related).

The structural dimensions layer also contains information on the consequences for the dimensions of an element when its general size is altered. For example, changing the length of a linear element that has the characteristic of axially transferring load under tension (e.g. a tie) will have no influence on its cross section. But when this characteristic is an axial transfer of load under compression (e.g. a column), making the element longer will require a larger cross section to counter the buckling problem.

The type of structural connection between elements is also expressed in this layer. For example, when a connection consists of two structural elements that both require bending moment height at their connecting sides, this connection will have to be stiff in bending.

7.6 Structural design possibilities

The layers of structural function and dimensions are closely related. Therefore symbols only are developed to express one of these two layers in the new structural language, namely structural dimensions. (For each characteristic of structural dimension, one specific characteristic of structural function is attributed.) These symbols can be implemented on different structural elements. These conceptual elements can be represented in one, two or three dimensions.

Each distinct combination of force or moment transfer (within structural dimensions) and element is represented in Figure 7-15. A distinction is made in the orientation of the applied symbol for parallel transfer of force and moment in a two-dimensional element, as this orientation has a different implication for the structural dimensions of the element.

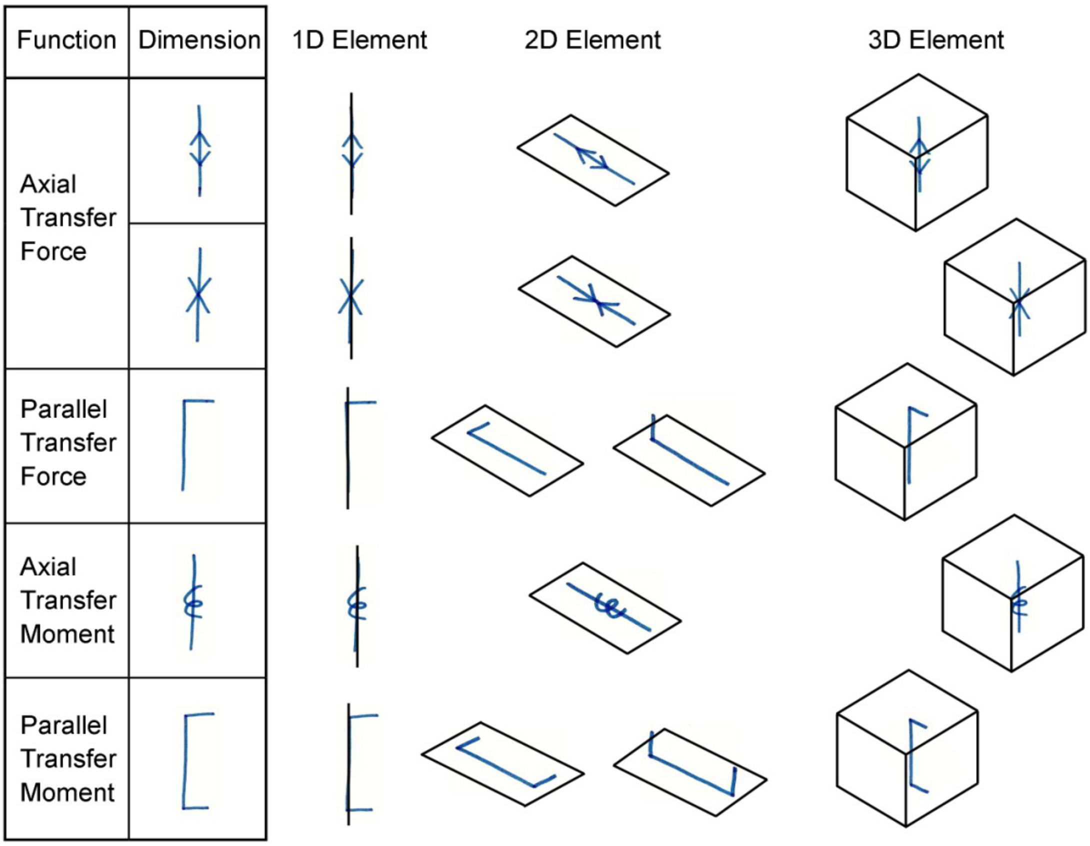


Figure 7-15. Structural function and dimensions in combination with elements.

For each structural (conceptual) element with specific characteristics of structural dimensions, a range of structural design possibilities can be presented. These design possibilities are to be understood as materialized structures that are already built, or at least designed in detail.

These materialized structures also operate in the realm of architectural design solutions, and thus can be characterized by architectural qualities as well. This layer of structural design possibilities forms a link between structural and architectural design solutions.

Each structural design possibility can be categorized through its specific characteristic of structural dimensions and the conceptual shape of the architectural element. (In this conceptual design collaboration, a structural element originates from an element of architectural design.) For example, a structural element of a rectangular surface with the structural dimensions characteristic of parallel transfer of force represents a range of design possibilities: a steel frame with a tension cable, a concrete Vierendeel-girder, a wooden truss-girder and so on (Figure 7-16). Turned around, this means that each of these design possibilities has the architectural conceptual characteristic of rectangular surface and the structural dimensions characteristics of parallel transfer of force.

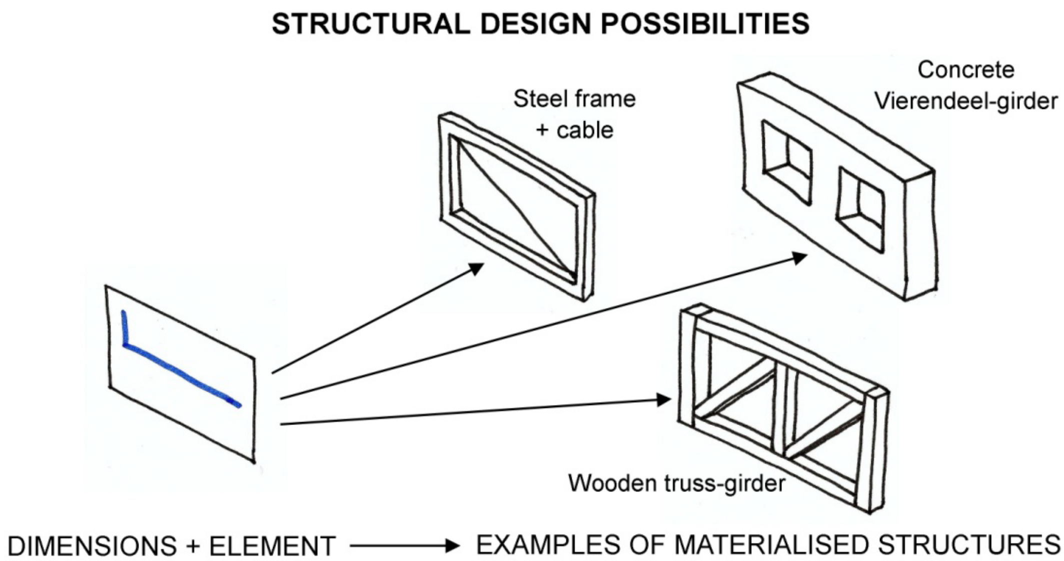


Figure 7-16. Structural design possibilities: rectangular surface + parallel transfer of force.

Other examples are given for a rectangular surface with an axial transfer of force, one under tension and one under compression. For the former combination, this leads to the design possibilities of a plywood panel, steel cables strung between hollow steel sections, and a slender concrete wall with a hole. For the latter combination, the design possibilities are a thick brick wall, a concave concrete wall with some window openings, and a steel frame of hollow tubular sections.

Structural engineers are familiar with designing structures by using structural typologies (like beams, column, slabs and girders). The structural design possibilities this layer addresses are further developed structural typologies or combinations of typologies. They are the end result of a structural engineer's design process: a built or ready-to-be-built structure that performs certain structural functions.

Although engineers are familiar with these structural design possibilities and their link with typologies, the power of this layer lies in the link between conceptual design and the wide range of structural design possibilities (rather than a single design solution). As engineers seem to be only modestly trained in conceptual design and in developing structural variants, attention might be needed to support engineers with this layer during collaboration to keep in mind the wide range of possible design solutions a conceptual design entails.

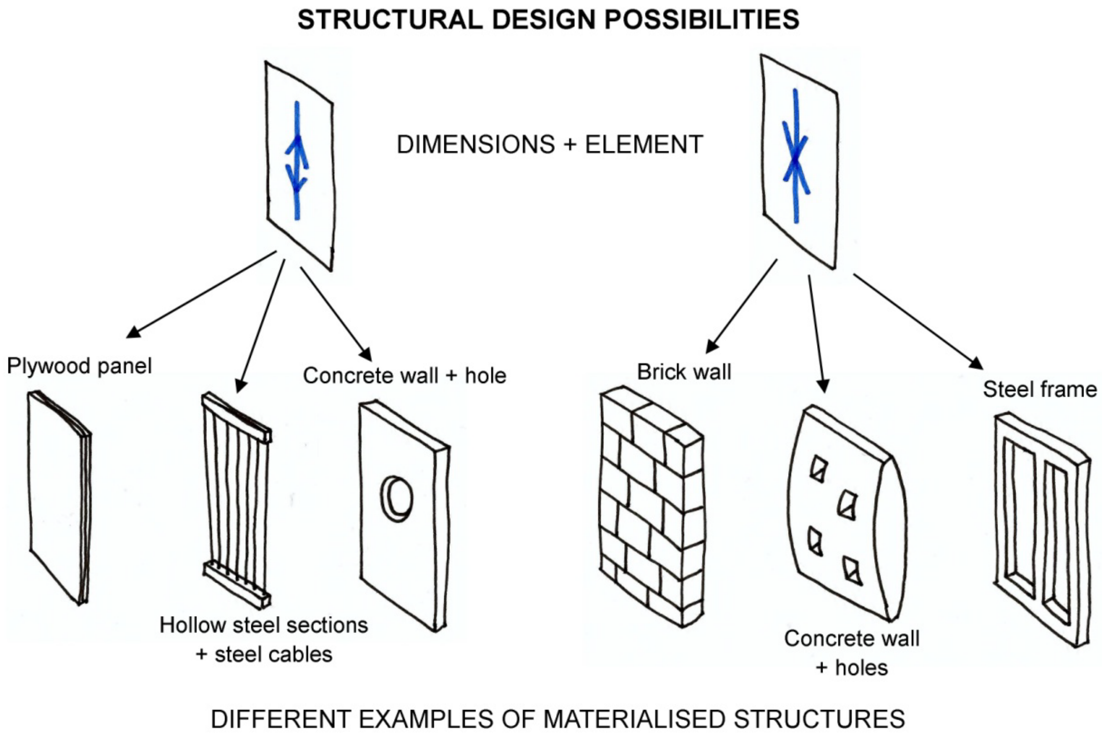


Figure 7-17. Structural design possibilities: rectangular surface + axial transfer of force.

For example, in Cecil Balmond's structurally creative design of some columns for the Kunsthal in Rotterdam (with architect Rem Koolhaas), the engineer investigates the wide variety of design solutions available for a conceptual element that transfers its load axially under compression (i.e. a column). Also, in designing the roof as a wind-bracing element (i.e. a parallel transfer of load), the investigation into possible structural solutions leads to a creative solution: a horizontal arch (Balmond 2002).

In the field of architectural design, it is common to find inspiration for conceptual design in built reality (cf. precedents in Chapter 2.3). By providing possible structural design solutions for conceptual elements in a built reality, structural conceptual elements enter the realm of architectural design, where they can be evaluated as architectural elements through their visual and tactile characteristics.

In the collaboration between architect and structural engineer, this layer provides a link between a structural conceptual design proposition and the wide range of structural design possibilities. Meaning is given to a design proposition through abstract terms that avoid a more limited description through structural typologies derived from a more in-depth understanding of structural analysis. (What's more, these typologies are often associated with stereotypical visual and tactile characteristics that also diminish the range of possible design solutions. For example, a truss-girder is often represented as a stringent rhythm of steel H-profiles, although other configurations are also possible.) This layer enables an architect to understand the richness of possible structural design possibilities for a conceptual proposition.

Developing a catalogue of built structural design possibilities for an architectural project can provide a tool for presenting a wealth of design possibilities as an inspiration for collaborative design work. This catalogue can be organized through the layer of structural dimensions and the conceptual (architectural) shape of the structural element. Such a catalogue relates to Goldschmidt's catalogue of 'precedents' or 'references' as a design knowledge database, which in this case overlaps architectural and structural design (Goldschmidt 1998).

Going through a range of built examples for inspiration is a known method in architectural design. For the structural engineer, such a catalogue can provide an overview of possible design solutions, which might prevent a structural design process aimed at finding only one solution (cf. Chapter 2.3).

Such a catalogue can also be used as a communication tool during negotiations between architects and structural engineers, helping them to express and refine their design characteristics and design intentions to each other – and also to themselves. For example, a built solution can present the kind of expression an architect is seeking in his or her design, or the structural scheme an engineer prefers.

The strength of this layer lies in the structural and architectural variety of possible structural design possibilities that can be provided for each conceptual combination. A catalogue should provide for this variety and for an appropriate retrieval method to present adequate design possibilities during collaboration.

7.7 Basic rules and understanding of language application

In collaboration, a structural language of symbols is applied on a form model of conceptual elements. These elements are conceptual, as they do not represent specific structural solutions or a specific structural typology: each conceptual element represents a range of structural typologies and thus also a range of design solutions. The representation of each conceptual element in structural design is based on its general architectural expression. For example, a rectangular surface can represent a conceptual element for a truss-girder typology with a rectangular outline, or a rectangular Vierendeel-girder typology. (In engineering science, such girders would commonly be presented through the axes of their different members.)

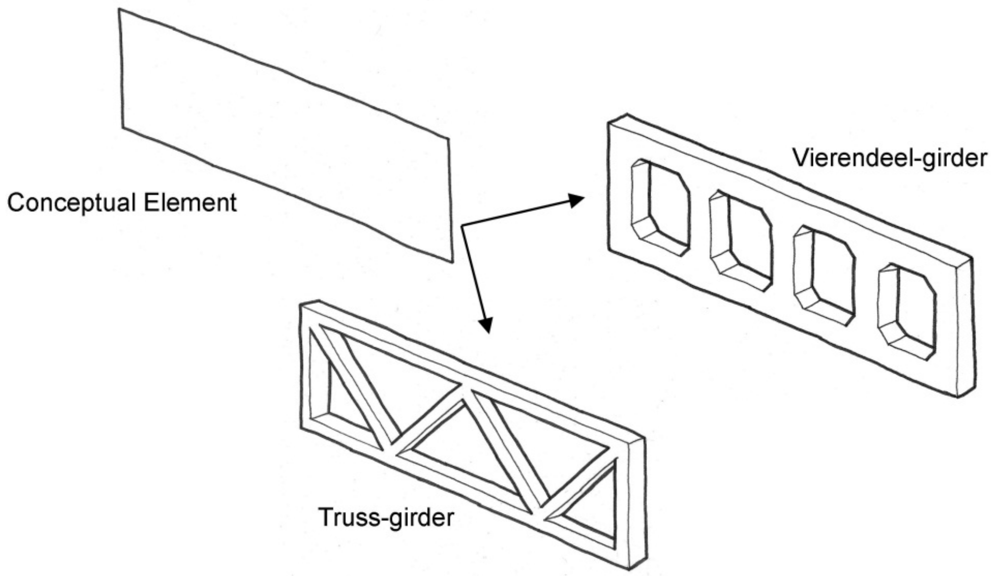


Figure 7-18. A conceptual element representing different structural typologies.

A conceptual element can be further detailed through a combination of other conceptual elements, giving it a more specific expression. For example, a rectangular surface can be developed into a combination of lines that represent the axes of the various members of a truss-girder. This further refinement limits the possible structural design solutions towards this more detailed architectural expression. Still, because each line represents a conceptual element with a linear expression, it does more than merely representing the design solution of a profile with a constant cross-section (e.g. a hollow tube); the conceptual line can also represent, for example, a three-dimensional lattice-girder with a linear (architectural) expression.

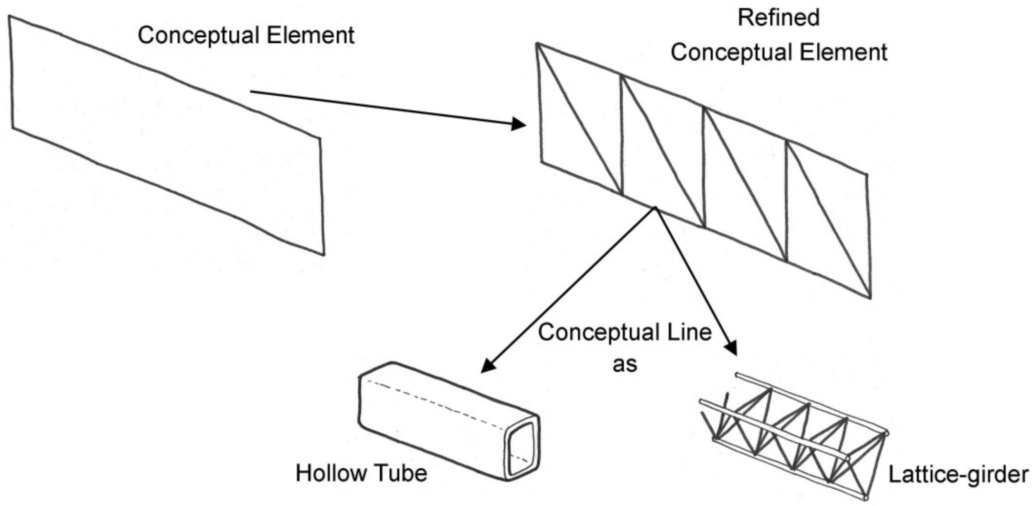


Figure 7-19. Conceptual line as part of a refined conceptual element.

This concept of representing an element through its architectural expression rather than the axis of a structural typology seems to be less common among engineers. Still, it should not be too uncommon in the engineering sciences, where the conceptual representation of a structural element through one axis can still signify that the element consists of several other elements (as for example a lattice-girder).

In architectural design, this rather abstract representation of an element through a general expression is common, as is alternating between more detailed expressions and the initial conceptual element during a design process (i.e. scaling up and scaling down, cf. Chapter 2.3).

By applying structural symbols to these conceptual elements derived from architectural design, structural and architectural design are brought together in one representation.

The new structural symbols applied to these conceptual representations are derived from the layers of structural order and structural dimensions.

The conceptual nature of these elements helps the engineer in designing on a more abstract level than through (more detailed) typologies, and supports a structural design process that explores various conceptual design propositions through a method of conceptual refinement and abstraction before entering the realm of typologies. (The proposed language provides for a more conceptual interpretation and investigation of structural design than current engineering language, which is developed for in-depth structural analysis.)

This language articulates and supports a design process in which an engineer proposes and evaluates various choices for possible structural elements and their composition, supports, loads and load paths, as well as element connections and the structural functions of the various elements. These design choices have an important impact on the range of possible design solutions, and delineate an exploration of structural space and form later in the design process through structural calculations and scientific optimization processes. Using the proposed language to express conceptual design propositions makes the engineer’s design decisions more apparent for negotiation with an architect.

Together the layer of order and the layer of function present a narrative of how loads follow paths through various structural elements to the supports, and how each element transfers these loads to enable the structure to function as a system. These load paths and the functions of the different elements are designed by the structural engineer. Both layers express the designing engineer’s intention. (A structural engineer in the role of designer, instead of calculator of structures, can be even better understood when each function of a structural element is seen as a process that transfers a load from input to output. A structure is then a system of processes by which the outputs of each element become inputs for the next element. And thus an engineer is primarily a designer of such systems of processes rather than a calculator. This is more extensively explained in the appendix of this thesis.)

The structural dimensions layer filters structural functions through the consequences these functions have on the structural form of an element. Through this expression of form that lies within the layer of structural dimensions, this layer generates a structural design proposition that is related to architectural design.

Both layers of order and dimensions contain an essential story of the structural logic of a conceptual design proposition. They provide necessary design characteristics of an engineer's conceptual design proposition, enabling to alter the given structural form model according to the intended conceptual design proposition.

For each structural element, the link between the layer of dimensions and the design possibilities provides for a wide range of design solutions for a specific proposition made by the engineer. This knowledge can then be used for negotiation between architect and structural engineer for the further development of the collaborative design.

7.8 Application in practice

In practice, the language presented above can be used in very intuitive ways. One of these ways is to combine adjacent elements into a single element. This compound element then takes over the various symbols (and thus the characteristics of each layer) of the separate elements.

An example of such a combination is given here by combining two elements with both requirements of structural dimensions due to a parallel transfer of force (Figure 7-20). Each element brings the load to its support (i.e. layer of order), and the combined element then brings the central load to both its ends, where the support is, as indicated by the ● symbols.

This division of load is thus two times a parallel transfer of one part of the total load to one end of the element. The stabilizing forces of the two parallel transfers keep each other in balance, and thus this division of force does not propagate stabilizing forces (outside the combined element). The symbol ▎ indicates where the highest bending moment occurs and thus also where the material form will require the highest section. The ▎ is placed below the axis, as tension will occur in the lower side of the material and compression in the upper side.

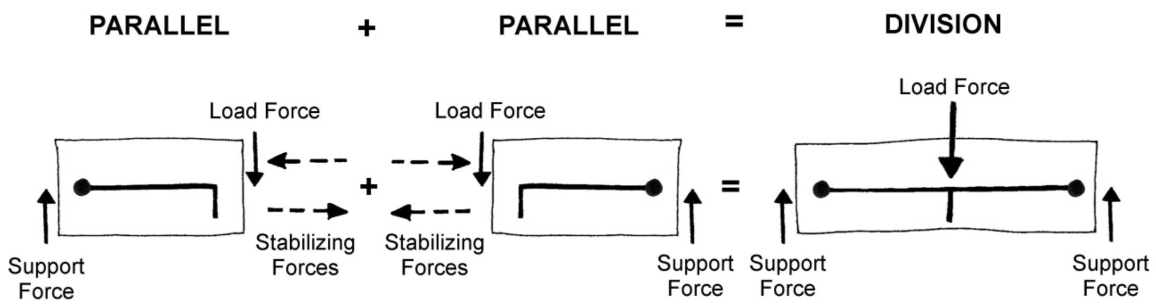


Figure 7-20. Combining two elements.

In this case, more of the load ends up on the left support than on the right. This can be expressed by the relative size of the symbols of structural order (●). This technique of expressing relative value through the size of the symbols can also be applied to the symbols of structural dimensions. This enables us to bring more nuance to a structural story.

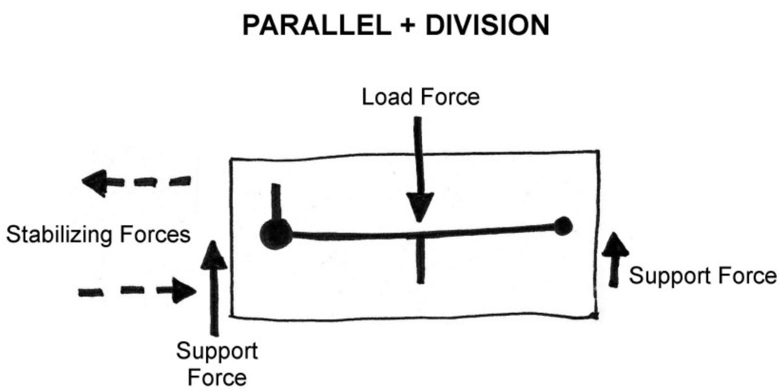


Figure 7-21. Superimposed symbols and relative size of symbols.

The language can be applied using only the symbols of structural order to describe the load path(s) of the structure, or using only the symbols of structural dimensions, or using both together. Each of these methods tells a different aspect of the structural story, and it is up to the engineer to apply this language as he or she sees fit to express the structural story of the given design proposition.

In essence, the language provides guidelines for using the symbols, but leaves a certain degree of poetic freedom. For example, it is possible to use the symbol ▌, which relates to bending moment, in more places than just where the maximum moment occurs in order to provide a specific kind of information (Figure 7-22).

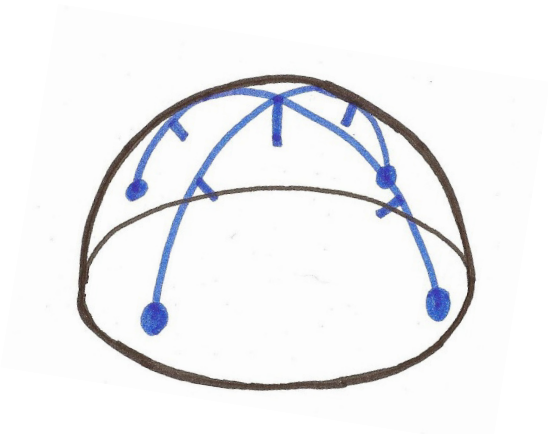


Figure 7-22. Multiple use of symbol ❙ on a dome under vertical load.

Another example of this poetic freedom may be seen in the case of a flat surface that brings a central load to both sides. This can be expressed through 'division of force' with a symbol ❙ for the maximum bending moment in the middle, or through a more specific expression of compression and tension lines (Figure 7-23). Both have the same result in dividing the load, but there is a clear difference in the nuance of design characteristics for both elements. In my view, this nuance is essential to enabling the individual structural designer to tell a personal story of design.

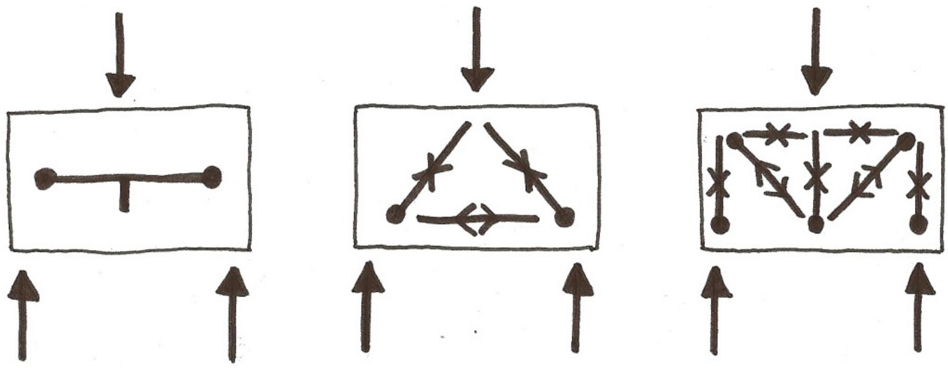


Figure 7-23. Nuances in structural storytelling.

7.9 Language applied on the Tomas project

We will now examine how this new structural language can be applied to the Tomas project. The architect presents his conceptual design proposition through a bundle of sketches, which enables me to develop a three-dimensional form model of the architect's proposition. This form model organizes architectural space but is not detailed, since certain sketches are still vague and even spatially contradictory.

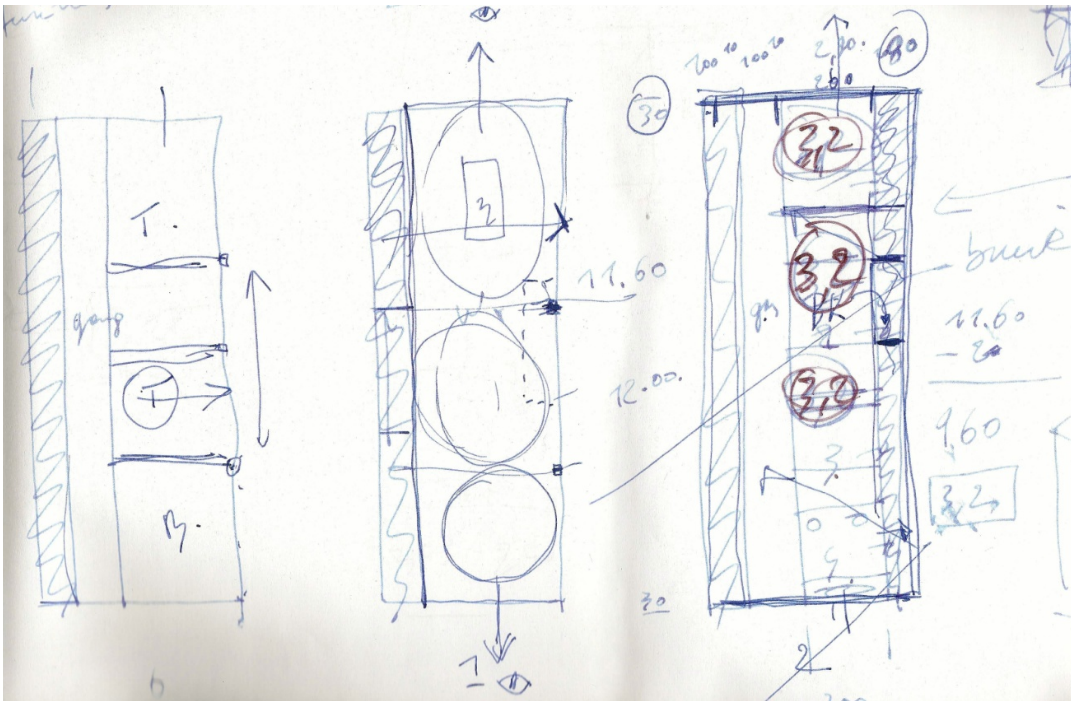


Figure 7-24. Architectural design proposition: ground, second and third floor.

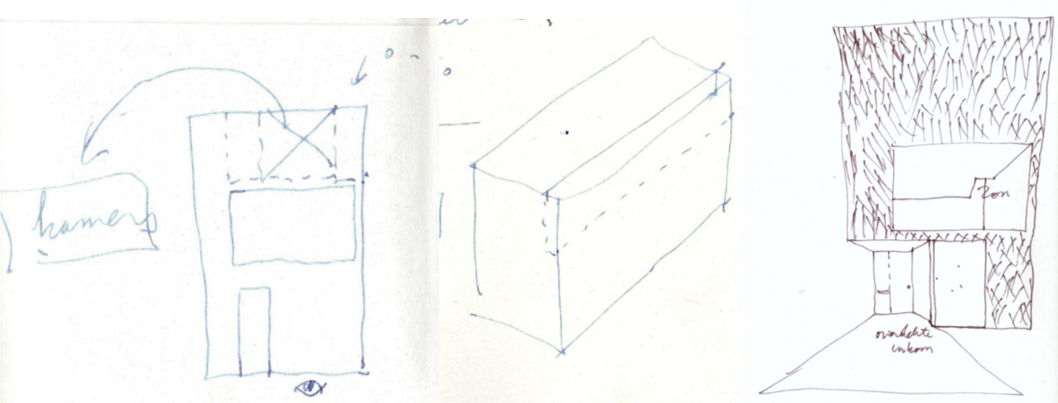


Figure 7-25. Front façade, overview and three-dimensional front view.

A representation of this conceptual form model is made by expressing dividing walls and floors as rectangular surfaces. (Smaller openings such as doors and stairways are not presented). The red arrows show where the zones of passage are situated on ground and top floors. The blue box indicates the service zone, which includes the staircase.

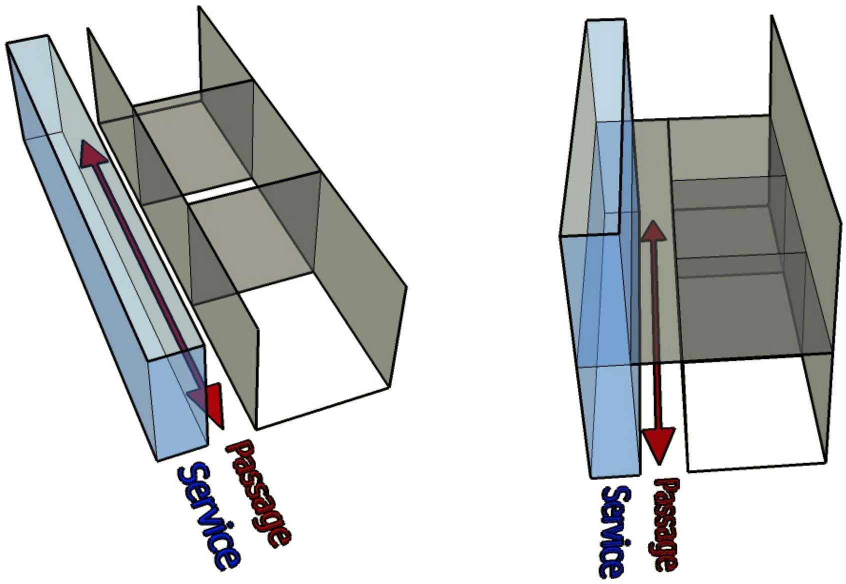


Figure 7-26. Representation of architectural form model: ground and second floor.

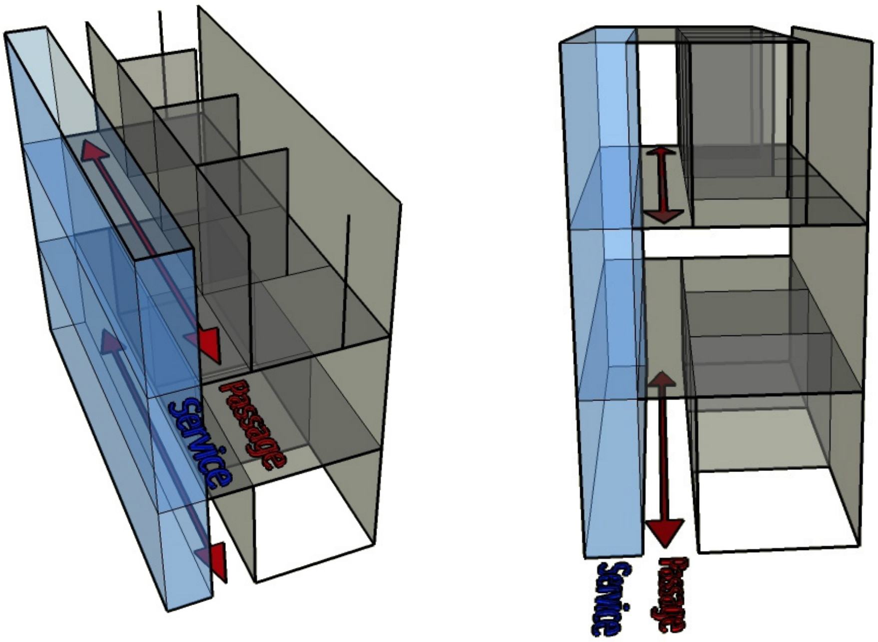


Figure 7-27. Upper floor and total form model.

For this collaboration, this form model gets structurally informed by applying the newly developed language on its various members. A first step in this application is to identify which elements are part of the structural proposition, and their orientation and load direction for a specific load case (i.e. structural order). Next, the main structural functions and dimensions can be expressed for each element that transfers a load to the supports. When the main structural functions and dimensions are known for a conceptual element, it is possible to explore a range of possible design solutions. This can be part of a negotiation between the architect and the structural engineer to further refine the structural (and architectural) design.

In this project, two main bearing walls are chosen to transfer vertical loads to the foundations (Figure 7-28). This is expressed by identifying the appropriate surfaces as structural elements, with a vertical orientation, transferring the load to the bottom of the element (as indicated by ●). This requires elements to transfer their loads axially under compression (as indicated by the arrows pointing towards each other). (The structurally richer story of the roof is discussed later.)

These two walls support the two floors indicated. In the service zone, these horizontal surfaces work in cantilever, bringing vertical loads onto the highest bearing wall as indicated through the language (Figure 7-28). The horizontal surfaces divide the vertical load between these two walls. The symbol ▌ indicates where high bending moments and material height are expected. The image also expresses that the cantilevered floor has a rigid connection to the other part of the floor to resist bending, as both elements have a symbol ▌ on top of their axes at their connecting ends.

Each structural element in this form model is conceptual, meaning that it is an expressive representation of a range of structural solutions. For example, the vertical surfaces (as bearing walls) can represent a solution with many openings in this surface through the use of beams and columns. Also the horizontal surfaces (as floors) can represent more than just uniform slabs as design solutions. For example, they could represent an array of beams that transfer their loads to the bearing walls and support thin slabs between them.

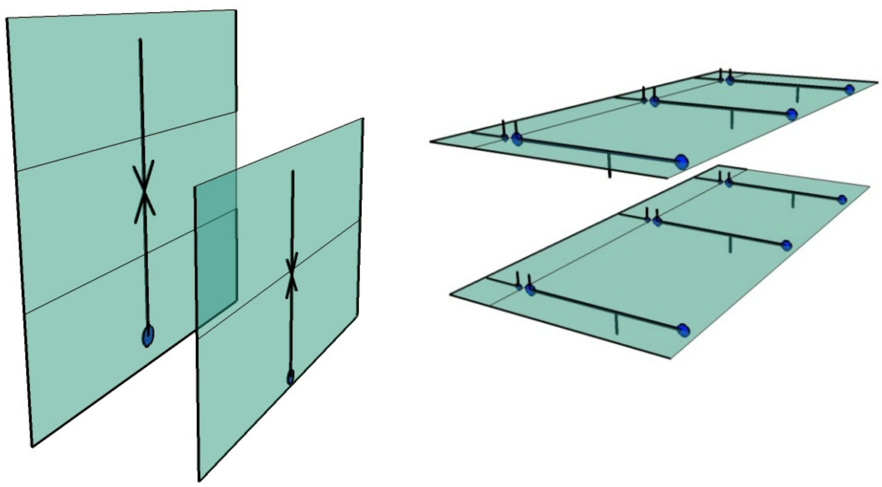


Figure 7-28. Structural story for vertical load: bearing walls and floors.

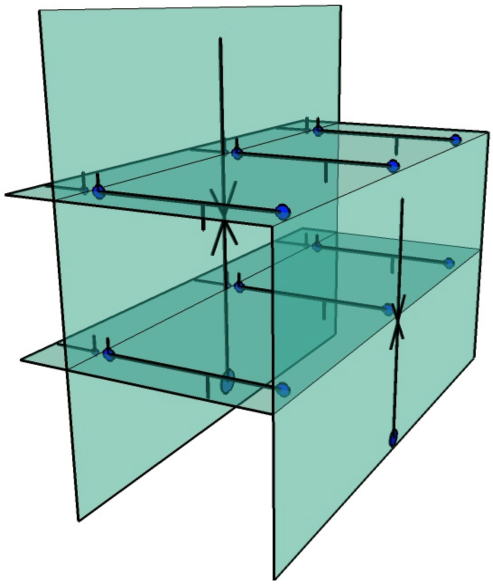


Figure 7-29. Structural story for vertical load: overview.

Besides transferring vertical loads to the supports, the structure also needs to transfer horizontal loads to the foundation. This structural story is expressed here in a different colour than the blue of the vertical load (Figure 7-30).

In order to withstand horizontal loads, the structure is provided with several vertical wind-bracing surfaces. Each of these wind-bracing surfaces has to transfer a horizontal load parallel to the load's axis. (The direction of this transfer is indicated with the symbol ●). Because this load can occur in opposite directions, the symbol ❙ is placed on both sides of the element's axis.

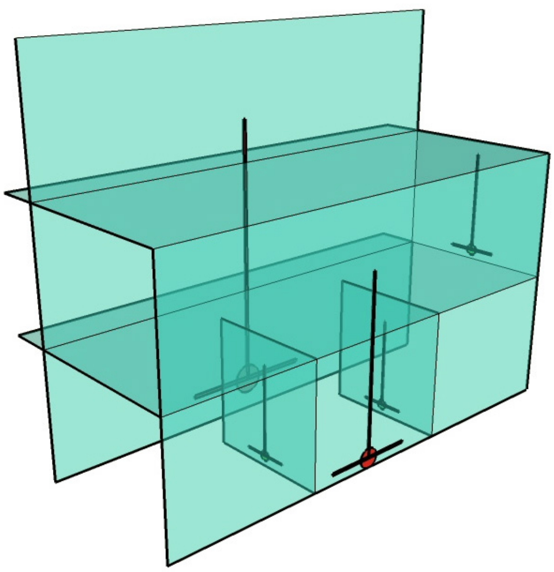


Figure 7-30. Structural story for horizontal loads: vertical wind-bracing surfaces.

A variety of structural design possibilities can be found through the combination of element and structural dimensions. The requirements on structural dimensions for all load cases need to be taken into account (Figure 7-31). For example, both bearing walls are also wind-bracing surfaces. This means that possible solutions with beams and columns for these elements would require this lattice to be a stiff framework (e.g. through rigid, bending-resistant connections or wind-bracing ties or struts).

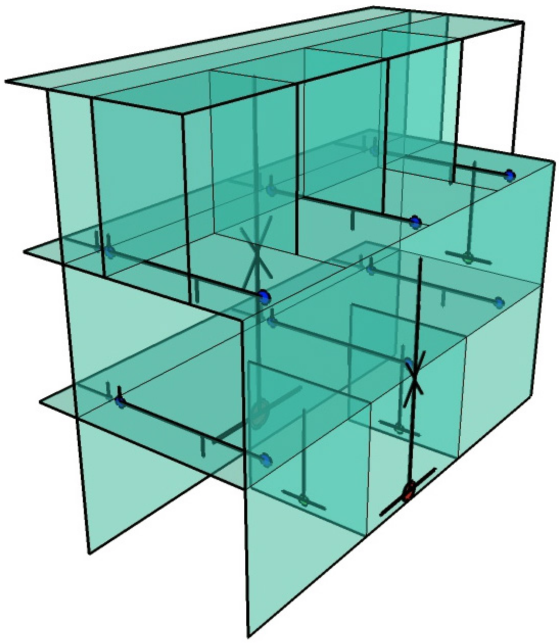


Figure 7-31. Structural story of the lower part for all load cases.

For the structure of the roof, two conceptual design propositions are developed. In the first, an extra vertical bearing surface is provided to carry the vertical load on the roof (Figure 7-32). This bearing surface transfers its vertical load to the floor, which in turn transfers the load to the two main bearing walls. In order to withstand the horizontal loads, three vertical wind-bracing surfaces are provided.

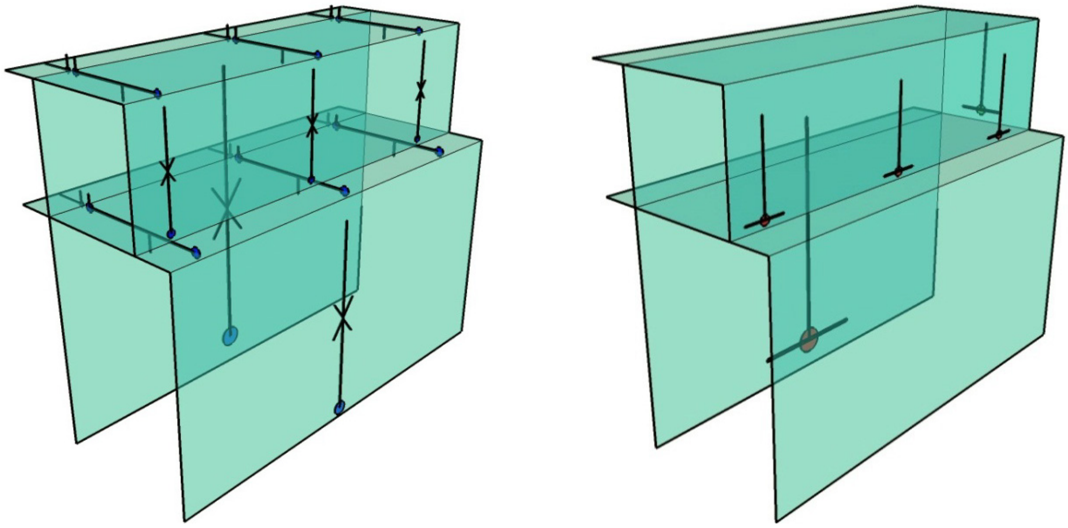


Figure 7-32. First structural conceptual design proposition for upper part: structural story for vertical load and wind-bracing surfaces for horizontal stability.

The second structural concept uses the interior partitions that separate the rooms in the architectural design (Figure 7-33). These walls carry part of the vertical load of the roof. But because they have no direct support underneath, these interior walls are extended to the two main bearing walls, dividing the vertical load of the roof between them. For the horizontal loads, again three vertical wind-bracing surfaces are provided.

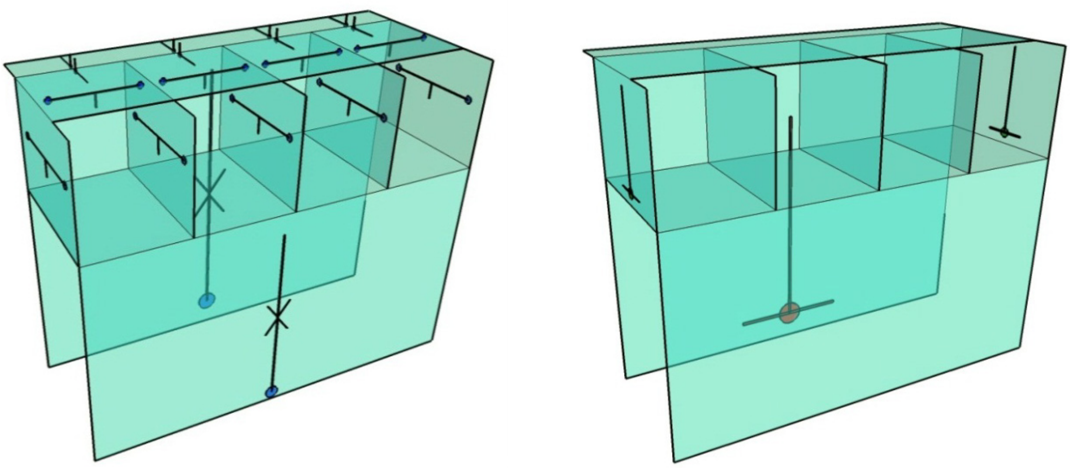


Figure 7-33. Second structural conceptual design proposition for upper part: structural story for vertical load and wind-bracing surfaces for horizontal stability.

These two structural conceptual design propositions not only have different structural organizations, they also organize architectural space and form differently. The first one keeps the interior space of the upper floor open, while the second clearly divides this space into four parts. Both propositions, however, still need to be further designed in order to fit the given architectural form model. The first proposition has an extra vertical bearing surface that in the architectural form model mainly consists of openings (i.e. windows) that allow views from the rooms to the upper terrace (Figure 7-34). The second proposition conflicts with the architectural form model because it extends the separating walls into the terrace, where the architect's design proposition calls for a single open space (Figure 7-37).

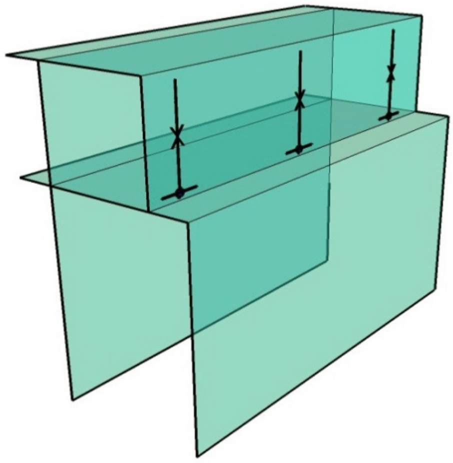


Figure 7-34. First proposition: vertical surface with bearing and wind-bracing function, requiring large openings.

In the first proposition, the vertical surface needs to be further designed so it can accommodate the large openings without losing its bearing and wind-bracing functions as indicated by the symbols. One way of refining this conceptual element is by introducing beams and columns within the surface (Figure 7-35). These columns follow the rhythm of the interior partitions. The beams transfer the vertical roof load to the columns, which in turn transfer the load to a load-spreading beam that rests on the upper floor. (Three ● symbols are used per element of the load-spreading beam to indicate the spreading of the load along its axis). The horizontal load is here transferred by the columns that are rigidly connected with the lower load-spreading beam (other solutions are also possible). These columns then work as vertical cantilever beams, working in both directions as indicated by the ❙ symbols.

This structural story can also be expressed by a volumetric language as introduced in Chapter 6.2. Here the structural form is designed to minimize the structural material needed, with the beams no higher than the bending moments require and the columns no thicker than required to prevent buckling. (The image presented in this volumetric language can be seen as a structural solution made in concrete.)

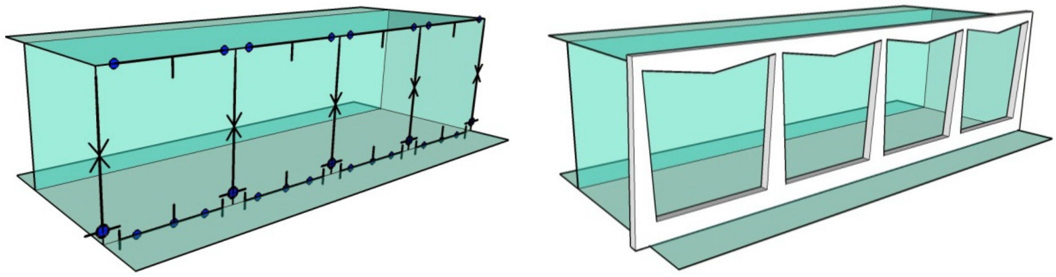


Figure 7-35. First proposition: first example of further refinement.
(Expression through symbolic and volumetric language).

Another way of refining this surface is to transfer the vertical load from the beams in the columns straight to the floor as point loads (Figure 7-36). This leads to large point loads on the upper floor, which in turn needs to be further detailed to withstand these loads. A possible solution is to reinforce the floor beneath these columns with extra beams. The beams then transfer the point loads to the bearing walls.

In order to transfer the horizontal load from roof to upper floor, the columns can be rigidly connected to the upper beams that carry the roof. This way of stiffening a frame horizontally is commonly used with, for example, dining tables. Again, this can be expressed in the new language or through a volumetric language.

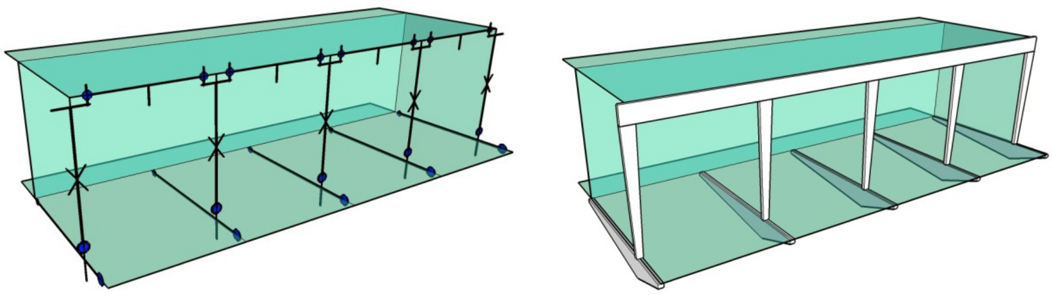


Figure 7-36. First proposition: second example of further refinement.
(Expression through symbolic and volumetric language).

In the second proposition, the load-bearing surfaces perpendicular to the two main bearing walls need to be opened not only at the terrace, but also at the passage (Figure 7-37). All these surfaces have the function of dividing the vertical load of the roof to both its side (like a very deep beam). Only the two surfaces of the facades have the function of transferring the horizontal load to its base.

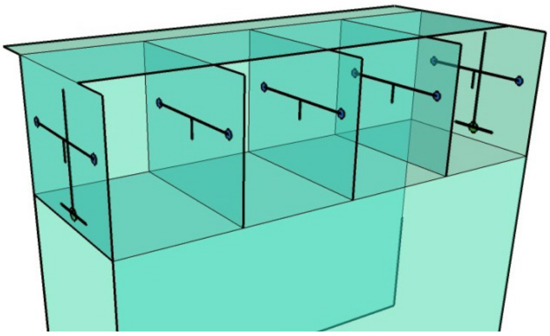


Figure 7-37. Second proposition: vertical surfaces with dividing and wind-bracing functions, requiring different openings.

One way of refining these vertical surfaces is by bringing the function of dividing the vertical roof load to the base of each surface instead of distributing it across the entire surface (Figure 7-38). This means that openings can be provided in a vertical surface that now only needs to transfer the vertical load to this base line. Only the vertical surfaces at the facades have the additional function of transferring the horizontal loads to the base. This structural story can be expressed by the new language or by a volumetric language. (In order not to overload the volumetric drawing, no thickness is given to the vertical surfaces.)

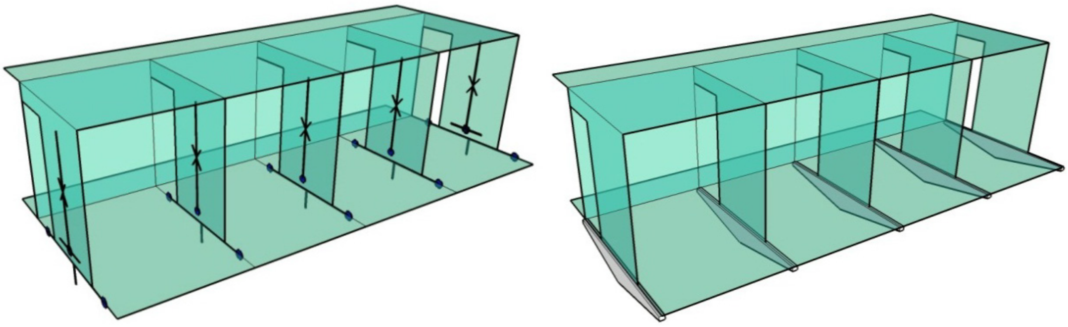


Figure 7-38. Second proposition: first example of further refinement. (Expression through symbolic and volumetric language).

Another way of refining the second concept is by bringing the function of dividing the vertical roof load, to the top edge of the surface (Figure 7-39). This requires an extra support at the end with the terrace, but not at the other end since it already has a bearing wall. This extra support then transfers the vertical load along its axis on the underlying bearing wall.

The walls of the facades still need to bring the horizontal load to the base: this can be achieved by part of the wall that remains after making the required openings. All the other interior walls can then be omitted as structural elements.

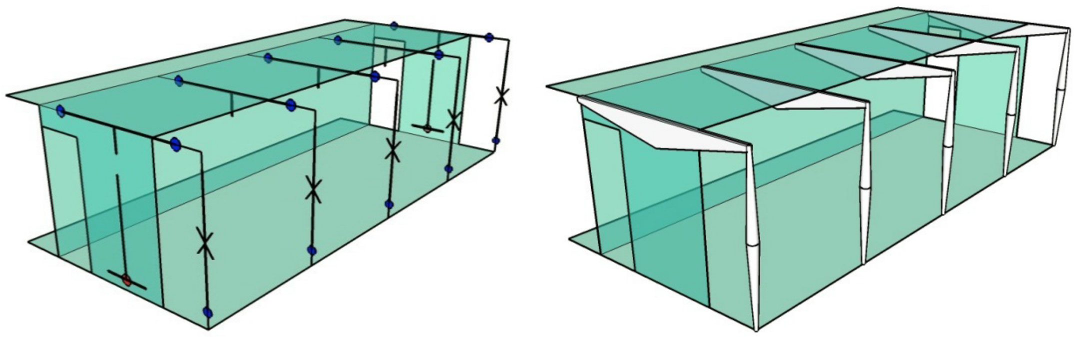


Figure 7-39. Second proposition: second example of further refinement. (Expression through symbolic and volumetric language).

In the collaboration between an architect and a structural engineer, this technique of conceptual refinement can help to advance the design in a more specific direction while retaining a maximum of possible design solutions.

For each element, with its characteristics of structural dimensions for all load cases (as expressed by the new language), an array of design solutions can be produced to inform the architect and the structural engineer (e.g. through a catalogue). This information can be part of the design negotiation and collaboration.

One of the reasons to develop this language is to allow an architect to grasp the range of possible structural design solutions entailed by a structural engineer's conceptual design proposition. Besides understanding the various structural solutions for each structural element, another aspect of understanding this range is being able to change the given structural form model according to the design characteristics of the proposition. The altered form model then still contains the engineer's intended structural logic.

The new language expresses this logic through the layers of structural order and structural function (that can be deducted from the layer of structural dimensions). This language expresses how a structural proposition deals with transferring loads to its supports. A structural form model can be altered within the same conceptual design proposition if the structural order and structural function of the various elements are maintained for all load cases.

Two examples of changes to a form model that stay within the initial conceptual design propositions are given here for the first structural proposition of the upper part of the Tomas project (Figure 7-40). The initial structural form model is presented at the top with all the symbols that express the structural order and functions of the elements under vertical and horizontal loads.

One of the different form models this conceptual design represents is found by moving the supporting vertical surface at the terrace inwards, making the interior space smaller and the terrace larger. In this altered form model, the structural logic of the initial model is maintained: each structural element retains its main structural function, and the load paths remain the same. (A basic structural understanding is required to be able to check these conditions.)

Such a form model change might lead to larger or smaller dimensions for the structural elements, but this does not affect the structural logic of the concept. In this case, the floor will require more structural height as the vertical load of the roof is received more towards the middle of the span. Still, the function of dividing load is maintained.

Another way of changing the initial form model within the structural conceptual design is by lifting the roof up. This way the interior space becomes higher. Here it is even more evident that the structural order and functions of the various elements are maintained. In this case, the vertical supports might have to be thicker to prevent buckling, but their structural order and functions remain the same.

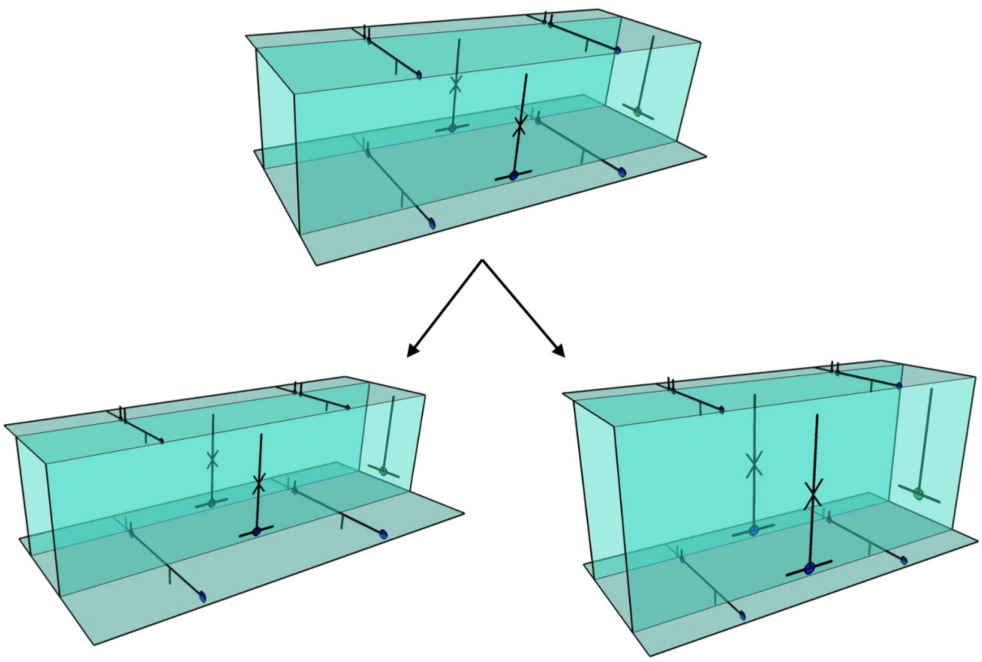


Figure 7-40. Two form model changes within a conceptual design proposition: vertical support translation and lifting up the roof.

8. Cases for explanatory research

8.1 Structural Seminar 2010

The new structural language has been developed for use by architects and architecture students during conceptual design. Therefore it is important to investigate whether architects and students are able to read a conceptual structural story written in this language, and even to use it to write such a story themselves. More specific questions can be posed in this investigation: does the newly developed language enable us to tell the most essential aspects of such a conceptual story, and how does it compare to storytelling with the traditional language of structural engineering?

Another important aspect of the application of this language includes the question of how much effort it takes to learn the new language, since it is developed to be used without much engineering-specific knowledge: it should be easy for architects and architecture students to learn.

A next type of inquiry is to investigate whether the new language enables its users to grasp the wide range of possible design solutions entailed in the conceptual design proposition of a structure, thus enabling them to change the given structural form model within its structural logic as expressed by the language. And further, we could investigate whether architects and architecture students experience a benefit from using this language when conceptually designing structural propositions, as the language brings to the fore the structural logic of a design.

To investigate these questions, various student seminars are arranged: Structural Seminar 2010, Research Seminar 2010 and Research Seminar 2011. The results of these seminars are presented below.

A first investigation of the applicability of the language for students is arranged in Structural Seminar 2010. This seminar is a material workshop for seventy-one interior architecture students in their third undergraduate year, and includes a design studio as preparation for the actual workshop.

These students have passed all their classes on structural theory. These classes are less elaborate than those for architecture students, but still contain basic engineering education covering, for example, internal forces, stresses and structural typologies.

Throughout the seminar, the students are unaware of the nature of the investigation. They are not informed about it, and the seminar is structured as any other regular design seminar.

Each group of two students is asked to select a different structural object and to investigate its structural behaviour. After getting some structural consultation to better understand their chosen structure, students hand in a presentation that expresses how they understand the structural behaviour of their object. The students are free to choose how they want to present this structural story. Through their theoretical education and experience in previous structural storytelling, they are accustomed to this kind of expression. For guidance, the students are asked to make this presentation for their fellow students.

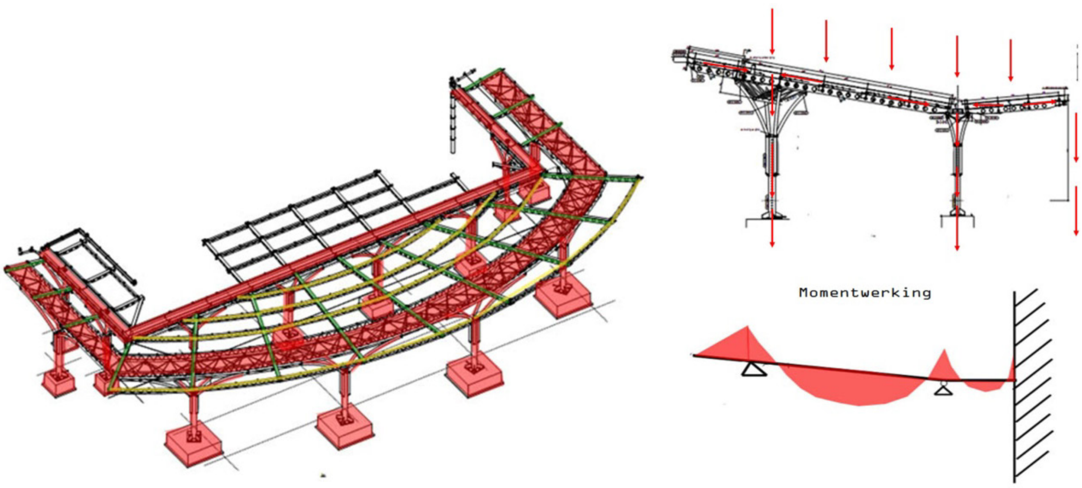


Figure 8-1. A students' presentation of structural behaviour in their own language. (Structural elements and order; flow of forces; bending moment.)

After the students have handed in their presentations, I present my new structural language to them in a short time span of one hour and a half, focussing on the various symbols and their use. After this course, students are given one week to retell the same structural story of the first presentation but now with the new language. Students get no support in applying the new language to their object. I test the ease with which the new language can be learned by spending a minimum of time teaching it and by providing only a short two-page manual.

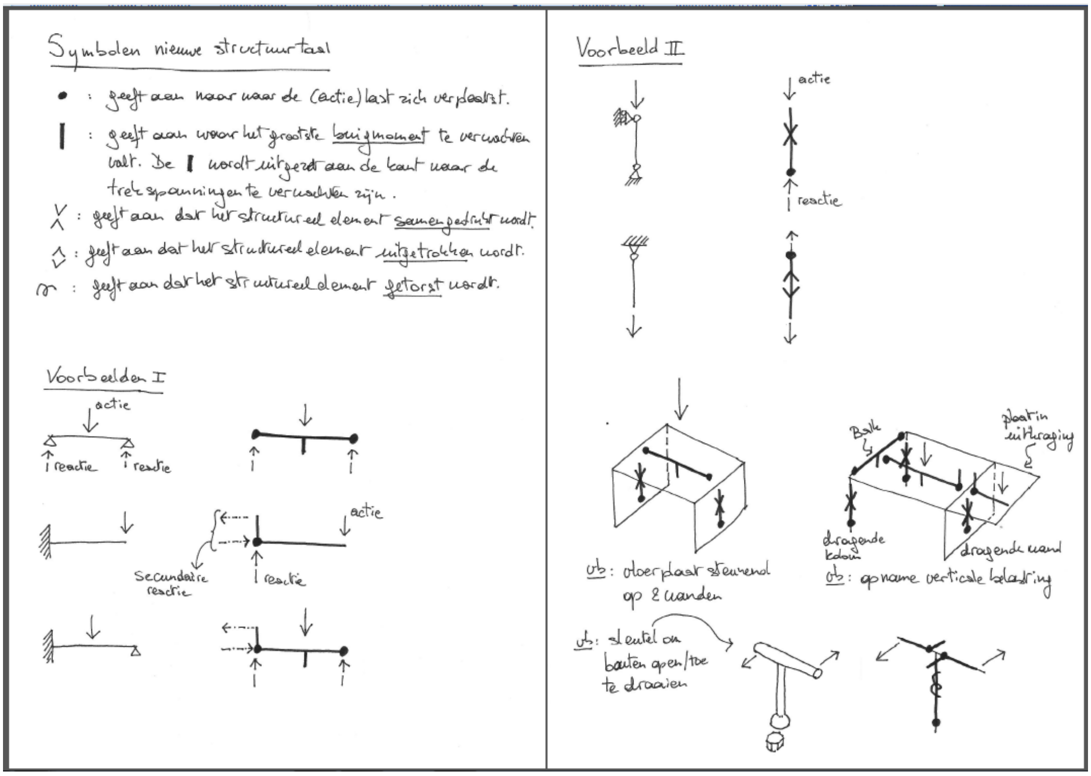


Figure 8-2. Short manual of the new structural language.

By letting the students express the same structural story twice, but different languages, it is possible to investigate the qualities and differences between the two narrations. I compare the two presentations to check whether the new language tells the same story, or tells more or less than the original story, and what information is added or lost in the second telling. Also the students who made the presentations compare both narrations to evaluate the relative quality of the new language. Their opinions are (anonymously) gathered through an extensive and well-prepared questionnaire.

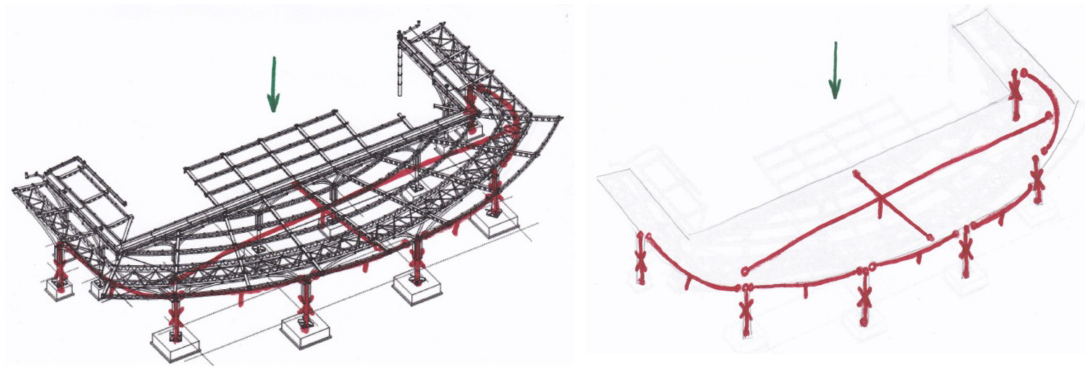


Figure 8-3. Example of same structural story by students with the new language.

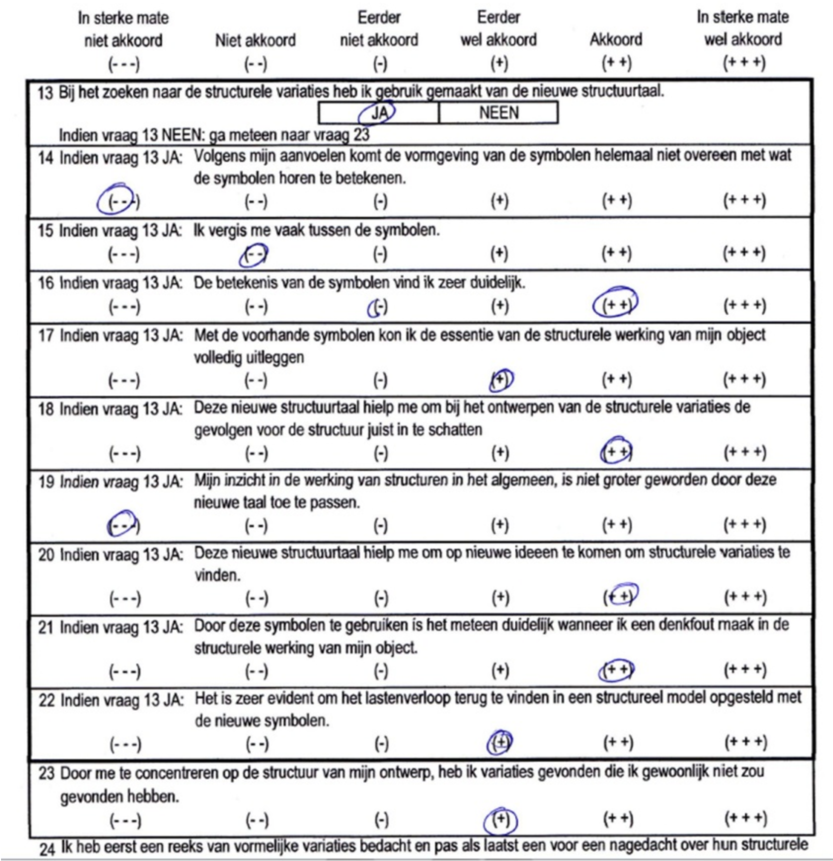
The questionnaire reveals the following:

1. The language is **easy to learn**:
   - Learning the language is perceived as being very easy. The symbols are not confusing and are linked to an intuitive understanding of what they mean. Only a few students found it difficult to learn the language.
2. The language is **easy to use**:
   - Most students (86%) are confident in their ability to explain the behaviour of a structure that they understand using the new language.
   - 90% of the students find that the essence of structural behaviour as they comprehend it could be explained well with the new language.
   - In stories with this language, the students find it easy to identify the structural load path.
   - In stories with this language, students find it easy to determine which internal forces occur in the structural elements.
   - Most students (81%) feel they can tell more about the structure in one image using the new symbols than with their usual language. With the new symbols they need fewer images to explain the structure.
   - Most students (75%) find that explaining a structure with the new language is more comprehensible than with the traditional diagrams of internal forces.
   - About half of the students first draw the symbol ● (structural order) for the whole structure and afterwards those of structural dimensions; the other half do not follow this procedure. About the same group of students follow the same procedure of going through the structural order and afterwards looking at function/dimensions when trying to understand a structure.

     (This last finding shows that some students might benefit from the language's ability to distinguish between symbols that explain structural order and those that explain structural functions/dimensions.)

Comparing the two presentations reveals that when the structural behaviour is well understood by the students, both structural narrations are often almost equal, although the narration with the new language does not require as many images. When the structural behaviour is not well understood, it is difficult to compare the quality of the narrations, since they sometimes tell different stories. (A review of the drawings made with the new language indicates clearly where students seem to make mistakes in their structural understanding.) In most cases, the students are capable of using the language correctly.

Evaluating the presentations made with the new language also reveals that some students do not apply the symbol ● in the right manner, putting it on top of the connection of two elements instead of before it. In the next seminar I will call this to the students' attention when explaining the language.


In sterke mate niet akkoord (- - -) | Niet akkoord (- -) | Eerder niet akkoord (-) | Eerder wel akkoord (+) | Akkoord (+ +) | In sterke mate wel akkoord (+ + +)

13 Bij het zoeken naar de structurele variaties heb ik gebruik gemaakt van de nieuwe structuurtaal.
JA | NEEN
Indien vraag 13 NEEN: ga meteen naar vraag 23

14 Indien vraag 13 JA: Volgens mijn aanvoelen komt de vormgeving van de symbolen helemaal niet overeen met wat de symbolen horen te betekenen.
(- - -) (- -) (-) (+) (+ +) (+ + +)

15 Indien vraag 13 JA: Ik vergis me vaak tussen de symbolen.
(- - -) (- -) (-) (+) (+ +) (+ + +)

16 Indien vraag 13 JA: De betekenis van de symbolen vind ik zeer duidelijk.
(- - -) (- -) (-) (+) (+ +) (+ + +)

17 Indien vraag 13 JA: Met de voorhande symbolen kon ik de essentie van de structurele werking van mijn object volledig uitleggen
(- - -) (- -) (-) (+) (+ +) (+ + +)

18 Indien vraag 13 JA: Deze nieuwe structuurtaal hielp me om bij het ontwerpen van de structurele variaties de gevolgen voor de structuur juist in te schatten
(- - -) (- -) (-) (+) (+ +) (+ + +)

19 Indien vraag 13 JA: Mijn inzicht in de werking van structuren in het algemeen, is niet groter geworden door deze nieuwe taal toe te passen.
(- - -) (- -) (-) (+) (+ +) (+ + +)

20 Indien vraag 13 JA: Deze nieuwe structuurtaal hielp me om op nieuwe ideeen te komen om structurele variaties te vinden.
(- - -) (- -) (-) (+) (+ +) (+ + +)

21 Indien vraag 13 JA: Door deze symbolen te gebruiken is het meteen duidelijk wanneer ik een denkfout maak in de structurele werking van mijn object.
(- - -) (- -) (-) (+) (+ +) (+ + +)

22 Indien vraag 13 JA: Het is zeer evident om het lastenverloop terug te vinden in een structureel model opgesteld met de nieuwe symbolen.
(- - -) (- -) (-) (+) (+ +) (+ + +)

23 Door me te concentreren op de structuur van mijn ontwerp, heb ik variaties gevonden die ik gewoonlijk niet zou gevonden hebben.
(- - -) (- -) (-) (+) (+ +) (+ + +)

24 Ik heb eerst een reeks van vormelijke variaties bedacht en pas als laatst een voor een nagedacht over hun structurele

Figure 8-4. Example of filled-in questionnaire.

In the next part of this seminar, students are asked to alter their self-developed structural form model of the investigated object while keeping track of the consequences of these alterations on the structural behaviour. After each alteration, students are required to investigate the new structural behaviour of the form model. They are not required to use the new language in this exercise. They are given examples of various alterations on a structural form model and the consequences these changes have on its structural behaviour. These examples are given using the new language.

One of the reasons for this exercise is to have architecture students develop structural designs and to investigate whether they would choose to use the new language as a design tool to make sound structures. Because the language brings to the fore essential characteristics of the structural behaviour of a structural proposition, it should help in this design process of making alterations. The language also enables a more explorative conceptual design process, since it does not require users to make detailed structural descriptions.

Since this investigation is still explorative, students are not forced to use the new language in this process. In my view, the natural diversity among students ensures that not all will prefer to use the same tools. Some students might feel more comfortable understanding structure through engineering science, others might need to experience a structure in a tactile way to understand it, and still others might prefer to use the newly developed language. Leaving the choice open to the students allows me to assess their preferences.

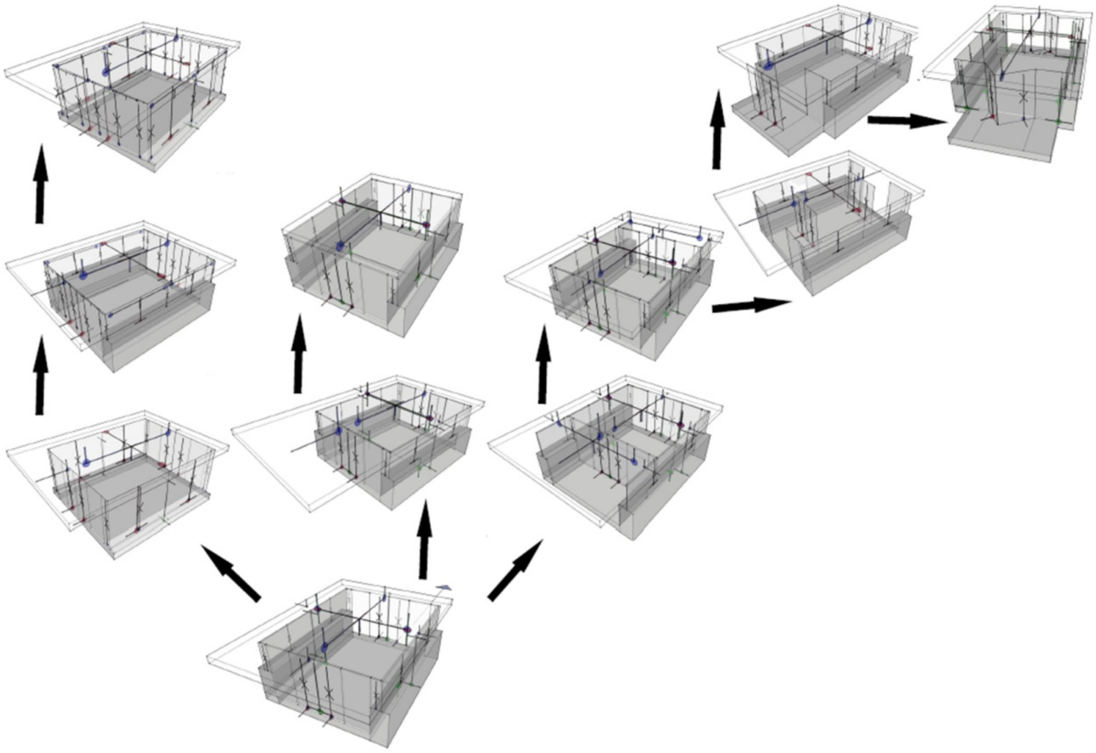


Figure 8-5. Example of variations on a structural form model designed by a student.

After the students hand in this exercise they are given a new, extended, and well-prepared questionnaire to fill in (anonymously). This questionnaire and part of the previous one reveal the following:

1. **Advantages** of using the language:
   - About half of the students feel that their general structural knowledge is increased by the use of this language (the other half do not experience an increase).
   - If other people understood these symbols, 75% of the students would prefer using these symbols above the traditional internal forces diagrams to explain a structure.
2. The language **helps in structural conceptual design**:
   - Most students (85%) find it an asset to be able to use this language for this variation design exercise.
   - 85% of the students find it positive for their design process not to have to conceive the structure of their design in detail, and to be able to work only with a more abstract conceptual structure.
   - About 70% of the students use the new language during their design process in this exercise.
   - 40% of the students that use the language during their design process get new structural design ideas at some point through the use of this language.
   - More than 70% of the students prefer to apply the same kind of design methodology of focussing on the structural behaviour in the future, in order to find creative design solutions.

Evaluation of the results of the design variations shows that some students are not very capable of understanding how a new structural behaviour – significantly different than the initial one – occurs due to certain form model changes, but most students understand well the structural consequences of a change in the form model. Most of the variations presented are structurally sound, and seem to follow an engineering logic of alterations through a consequent procedure: there are no extreme (artistic) leaps in variations. In my educational experience, these variations excel in the way the students understand their structural behaviour, but pay a price in being less innovative or creative.

In order to have a better understanding of how students explore design variants for a structural design proposition, a small test is developed for

Research Seminar 2011. Ten architecture students at the master's level are asked to develop variants for a structural design proposition. These variants must maintain the original structural order and structural function of the elements.

The structural design proposition is only presented through a structural form. In a three-dimensional form model, the beams, columns and plates are presented as concrete structures, the walls as masonry. (All structural elements are prismatic, as they would be in a professional design, and not designed for minimum material use.) No explanation is given for the structural behaviour of the design. Students are then asked to change the form model while maintaining the structural order and the structural functions of the elements.

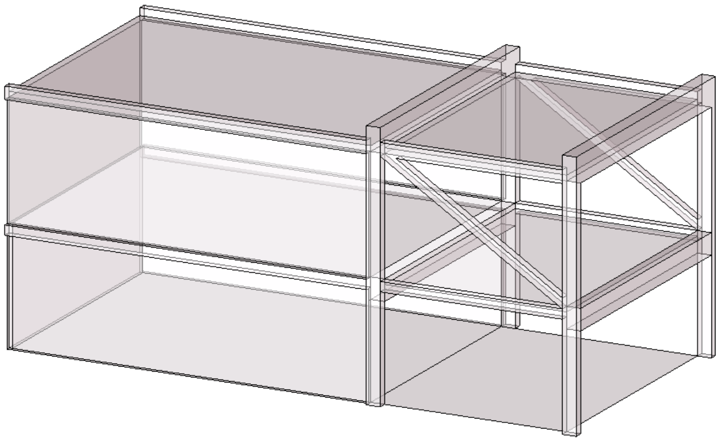


Figure 8-6. Research Seminar 2011: structural form model for alteration test.

In an open discussion following this exercise, the students describe their approach to the assignment. They first try to understand the structural behaviour before they alter the form model: their structural understanding guides their design of variants. They do not alter the form model on some gut feeling of what might still be the same structural concept. And thus, presenting a structural proposition in the new language helps them understand this behaviour and thus develop sound alterations. (Sometimes structural form can even be confusing when trying to understand structural behaviour. For example, a strut can function as a tie and change structural order: structural form as presented in this exercise does not indicate whether an element works under tension or compression.) The students express to seek help in this language when exploring form model alterations within a given concept. As the number of students is small and they have deliberately chosen this structural seminar, one of the conclusions of this small test should be that the new language helps certain students in finding structural design variants, but that other students may in fact still follow a gut feeling and therefore benefit less from the language.

The investigations of Structural Seminar 2010 show that for most students the language is easy to learn and use. The nature of the language and the conceptual design paradigm for which it stands seem to be closely related to the student's architectural design paradigm, as most of them voluntarily choose to use this language during their design process. Some of the results of the questionnaires might be biased, as for example a change in routine might always lead to an improved experience, even if the change has no benefit in the long run (i.e. the Hawthorne effect). Still the students' seminar presentations show that they are able to use the language to tell a structural story as they intend it.

It seems that in some cases students experience a gain in their general understanding of structural behaviour due to the use of the language. This experience may also be the result of a learning effect. Still, it is possible that this learning is made possible by the clarity of the language, which brings the essential characteristics of structural behaviour to the fore.

Even when the possibility of bias is taken into consideration, the results of the variation exercise and the students' responses show that the language helps an important number of students to design a structure. It is possible that only a certain type of student finds benefit in this design language, while others benefit more from the traditional engineering language.

8.2 Research Seminar 2010

Research Seminar 2010 presents another chance to test the new language. The first part of the seminar is used to teach the language to one interior architecture student and six architecture students, all in the master's program, and to evaluate if the language can be learned and used by the students to express structural behaviour, as well as being beneficial to their structural design. The second part of the seminar will be used to evaluate the language and various developed collaboration proposals during several face-to-face meetings in a design studio setting.

A language for architects

In the first part, the language is taught in the same manner as in Structural Seminar 2010, only this time more attention is spent on providing feedback on the students' understanding of the language. The structural behaviour of a table is explained to the students and they are asked to describe this behaviour with the new language.

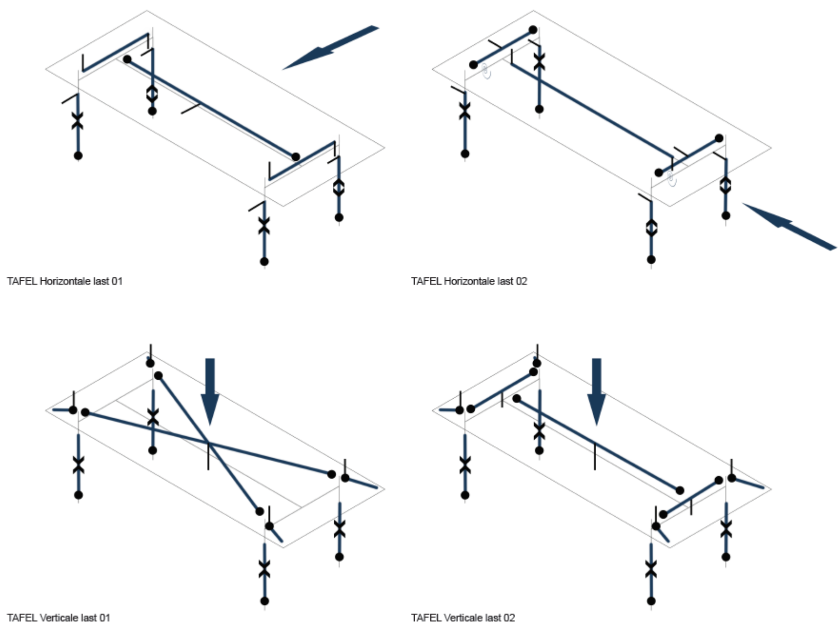


Figure 8-7. Example of language applied on the structure of table by a student.

After the students hand in these presentations, they are shown an example of making various structural variations using the new language. The students are then asked to design, on their own, variations on their structural form model of the table. After handing in these variations, they are asked to fill in an elaborate questionnaire, similar to the ones used in Structural Seminar 2010. The results are similar to those of Structural Seminar 2010, and are confirmed in an open discussion with all students afterwards:

- Most students have no problem learning and using the language.
- Symbols are clear and intuitively understandable.
- All students experience gaining a better insight into structural behaviour through the use of the language.
- All students prefer to use this language to explain structural behaviour over the traditional engineering language.
- Students find that the ability to tell a structural story in different ways afforded by this language increases their structural understanding.
- Half of the students go through the load paths first before looking at the structural functions; the other half do not.
- When designing variations on structural form models, most students have chosen to use the language during their design process.

- Some students design in a more abstract conceptual form model without matter, others need to materialise their object of design.
- All students find advantage in the use of this language when designing structural variants.
- All students prefer this conceptual design approach that does not require them to go into detail while conceiving a structure.

Analysis of the different presentations shows the same kind of results as were seen in Structural Seminar 2010. In most cases the language is applied as taught to correctly explain the structural behaviour of the table. Most of the design variations developed by students are structurally sound, and the development of the different variations seems to follow an organized engineering logic.

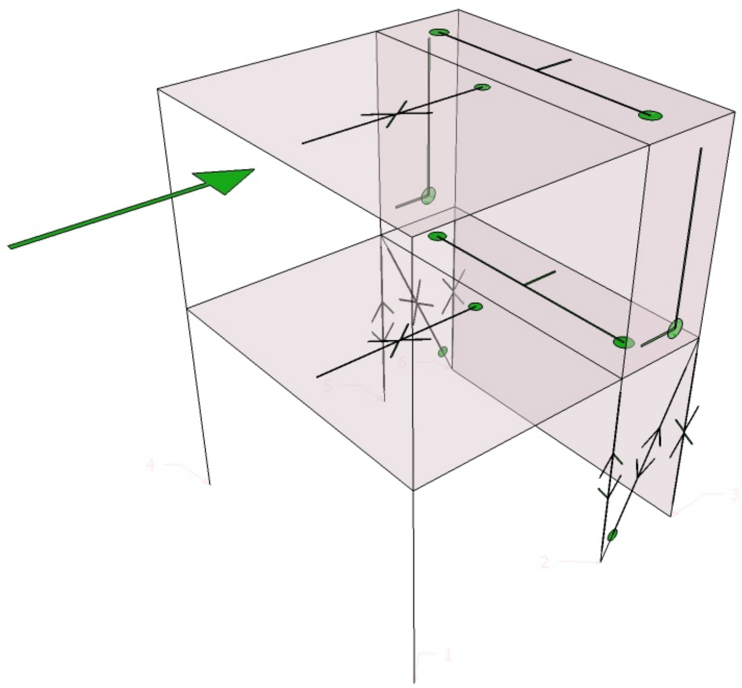


Figure 8-8. Reading test: form model with structural story under horizontal load.

In this seminar, we develop an explicit reading test in which a rather unusual structural behaviour is expressed only through the application of the language with no further explanation given. The students are then asked to describe certain load paths and to materialize certain structural elements with a minimum of material use (i.e. similar to the volumetric language described above).

After analysing the results of these tests, the following can be concluded:

- Most students are able to follow the load path for a vertical load, but fewer can follow it for a horizontal load.
- Most students understand the link between the applied symbols of the layer of structural dimensions and the required dimensions of a structural element.

In order to understand this problem of misreading the structural order for horizontal loads, this test is implemented again in Research Seminar 2011 with ten architecture students in the master's program. The same kind of results are found with these students and an open discussion with the students reveals that their own understanding of the flow of forces confuses them with the one presented in the structural form model. In this form model, a load path is expressed as the path that follows the horizontal load, but not all the forces that originate from this load case. This difference can best be explained through a simple example (Figure 8-9). Here a beam is connected to two columns. A vertical load (green) is applied to a cantilevered beam. This vertical load is transferred (as shear force) through the beam (i.e. the green ●), and then through the column (as normal force) to its support. This could be defined as the load path of the vertical load, as this is the path the load force follows to arrive at the support.

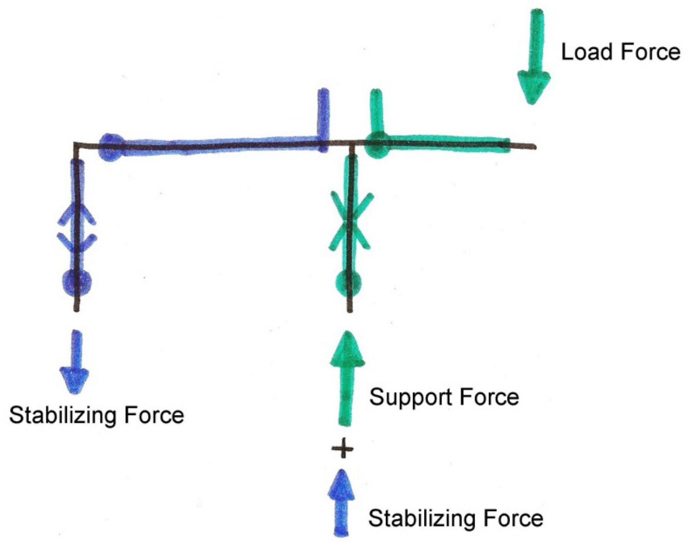


Figure 8-9. Example of different interpretations of structural order.

To prevent the cantilever beam from tipping over, the beam is extended to the next support (i.e. the column indicated in blue). The green bending moment at the end of the cantilevered beam is stabilized by the blue bending moment of the extended beam, which is held in place by the column under tension. The blue (stabilizing) force at the support of this column keeps this column in place. The whole structure is kept in balance through the (second) blue (stabilizing) force at the support of the first column (where the green support force can be found).

The blue ● symbols indicate how stress is propagated through the left portion of the structure to keep the whole structure in balance. This propagation does not contain any component of the vertical (green) load, but is a story of keeping the structure in balance through additional stabilizing (blue) forces.

A discussion with the students reveals that their natural understanding of a load path or flow of forces includes this blue path or flow. In the form model of the test, only the (equivalent) green path was indicated and not the blue one, which explains the unexpected answers of the students: they did not literally follow the written structural story, but added their own understanding of how the structural load path should look. (The green path provides for an interesting view on structural design, as it presents those structural elements that actually take part in transferring the load. The blue path then indicates those elements that are needed to support those green path elements in transferring the load. These blue path elements do not actually transfer the load themselves, and can be seen as an indication of a conceptual (in)efficiency of a structural design.)

In Research Seminar 2010, an open discussion is held with the students on the language after they have become acquainted with it. Students remark that in certain situations, drawings get overloaded with information (i.e. too many symbols on one drawing) and become hard to read. This occurs when the structural behaviour of different load cases is expressed on the same drawing. Even when using different colours for each different load case (e.g. vertical and horizontal loads) a risk of overloading the drawing remains.

Students suggest using several two-dimensional drawings instead of one three-dimensional drawing, or even developing extra symbols for certain symbol combinations, as in the case of a stiff connection to resist a bending moment (Figure 8-10).

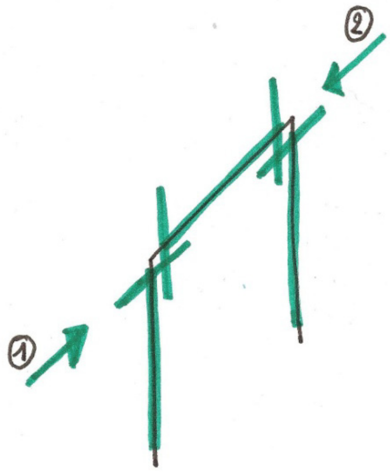


Figure 8-10. Expressing stiff bending-resistant connection in a portal frame for two opposite load cases.

This problem of drawings being overloaded with information mainly occurs in the exercise of explaining the structural behaviour of the table. In this exercise, students try to express structural behaviour for different load cases at the same time (e.g. horizontal and vertical), which leads to an accumulation of symbols that can be hard to distinguish one from another. When the students and I later apply the language in a design workshop, the students express that they no longer experience this problem, since often only one load case is addressed in a workshop drawing. In a later follow-up discussion, students express that they highly value the limited number of symbols used in this language, and advise against introducing more of them.

In practice the language of symbols is often used in general structural drawings when only one load case is investigated (e.g. horizontal or vertical load). In such a case, conceptual drawings – even in three dimensions – are normally feasible and readable with the symbols provided.

Mostly several symbols are combined when possible structural solutions for one element are explored. In such a case, the symbols for the structural dimensions for all important load cases should be applied on one element to understand its range of possible design solutions. When investigating this range of possible solutions, an element is best described with the language on its own, detached from the overall structure. Such a drawing of an isolated element is again feasible and readable with the symbols provided.

Much attention has been given to the development of the symbols. The generative idea behind the development of the language is to load an architectural three-dimensional image or physical model of a design proposition with structural information about the engineer's design proposition. This is one of the reasons why the symbols are developed to be used in three-dimensional drawings. Three-dimensional representations also allow us to give an orientation to the symbol I for bending so that the same symbol can be used for each direction in which the bending occurs. (A disadvantage of this three-dimensional symbol I , however, is that it requires a different symbol when viewed from directly above so it does not appear as a dot.)

Because the proposed language is intended to be used in design workshops, the symbols are chosen to be easy to draw in a few simple lines. However, using these symbols on wire-frame models of the design object can become confusing, as the Tomas project has shown. Therefore colour is introduced for the symbols and/or a thicker line than is used for the wire-frame model lines. Also, the line that indicates an architectural element as structural is made shorter to make it stand out from the lines of the wire-frame model (Figure 8-11).

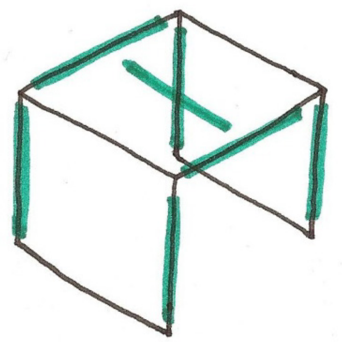


Figure 8-11. Indicating architectural elements as structural.

A problem that can occur with the symbols in theory (but is not very likely in practice) is when an element contains two structural directions and a symbol I for bending is drawn on the crossing of these direction lines. In this case it is unclear to which direction line this bending is attributed. This can be solved by extending the symbol with directional lines as shown (Figure 8-12).

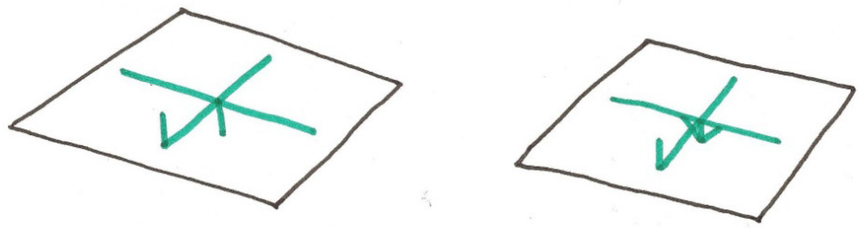


Figure 8-12. Clear attribution of lower moment through directional symbol.

A lot of attention has been given to designing the symbols so that they are still readable in various combinations. In these combinations, attention is given to preventing the symbols from overlapping so that every symbol can be recognized. Practice has shown that most combinations are easy to read, and that certain problematic combinations hardly ever occur in structural propositions.

As these symbols are rough or conceptual representations of discrete mathematical functions (i.e. bending moments, normal forces and torsion), they provide less information than engineering diagrams. In most cases, this filtered information is sufficient and preferable to an overload of information. When this information is not sufficient, more engineering information can always be provided.

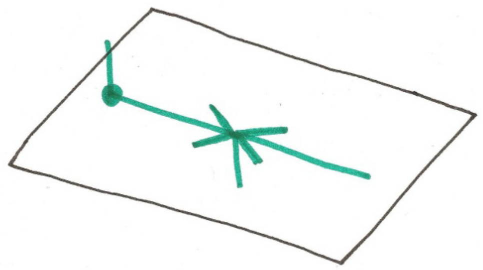


Figure 8-13. Readable combination of several symbols.

As already mentioned in the description of the ‘structural design possibilities’ layer, a structural element and its characteristics of structural dimensions represent a range of structural solutions. The link between a conceptual element and its possible design solutions can be contained in a catalogue. These possible structural design solutions need to be understandable in the field of architectural design, and must contain the architectural characteristics of real-world objects, such as distinct form, colour and tactility. Such a catalogue of real-world solutions can be organized according to the characteristics of structural dimensions, conceptual (architectural) shape, and architectural characteristics.

This catalogue can function as a design tool for architects by showing the variety of possible structural design solutions inherent in a structural engineer’s conceptual design. For architectural design, it prevents narrowing down the possibilities (too) early in the design process, and provides an architect with inspiration for the further development of an architectural design process. (Architects often find inspiration in already built projects.)

This catalogue also functions as a design tool for structural engineers, not only by providing possibly unknown design solutions, but also by reminding an engineer of the wide range of available solutions (before he or she commits to a single solution).

This catalogue of images also provides a communication tool through which both architectural and structural design characteristics can be made explicit and can be refined by architects and structural engineers for each other (and even for themselves).

In this seminar it is determined that a first step is to develop such a catalogue. The intention is to explore the feasibility of creating such a catalogue and how it should be organized for use by architecture students and structural engineers. By involving students in the creation of this catalogue, the intention is to use their design experience to make this catalogue a viable tool: students can determine through experience if the catalogue under development operates in the way they would want to use it in design.

A format for the catalogue is developed with the students' participation, and about a hundred examples are loaded into the catalogue. I investigate how well the catalogue operates, and an open group discussion is held with the students to get their opinions of the catalogue.

For the catalogue students gather examples of structural solutions used in architectural design. The conceptual element in each example is represented by a rectangular surface. Students are free to define some architectural characteristics for these examples that they find valuable during their conceptual design process. These architectural characteristics (i.e. transparency, tactility and size) then organize the examples in the catalogue through a scale.

In an informal group discussion afterwards, students express their appreciation for such a catalogue, not only as a useful design resource, but also to be used in theory classes. Such a catalogue would link the more theoretical approach of structures with a wide range of built examples.

Students appreciate the strong value of an image of these built solutions in this catalogue. They also come to the conclusion that the conceptual element should be marked on the images in order to clearly communicate which aspect of the image is being used as an example. They request many more examples in this catalogue.

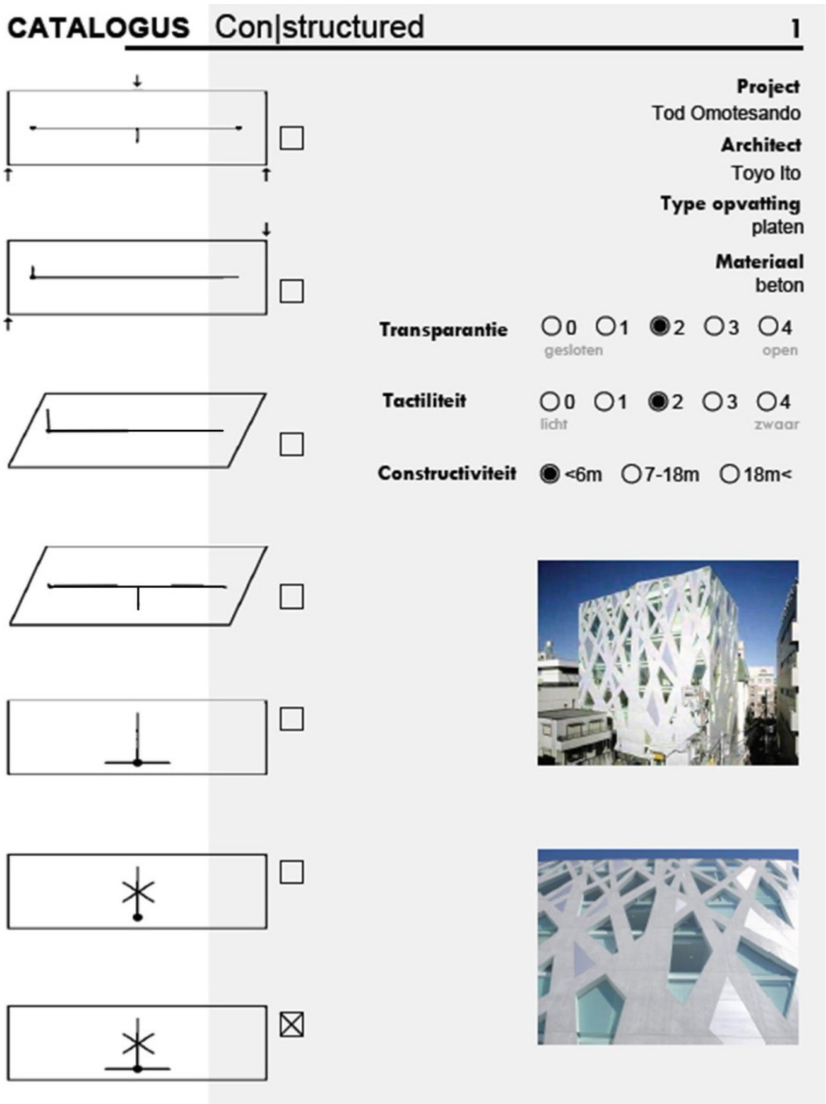


Figure 8-14. Example of catalogue entry.

Analysing the format of the catalogue shows the following: the images should be more at the centre of the outcome of an inquiry; some characteristics of structural dimensions might be filtered out, as they hardly ever occur in practice; and combinations of different characteristics should be made possible. If this catalogue were to contain shapes of conceptual elements other than rectangular surfaces, these elements and characteristics of structural dimensions should be separate entries of inquiry. In all, creating this catalogue seems to be feasible and promising.

A language for collaboration

The second part of this seminar investigates the use of the language during a design collaboration between architecture students and a structural engineer in a design studio setting. In this setting, various collaboration proposals are also implemented and evaluated. Design collaboration occurs in face-to-face meetings spread over several weeks.

As this collaboration intends to structurally inform architectural design, the collaboration is set early in the design process, when design propositions are still in a conceptual phase. Attention is given to communication that mainly brings to the fore essential design characteristics of each proposition. By presenting these design characteristics, unnecessary information is filtered out and collaboration is focussed on essential aspects of each proposition. In this design studio, students are asked not only to express their architectural design characteristics but also to paraphrase structural design characteristics. As the structural engineer in this collaboration, I in return paraphrase the architectural design characteristics of the students' propositions. This communication technique makes it possible to check if a conveyed message is being understood, but it also serves as a design technique that allows the designer to view his or her own proposal at some distance through the words of an external interpreter.

In this design studio, we also also investigate whether it is possible to negotiate and further inform a design through these conceptual design characteristics. Using the new language for design communication, only the conceptual design characteristics of the structural design are provided, and negotiation can only occur through them. (Materialized structural solutions are not expressed in the early phase of these design collaborations.)

This structural language also filters structural information by only presenting structural order and indications of structural dimensions. In these design collaborations, we investigate whether this information is sufficient to tell the structural story of an engineer's design proposition, and whether it is sufficient for the architecture student to grasp the range of possible structural solutions, alter certain given structural form models and inform his or her architectural design process.

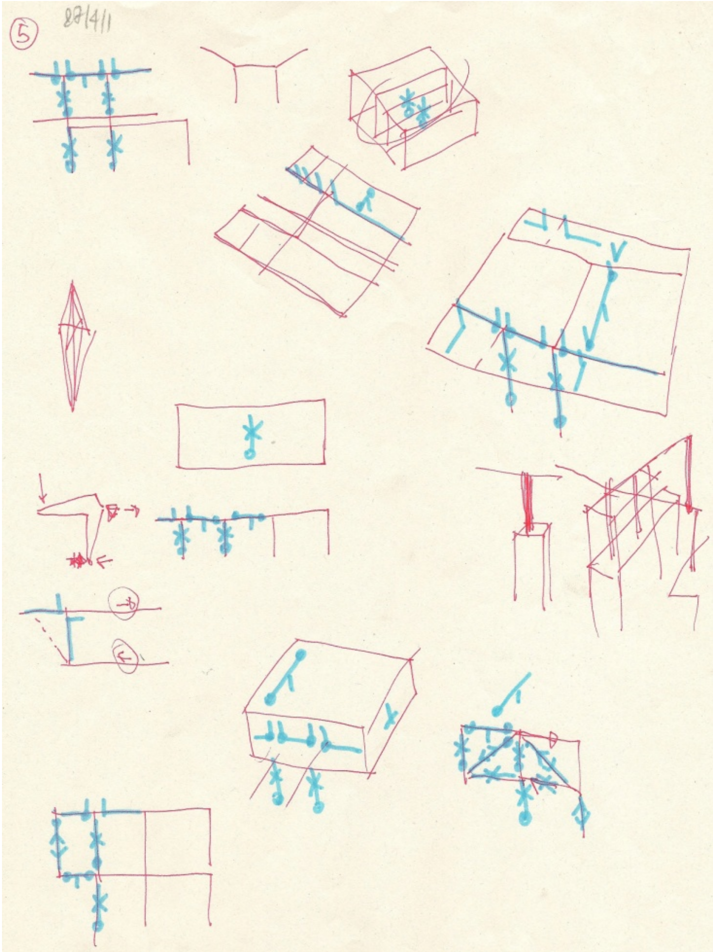


Figure 8-15. Example of workshop drawings of structural propositions.

A design studio is organized with seven students, leading to six cases as two students work together on the same project. Similar to previous design studios developed for this research, students are asked to work together in design workshops with a structural engineer from the start of their design process. In this case, however, the description of the design studio project is developed by an experienced architect and teacher. This architecture teacher is experienced in developing and conducting such design studios. Throughout this design studio, the teacher also gives architectural consultation to the students. Based on my previous experience in design studios for this research, the lack of such an architecture teacher who focuses on the architectural aspects of the students' projects often leads to architectural designs that lean too much towards structures at the cost of architectural quality. The architectural consultations between students and architecture teacher are implemented from the start of the studio, right after this teacher introduces the design studio project to the students. The studio lasts about six weeks, and each week includes structural consultation during face-to-face meetings.

Students are asked to keep a log of their design processes, especially before and after a face-to-face meeting, and to reflect on the influence the structural consultation has on their design process. This is to make them aware of their own design process and the relation with structural information. This awareness helps generate a more informed evaluation at the end of the studio, expressed in questionnaires and open group discussions.

During and right after each face-to-face meeting, I take note of enlightening events or insights, especially concerning my ability to express my design propositions with this language.

After handing in their design projects, students fill in a questionnaire with open-ended questions about the face-to-face meetings and the use of the language. Afterwards, I hold a follow-up discussion with all students on their appreciation of the design studio in general and the use of the structural language in particular. Both inquiries reveal the following:

- Students describe the structural language used in the face-to-face meetings as clear, direct, pure, intuitive, understandable and quick: you can learn it by using it; it does not need much explanation.
- Students state that the language is useful for the first phase of the design process, when there is a need for more abstract structural ideas, but that something ‘more’ is needed later on in the design process, when there is a need for more detailed information that this language does not provide.
- There is a limit on the amount of understandable information that can be put in one drawing. Thus in case of complex structures or too many load cases, more than one three-dimensional view is needed, or more (two-dimensional) drawings need to be made.
- The language provides structural information on the level of an architect’s design culture. Students value the visual communication (with the language) more than a spoken one.
- Some students perceive a direct link between the applied symbols and the structural dimensions.
- Students say they use the language in their mind without putting it on paper, and that through the use of simple wire-frame models for the structural form models they are able to manipulate the conceptual design in their mind.
- Some students say they find it essential to limit the number of symbols in the language in order to gain more insight into the structural essence.

- One student felt too familiar with the traditional engineering language to see a benefit of using this new language, except for the use of a catalogue with built examples.
- Students look forward to using a catalogue that links the conceptual design (expressed in the language) with the variety of built reality for their architectural design process.
- Students would like to see this language applied in and linked with present theory courses.
- Students say they have let the structural input guide their design process.
- One student says she uses the language in other design studios now, and even with student colleagues who are not familiar with the language. She says these other students find the language easily to learn.

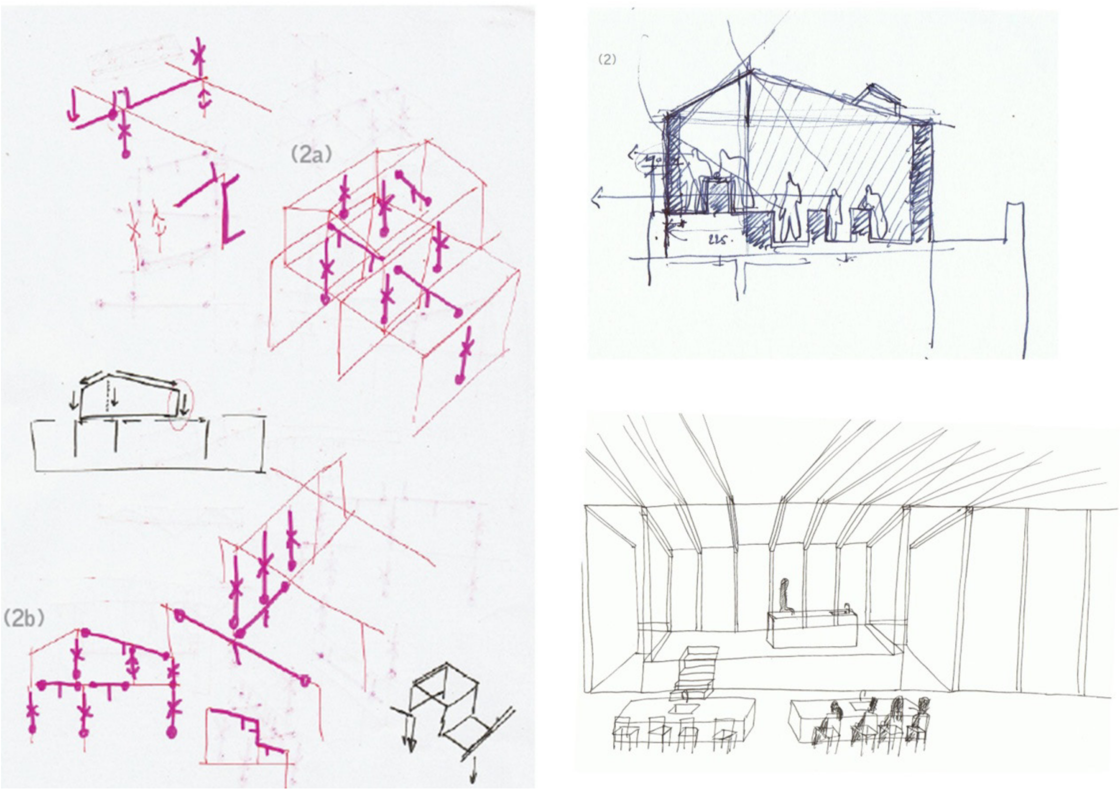


Figure 8-16. Example of student project. (Structural proposition; initial architectural concept; developed architectural design after structural consultation).

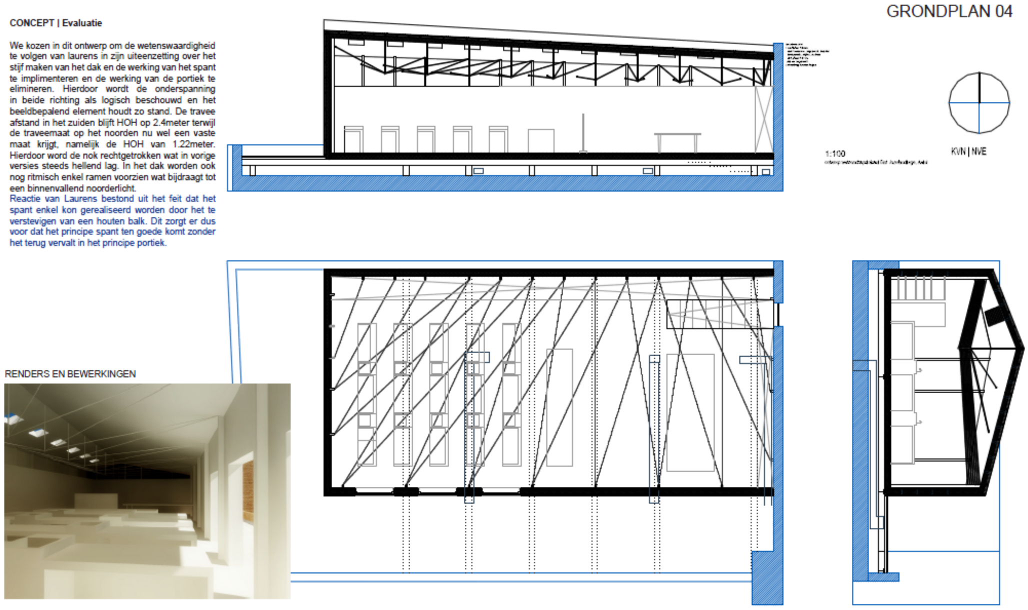


Figure 8-17. Example of design outcome of student's project.

After going through my notes and the student work produced in the seminar, I come to the following conclusions:

Using the new language during the workshops allows me to quickly and easily write down the structural story of a conceptual design proposal: the language enables me to express the essential design characteristics of my structural proposal. Since this communication is put on paper, someone can read it again later if they don't understand it from the start. This allows students to go through the proposal again after a meeting. (During common structural consultations, conceptual explanation of structural behaviour occurs only through spoken communication, which is fleeting.) One student even advocates for an even more elaborate format for expressing a structural proposal that includes an overview drawing, drawings of structural details and dimensioned sections. The purpose is to make all the information about a proposal conveyed during a face-to-face meeting available for retrieval later during their design process after the meeting.

Drawing with a different colour marker to indicate the structural information on the wire-frame model is a bit tedious, but it gives good results. Although the three main load axes each has its own accompanying colour, the workshop shows that one colour is sufficient to provide the necessary information to the students, because it is seldom that more than one major load case needs to be drawn on one form model image.

In the first face-to-face meeting with the students I emphasized the communication of (architectural and structural) design characteristics and paraphrasing each other's design proposals. It seems to me that this technique works well to improve the communication as well as the collaboration in the early phase of the design process (i.e. when the design project is still unclear and design team members are unfamiliar with each other).

In the following weeks, the communication through paraphrasing becomes less explicit because it feels a bit unnatural and eventually stands in the way of a friendlier and warmer relationship between design team members. It even seems that there is less need to emphasize this explicit type of communication (i.e. of design characteristics and through paraphrasing) in the later stages of design, since there is sufficient more implicit communication.

Although sometimes students are not able to precisely express all the essential design characteristics of their conceptual design propositions, they are always able to produce a set of design characteristics in addition to the given form model during a face-to-face meeting.

All structural proposals are communicated through the new language in two- and three-dimensional representations of form models. Through this language, design characteristics are expressed that enable students to understand the structural behaviour of my design propositions. Once these are understood, the students are capable of changing the structural form model within the boundaries of my structural design characteristics (and sometimes even further) to arrive at a valid structural design proposition.

Not all students acquire the same level of structural understanding of a structural proposition. Using this language does not resolve this difference. But because only this language is used to explain structures (and not typologies or materialised solutions), it is shown that the language provides sufficient information to understand the structural behaviour of a proposition. The students show this through paraphrasing and through correctly modifying the given form model.

The evolution and results of the different design processes also make apparent that the architectural design process is guided by the given structural information, and thus that the architectural design gets structurally informed through the use of the new language and the applied collaboration process.

Research Conclusions

9. Proposals for a mutually informed collaboration

Interdependency of architectural and structural design

An architect and a structural engineer depend on each other when designing architectural projects. Each requires information from the other, and each one's contribution influences the other's design process. The architect sets conditions for structural design by providing an architectural form for which a structure needs to be designed. He or she will also have the final word on whether a proposed structure is sufficiently adapted to the architectural proposition. The engineer in turn can refuse a proposed architectural form as structurally unviable and set structural conditions that the architectural design must take into account. Thus both designers create design conditions that the other designer has to take into consideration and both take part in the design evaluation of the other's design (cf. Chapter 2.4 and 3.3).

Comparing architectural and structural design

In Chapters 2.2, 2.3 and 3.1 it is argued that architectural and structural design have similar characteristics and mechanisms as design processes. Both are the result of personal (i.e. subjective) readings of a design question. In architectural design culture, this personal approach is not only central to the design process, it is also an essential quality of the design outcome. Structural design, on the other hand, seems at first glance to be only a result of objective and impersonal calculation procedures. But structural design also begins with the engineer's personal choices and ability in the development of a structural concept that will eventually delineate the character of the structural design outcome. This subjective aspect of structural design is often underexposed in the engineering culture, which tends to evaluate design quality through scientific proof (i.e. based on objective assessable facts) rather than subjective argumentations (i.e. based upon personal opinions and emotions).

From a design question that is framed within a set of conditions, both designers derive a design concept. This concept structures the design question towards a problem/solution format by bringing to the fore certain design issues understood as key by the designer, as well as a broad direction for design solutions. Most architects are trained for and capable of a broad exploration and evaluation of various design concepts and conceptual design propositions. They are aware from the start of a design process that one design question can lead to more than one qualitative design solution (cf. Chapter 2.2 and 2.3).

In structural design, most engineers seem to be more driven towards finding just one design solution that is structurally computable, rather than towards developing a variety of solutions. This one solution is often the product of a process of striving for optimal efficiency (e.g. of matter, manufacturing, construction and/or cost) within one chosen design concept. Establishing a design concept is then mainly a necessary step towards developing this one solution, rather than an opportunity for a broad-ranging design process before choosing which design path to develop in depth (cf. Chapter 2.2 and 2.3).

The inexperience of engineers in general at designing concepts and searching for a variety of possible design solutions is reflected in commonly available design vocabulary used to describe and create structures. For example, structural typologies, as mental building blocks for design, are closely related to calculation methods that quickly lead to specific design solutions. Thus design propositions developed through these typologies are already rather concrete and represent only a limited number of possible design possibilities (cf. Chapter 2.3 and 3.1). One reason architects are able to develop conceptual design propositions with a wide range of possible solutions is that they can rely on design precedents as mental building blocks for design. These precedents allow diverse and rather abstract types of interpretation (e.g. organization, expression and function). They stand in relation to architectural history and are articulated through a culture of design critique (cf. Chapter 2.3 and 3.1). In engineering design culture, these relations of design to history and to design critique are both underexposed.

Characteristics of a mutually informed design collaboration

Both architects and engineers, with their specific approaches to design, need to work together to come to a design outcome. The quality of this design outcome relies partly on their ability to collaborate by efficiently informing each other of their own design process, and by applying knowledge pertaining to both disciplines when making design decisions (cf. Chapter 2.4 and 3.3). This collaboration should add up to more than their individual design abilities can provide separately: the goal of designing together is to establish a multi-disciplinary design knowledge that transcends the sum of knowledge from the two disciplines. This requires that both designers when working together (1) establish a qualitative communication of conceptual design propositions and (2) pursue adequate collaboration strategies (cf. Chapter 2.4, 2.5, 3.2 and 3.3).

1. Establish a qualitative conceptual design communication

As architectural form and structural form are interdependent and decisive for both design processes, architects and structural engineers need to collaborate early in the design process, when form is still under investigation. This means that for both designers to keep each other well informed early in the design process, each needs to convey conceptual design propositions that must be sufficiently understood by the other (cf. Chapter 3.2).

Design propositions are often communicated using form models. However, a form model needs to be further enriched with design information in order to convey a more profound understanding of the conceptual design proposition. In this research, I advocate that this enrichment should be provided by communicating essential design characteristics of the proposition. These characteristics relate to the underlying design concept and to the design criteria identified by the designer as most important for the evaluation of the design (cf. Chapter 2.5 and 3.2).

These conceptual design characteristics are embedded in the terminology, logic and culture of the design discipline, and require sufficient knowledge on this discipline to be understood. In order to reduce this required knowledge, the information exchange needs to be adapted for the design discipline to which it is communicated, adapted even for the specific designer involved and the type of collaboration established over time. Redundant information is best avoided and the essential characteristics of the design proposal should be brought to the fore (cf. Chapter 3.2).

For both designers, understanding the conceptual design characteristics as expressed by the other enables each designer to alter the other's form model while staying true to his or her conceptual design proposition. Changing the other's form model within the spirit of the given proposition can be necessary to improve one's own design outcome. For example, when a given architectural form model needs to be adapted in order to develop a qualitative structural proposition, the engineer can alter the architectural form model in such a manner that it will be approved by the architect. This ability requires the engineer to have experience in architectural design, but also to know what this particular architect prefers, especially in the given design project. Expressing these design characteristics helps each one to understand the other's preferences and is as such an important source of information in a mutually informed design process (cf. Chapter 3.2 and 3.3).

The ability to appropriately alter a form model is expressed in the theory of multi-disciplinary design optimization in the Rational Reaction Set, which enables each designer to anticipate the outcome of the other's design process as a result of his or her own design proposition. To some degree this Rational Reaction Set enables an architect to design structurally and a structural engineer to design architecturally. Collaboration improves when each designer acquires an appropriate Rational Reaction Set, which is strengthened by a communication of design characteristics (cf. Chapter 2.4 and 3.3).

In my research, I have given special attention to the need for explicitly expressed architectural conceptual design characteristics in addition to a form model. Various study cases show that communication of these design characteristics often occurs implicitly, and that special attention is required to make it more explicit. (For example, architecture students are not always able to state their design characteristics clearly, cf. Chapter 6.1.)

Structural design characteristics are brought to the fore in design communication through the use of a newly developed structural language (cf. Chapter 10) that enables a more conceptual communication than current engineering language provides.

Design characteristics are sometimes rather abstract concepts and are prone to misconception. A technique of paraphrasing design characteristics helps make them more clearly articulated and more easily understood. This technique seems to be a useful tool at the start of a collaboration, when design direction is still vague, but might stand in the way of a smooth collaboration later in the design process, when more implicit communication is often sufficient (cf. Chapter 6.2, 6.3 and 8.2).

Paraphrasing is also an interesting technique to help a designer get some perspective on his or her own design proposition through the description of another designer, and to evaluate his or her own proposition more objectively from a distance. Additionally, paraphrasing can support a design negotiation process towards an agreed set of design characteristics for the overall design (cf. Chapter 6.2).

A successful communication setting for an informed collaboration is a face-to-face meeting. As engineers and architects have different cultures in expressing and interpreting a design proposition, special attention is needed in communication when abstract concepts are conveyed. In face-to-face communications, sender and receiver can closely monitor whether the right message gets across through direct feedback. In these meetings sketching can serve as a qualitative communication tool across disciplines (cf. Chapter 2.5 and 3.2).

Another advantage of face-to-face communication in collaborative design is that it allows for several information cycles in a short period of time. Each designer is then able to stay up to date on the evolution of the other's design process. This close relationship also enables quick responses to questions, which helps keep the design thoughts going (cf. Chapter 2.5 and 3.2).

2. Collaboration strategies

When two collaborating designers inform each other through conceptual design propositions as a range of design solutions rather than single design solutions, they are able to follow a delay decision strategy. In this strategy, decisions are delayed until sufficient information is gathered to make well-informed decisions. Each designer obtains the information necessary to make such well-informed decisions from the other designer by communicating conceptual design propositions, while allowing ill-informed decisions to remain open. Such design propositions provide for a range of solutions instead of a single design solution (where all design decisions are already taken). Each
designer gradually becomes more informed about the other's design through a cyclic process of informing each other of his or her own design development progress, which enables both to make more well-informed and accurate design decisions that further their own designs (cf. Chapter 2.4 and 3.3).

In design negotiations between an architect and a structural engineer, the main focus of discussion is the subjective aspect of design – i.e. where designers make personal choices. Conceptual design characteristics address this subjective aspect and form important elements in such negotiations. By resolving conflicts in the design characteristics of the two design propositions, a congruent set of design characteristics can be developed. This set of agreed design characteristics provides a common design goal for both designers, which transforms the individual designers into a synergetic design team. This congruent set of design characteristics then guides the designers' further design processes in their own design disciplines (cf. Chapter 3.3 and 6.2).

When a designer understands the expressed design characteristics of the other's design proposition, and has the intention to keep his or her own design process in congruence with these characteristics, his or her discipline's design process can incorporate the other's design characteristics as design aims. By implementing these unfamiliar aims, a novel approach to the own discipline's design can take place that leads to creative output as a product of the design knowledge of both disciplines (cf. Chapter 3.3).

Proposals for a mutually informed design collaboration

A referential background is developed for the design processes and cultures of both the architectural and the structural engineering professions, and for design collaboration and communication between them (cf. Chapter 2). Based on this background, and through an investigation of my own design experiences backed up by interviews and discussions with several architectural and structural designers, various diagrams are developed that describe the characteristics and mechanisms of mutually informed design collaboration, communication and design processes between architects and structural engineers
(cf. Chapter 3). This study has enabled me to establish several proposals for a mutually informed design collaboration that have been implemented, evaluated and further developed in several study cases of design collaboration through methods of participatory action research (cf. Chapter 5.3, 6.1, 6.2, 6.3 and 8.2).

The proposals thus developed for mutually informed design collaboration are:

- Communicate explicitly through form model and additional design characteristics of conceptual design propositions.
- Filter the information exchange in order to bring to the fore the essence of a conceptual design proposition, tailoring it to the receiver's design discipline and design preferences.
- Develop a congruent set of conceptual design characteristics across the different involved design disciplines.
- Provide for a cyclic information exchange through conceptual design propositions as a range of design solutions, in which design decisions are delayed until sufficient information is obtained.
- Provide for face-to-face communication in which information exchange is supported through sketching.
- Paraphrase each other's design proposal early in the design process.

10. Structural language

Conceptual design of architect and structural engineer

As described in Chapter 2.2 and 2.3, structural engineers are in general not well trained in developing and evaluating design concepts – or very conceptual designs – for exploration into a wide range of possible design solutions. They are mostly driven towards a single-solution design process. This is reflected, for example, in the development of structural design propositions through a design vocabulary of structurally computable typologies. These typologies are closely related to design solutions and therefore limit a more conceptual (i.e. abstract) exploration of structural design possibilities that are not retained by an interpretation of structural design through in-depth structural analysis and the engineer's calculation abilities.

Architects, on the other hand, often start their design process with a broad search for possible design concepts and conceptual designs, as they are aware that more than one qualitative design solution is possible. This can lead to architectural conceptual design propositions that do not contain a fixed design of form and space, and are described in very abstract terms. Further design explorations – including structural ones – can then direct the development of such a proposition. This exploration in conceptual design requires an adapted discourse between structural and architectural design.

Qualities of the proposed structural language

This thesis includes a proposal for a new structural language designed to allow such a conceptual discourse between architects and structural engineers when they design together. This conceptual discourse enables a structurally informed architectural design process from the start. The proposed structural language contains several qualities:

1. *Communicate structural logic*

When a structural engineer presents a conceptual design proposition, it represents a range of different design possibilities. By understanding the defining design characteristics of this proposition, it is possible to grasp this range. The proposed language expresses essential design characteristics of this conceptual design proposition by revealing its underlying structural logic. This structural logic is at the centre of a conceptual design proposition, and demarcates the range of design possibilities this proposition entails.

The proposed language expresses structural logic through an abstract representation that finds meaning in four different layers: structural order, structural function, structural dimensions and structural design possibilities.

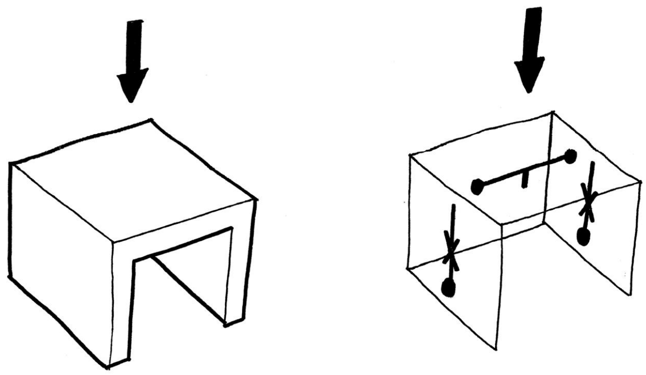


Figure 10-1. A language to express structural logic. (Structural form; language)

Structural order reveals the structural relations between different structural elements for a specific load case: it shows which element is supported by which other elements. It brings to the fore the path(s) a load follows throughout the system of structural elements to its supports (cf. Chapter 7.3).

The layer of **structural function** expresses the type of load transfer that occurs in a structural element: axial or parallel transfer of force, or axial or parallel transfer of moment. Each structural element is required to perform its structural function(s) to enable the structural system to bring the load to the supports (cf. Chapter 7.4).

The consequences of performing a structural function on the structural form of an element are expressed in the layer of **structural dimensions**. This leads to five major types of structural dimensions: one for each type of structural function, where axial transfer of force is split into tension and compression. This means that expressing the characteristics of structural dimensions also reveals the underlying characteristics of structural functions that each element needs to perform (cf. Chapter 7.5).

The layer of **structural design possibilities** links each element and its characteristics of structural dimensions with a wide range of possible (built) structural design solutions. These solutions as material form bring the conceptual design into the realm of built reality of structures – and also of architecture, because each material form contains architectural qualities (cf. Chapter 7.6).

Understanding the structural logic of a form model allows us to alter this form model through structurally sound rules. In most conceptual design propositions, only a single structural form model is presented as a geometrically defined form. Such a form model is an important tool for negotiation between architectural and structural design. The ability to change the given structural form model in a manner the engineer would approve enables an architect to adjust this form model to the benefit of his or her own architectural design without creating a design negotiation conflict. One favourable way of changing a given form model in order to avoid conflict is by maintaining the structural logic of the structural engineer's conceptual design proposition. The proposed language expresses this logic through its layers of structural order and dimensions. This means that a structural change to a given form model is likely to be approved by the engineer when the structural order and characteristics of the structural dimensions are maintained (cf. Chapter 3.2, 7.7 and 7.9). (The layer of structural dimensions will even indicate the consequences for material dimensions when the size of a structural element is altered.)

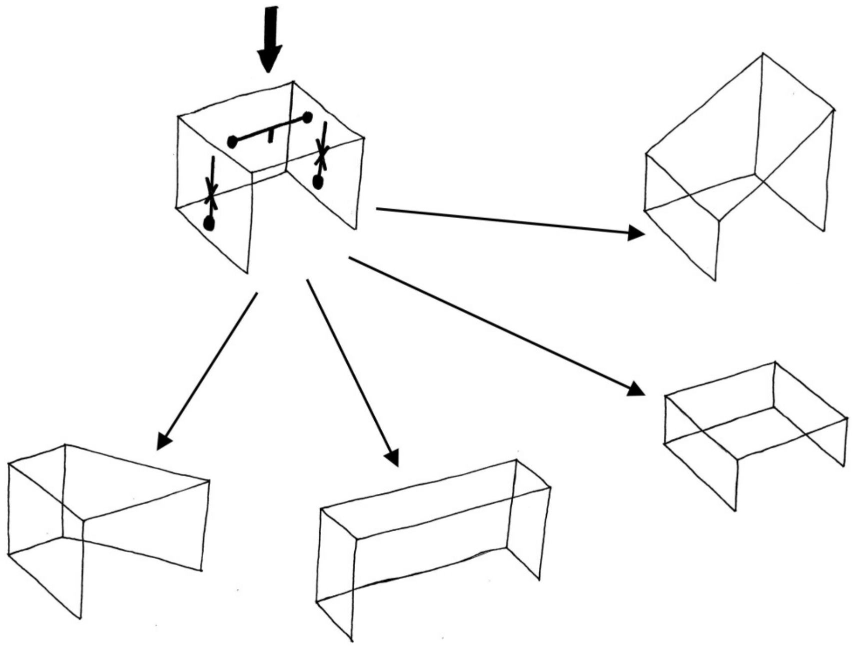


Figure 10-2. Possible form model changes within the structural logic of a conceptual design proposition under vertical load.

2. *Articulate conceptual design decisions of the engineer for negotiation*

In the early stages of structural design, an engineer makes personal design choices that narrow down the range of possible design solutions. These choices importantly delineate the further design possibilities of structural space and form that can be explored later in the design process through structural calculations and scientific optimization processes.

This language brings these personal decisions to the fore in early design for negotiation with the architect in order to develop a structural design strategy in congruence with the architectural design development.

These personal design decisions mainly involve identifying:

- the structural elements that form the structural system,
- the loads the structure is going to address,
- the path a load is required to follow through the structure to its supports (i.e. the order of the elements),
- the supports that will receive loads,
- the function each element is to fulfil (together with the implication on structural form), and
- the type of connection between structural elements.

These early design decisions are articulated through the abstract nature of the proposed language, which mainly focuses on expressing the different components (as listed above) that are identified by the engineer. The structural sketches drawn with the proposed language contain information on structural space and form that relates to architectural design on levels such as rhythm, order, axis, composition, proportion, expression and so on. If necessary, these design characteristics can then be negotiated between the architect and the structural engineer (cf. Chapter 7.9).

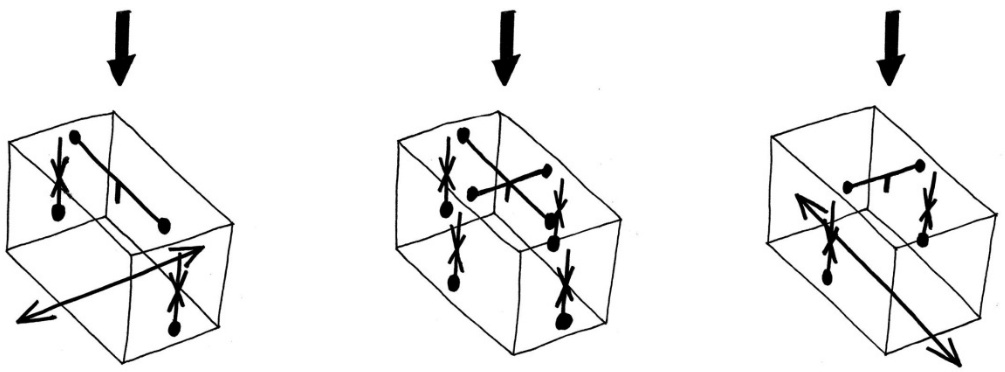


Figure 10-3. Implication on space and form of different structural design strategies.

3. *Provide for more abstract building blocks of design and even structural prototypes*

The proposed language provides for an articulation of building blocks for design development that are more abstract than current ones, which are linked to structurally computable typologies. Such abstract building blocks are not related to an interpretation of structural design through in-depth structural analysis and calculation models, and can represent a wide variety of possible structural typologies. They help answer the question of how loads are transferred to the supports in a most fundamental manner with very little indication of a specific structural form. These abstract building blocks consist of conceptual elements that give form to a general architectural expression and not to the central axis or plane of a structural design solution (cf. Chapter 7.7).

Such conceptual elements with characteristics of structural order and dimensions enable us to develop conceptual design propositions in which few structural design decisions have been taken, and which therefore represent a wide range of possible design solutions.

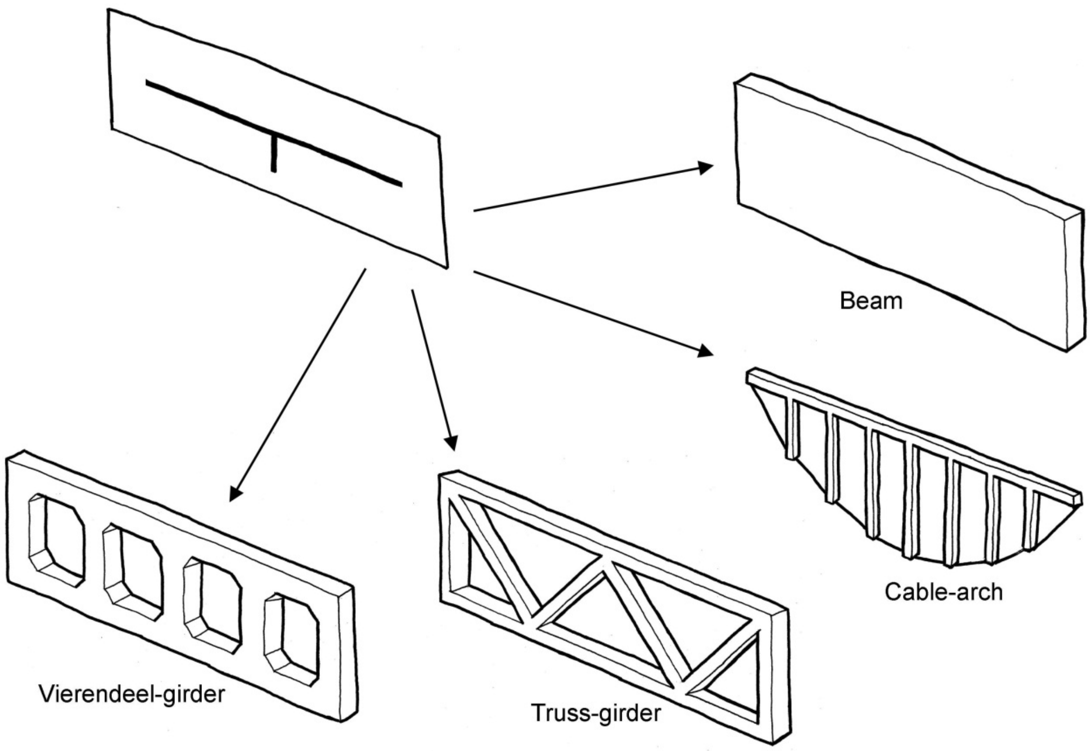


Figure 10-4. A conceptual element and its characteristic of dimensions and various typologies it can represent.

This abstract language can even lead to the development of structural prototypes as starting points for structural design. Such prototypes give a fully formed but profoundly abstract answer to a design question. They represent a wide variety of structural design solutions. Through refinement and transformations, they are further developed and result in appropriate design solutions.

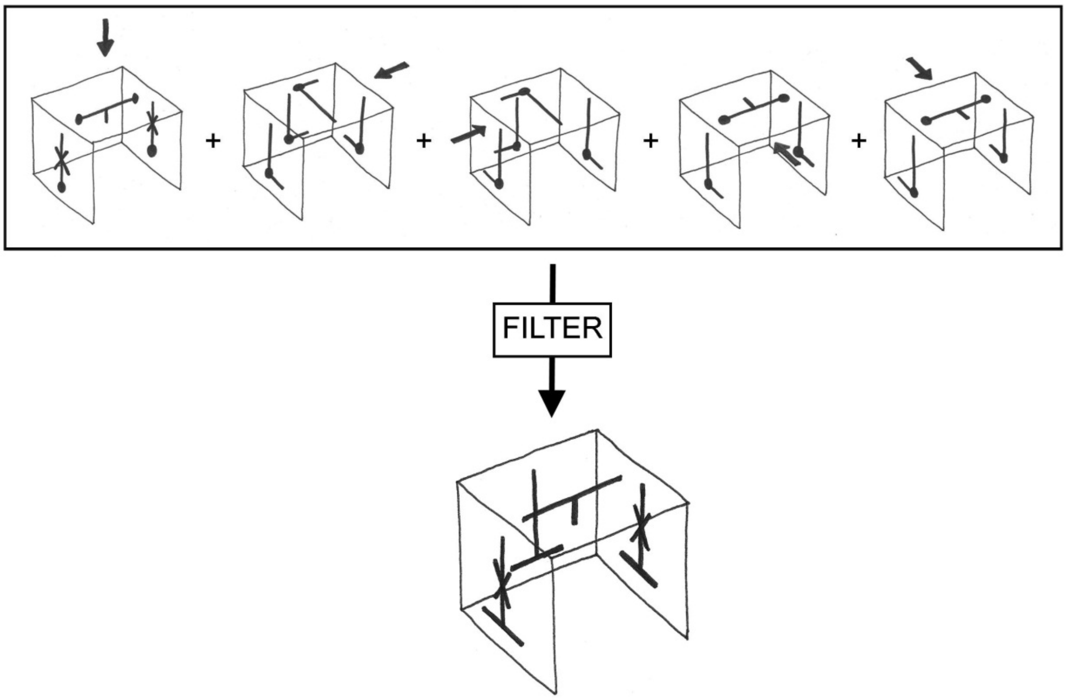


Figure 10-5. Structural prototype: filtering of implemented load cases.

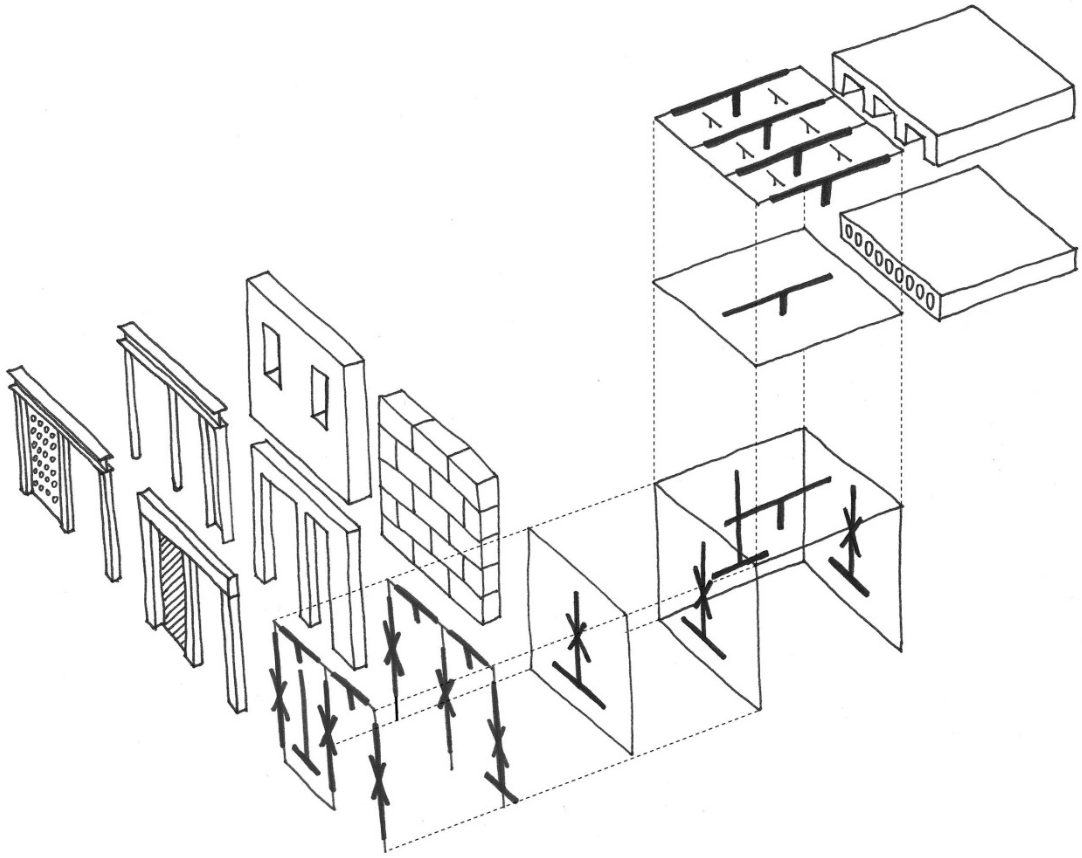


Figure 10-6. Structural prototype: variety of structural design solutions.

4. Enable a delay decision strategy

The proposed language enables us to express the structural logic of a design proposition without the need for more detailed information of structural typology, material or dimensions. Since this structural logic lies at the start of a structural design process, the proposed language enables the engineer to convey structural information to the architect even when only a few structural design decisions have been taken. This allows the two to communicate in a delay decisions strategy in which well-informed decisions are taken and conveyed, and ill-informed decisions postponed until sufficient information is available (cf. Chapter 2.4 and 3.3).

5. Filter structural information for the architect

In the engineering sciences, structural logic is mainly expressed through the wide variety of mathematical diagrams of deformations, internal forces and stresses that pertain to an understanding of in-depth structural analysis. One must have sufficient knowledge of structural engineering and its terminology to comprehend structural logic as explained through these diagrams. The proposed structural language reduces the amount of engineering-specific knowledge required to understand structural logic: it mainly expresses the structural order of the various structural elements and the general dimensional consequences for the function each is required to perform. Both structural order and dimensions are closely related to an architect's understanding of structural phenomena (cf. Chapter 7).

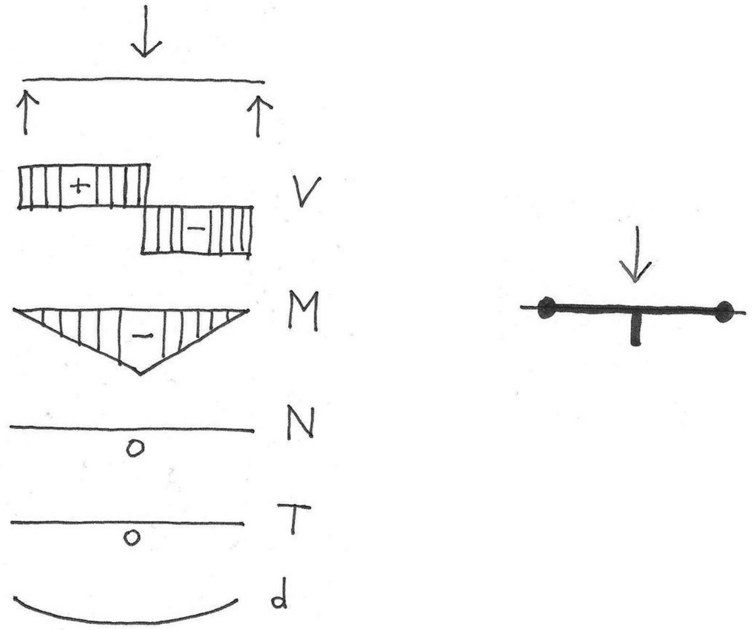


Figure 10-7. Engineering information compared to a proposal for a new language.

Even more, the layer of structural dimensions only brings to the fore essential characteristics that determine the final sizes of a structural element by leaving out the non-decisive characteristics of structural dimensions. This enables us to filter even further the abundance of engineering information and focus on the relation between structural dimensions and architectural form.

6. *Easily and quickly drawn and intuitively understandable*

As this language is to be used during face-to-face communication, the symbols of this language have been developed to be drawn quickly and easily (cf. Chapter 7.1). As the accessibility of graphic language is heavily dependent on associations with familiar objects or experiences (Laseau 2001), an appropriate semiotic is sought for an intuitive comprehension by architects and engineers (Figure 10-8).

Since three-dimensional sketches of a structural design can produce interesting overviews of a proposition in one image, the symbols are developed to support such three-dimensional drawings even when symbols are combined.

The symbols enable us to identify the structural elements and their axial orientation(s), together with a direction of load transfer. A limited number of symbols is used to express the characteristics of structural dimensions, and at the same time also reveal the characteristics of structural function (cf. Chapter 7.5 and 8.2).

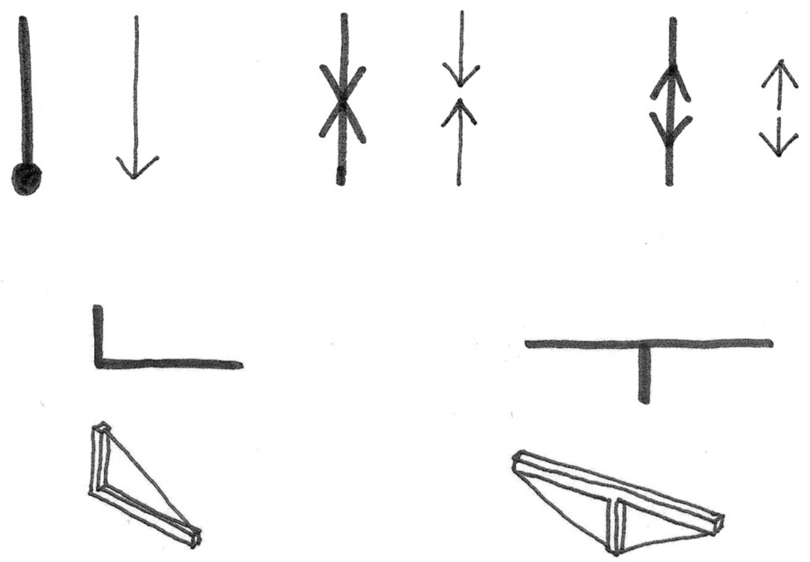


Figure 10-8. Intuitive understanding of symbols.

7. Organize structural knowledge through a process of design refinement

In design, a design object can be refined at different levels. This language supports these different levels of design refinement, from conceptual principles to detailed design solutions. In structural design, these levels of refinement start in the most abstract representation with the use of the proposed language which expresses basic structural logic without going into details and calculations. The layer of structural design possibilities then further links each element and its characteristics of structural dimensions with a wide range of possible structural design solutions. These solutions, as material form, bring the conceptual design into the realm of the built reality of structures – and also of architecture, as each material form contains architectural qualities (cf. Chapter 7.6).

A catalogue of such structural design possibilities can be used as a tool during design collaboration: it helps architects and engineers to explore the range of possible design solutions contained within a conceptual design proposition, and it can be applied during design negotiations to refine architectural and structural design characteristics through its exemplary images (cf. Chapter 8.2).

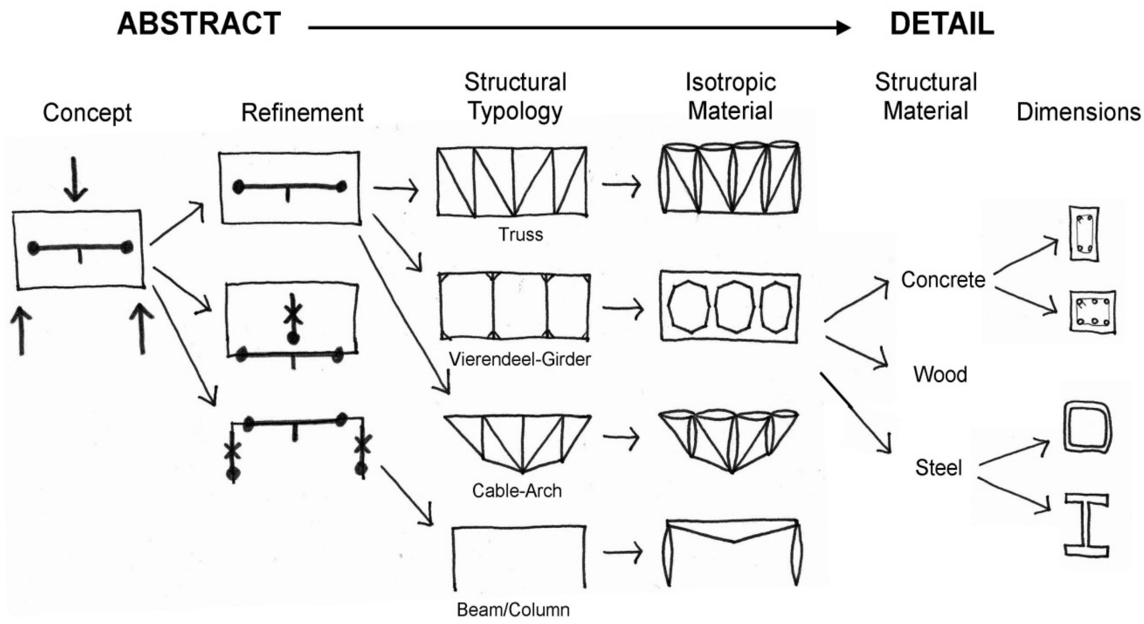


Figure 10-9. Example of design refinements.

8. Allow a personalized expression of structural design

This language can be applied to produce structural 'proposition drawings', as Lawson calls them (Lawson 2004, pp.45–49), in order to step back and review a design proposition from a distance. Such proposition drawings can be produced for interpersonal use (i.e. to enable an informed collaboration between architect and structural engineer), but also for personal use (i.e. to enable a conceptual design of structures). In both cases the language allows poetic freedom in use, which enables a designer to give a personal expression to structural phenomena. This personal expression is important because conceptual design is a personal interpretation of a design question (cf. Chapter 7.8). (In the engineering sciences, the production of various engineering diagrams does not allow for such poetic freedom, as it is subject to strict rules of construction.)

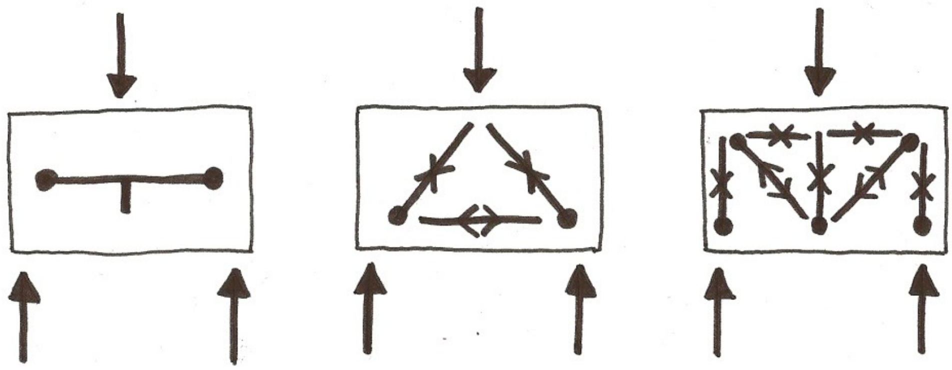


Figure 10-10. Nuances in structural storytelling of a division of load.

Applying the language

During an informed collaboration between architect and structural engineer, the proposed language of symbols can be applied to an architectural form model by providing each conceptual element with structural information about its structural order and dimensions. This means that a structural element is represented according to its architectural expression, and structurally informed with this new language. This can lead to rich three-dimensional drawings that on the one hand express the structural behaviour of a system of conceptual elements, and on the other hand create spatial experiences that relate directly to architectural design. Such drawings then provide common ground for communication during design collaboration between architect and structural engineer (cf. Chapter 7.9).

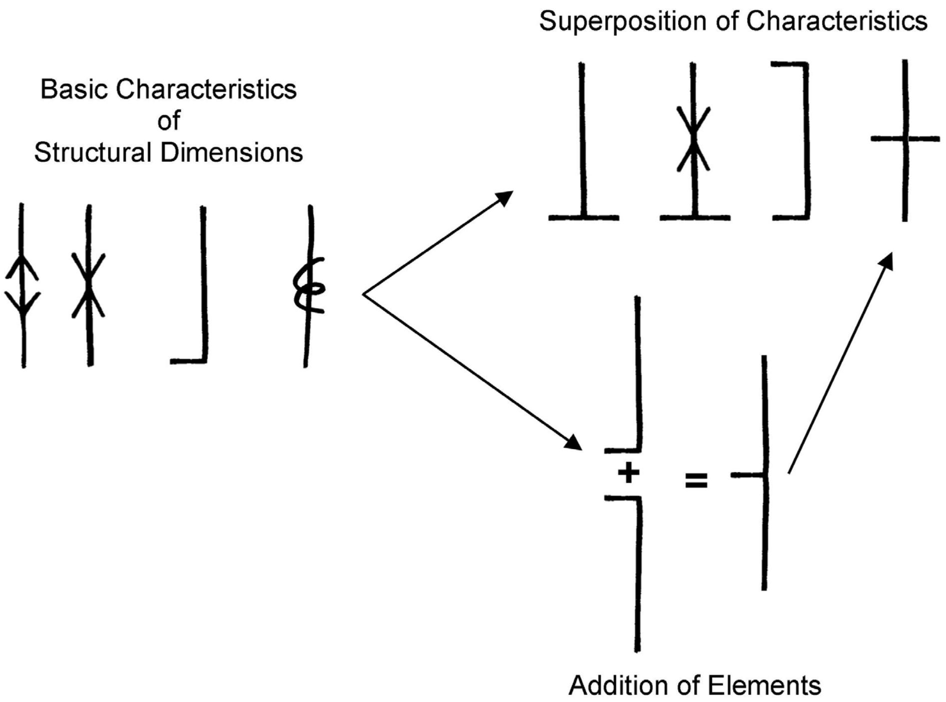


Figure 10-11. Most common characteristics of structural dimensions through superposition and addition of basic characteristics.

The language allows us to combine symbols through superposition of structural dimensions and through the addition of structural elements (Figure 10-11). This provides for a broad range of structural storytelling using a limited number of symbols. By changing the size of various symbols, and because the language enables to explain structural behaviour in a variety of ways, a structural engineer can give a personal touch when expressing his or her personal choices in answering a structural design question (cf. Chapter 7.8).

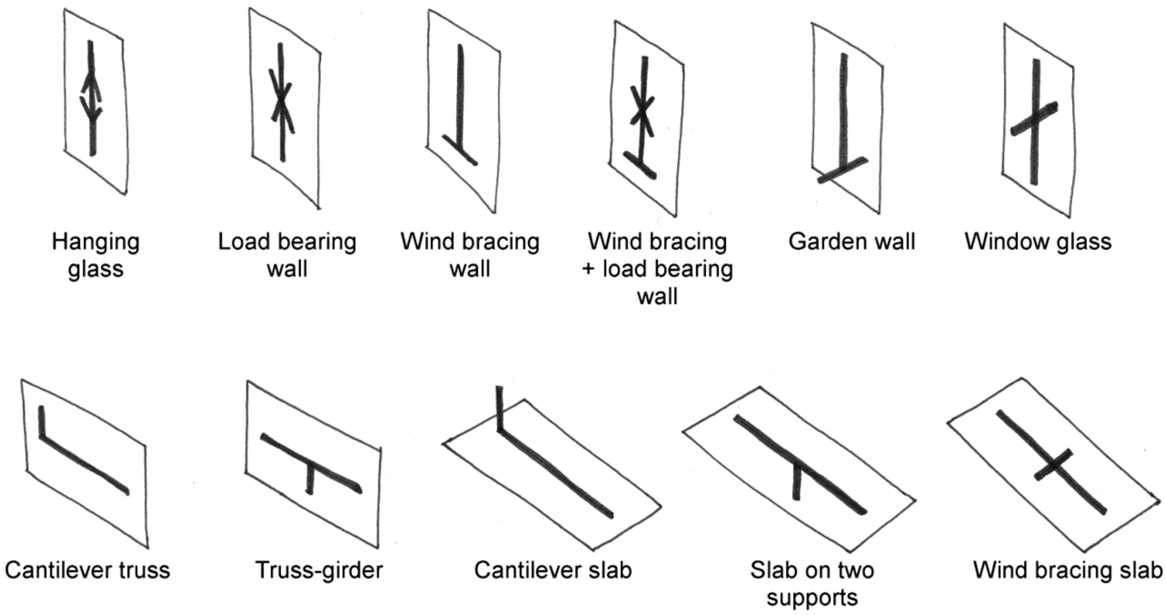


Figure 10-12. Most common characteristics of structural dimensions for a rectangular surface and a single axis, with an example of structural solution.

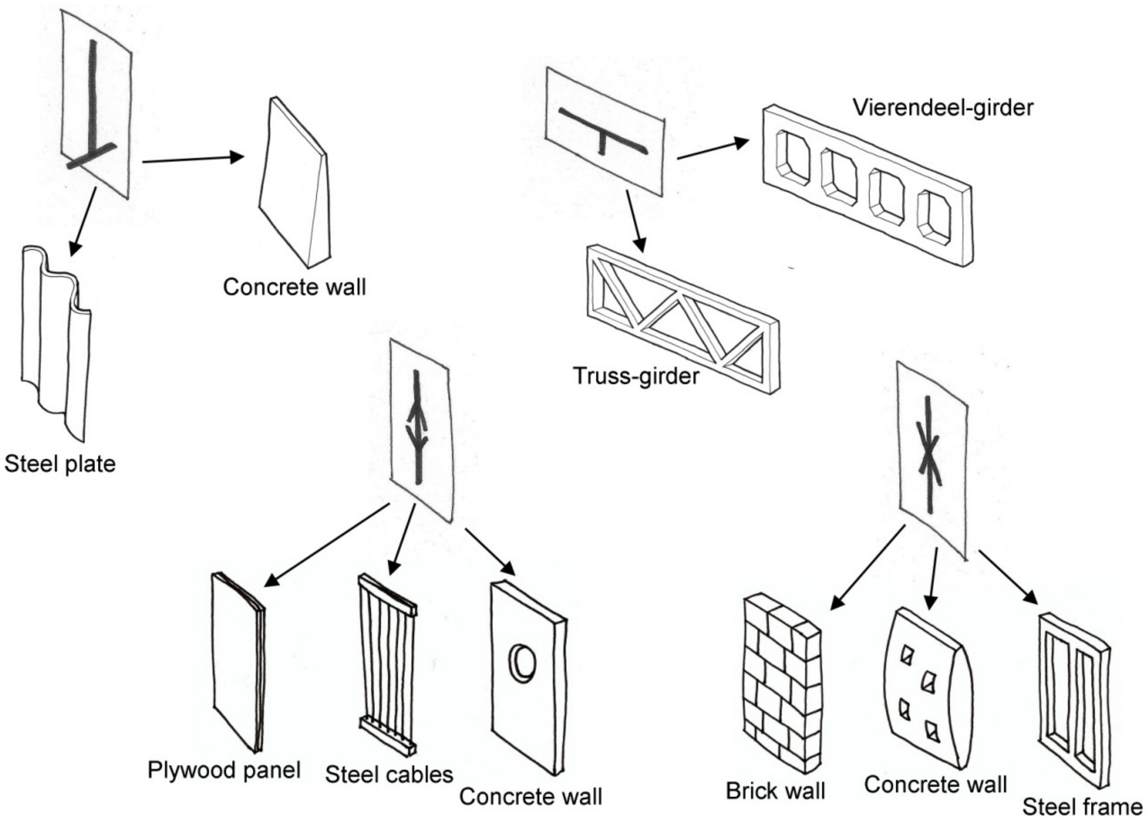


Figure 10-13. Examples of structural design possibilities for a rectangular surface with some common characteristics of structural dimensions.

A language for architects

If the proposed language is to be used in a structurally informed architectural design process, it is vital that architects and architecture students are able to understand the language. Therefore the language is tested to evaluate whether architects and architecture students are able to learn, read and apply this language. These tests include a rough evaluation with a practicing architect on the Tomas project (cf. Chapter 6.3) and a more extensive evaluation with architecture students in Structural Seminar 2010 and Research Seminars 2010 and 2011 (cf. Chapter 8).

These evaluations show that both architects and architecture students find it easy to learn the language. Little knowledge of engineering science is required to become familiar with the language as it relies mainly on an understanding of structural order and a rough comprehension of structural dimensions due to a specific transfer of load. Both understandings are closely related to architectural knowledge. This close relationship might also account for the ease with which students are able to actively apply this language to communicate structural behaviour, and to understand structural behaviour when reading a story written in this language.

Students express their appreciation for having structures explained to them in this language (preferring it to the established traditional engineering language), and even for using the language to explain structures themselves. When they design their own structures, some students voluntarily apply this language during their design and find support in this more conceptual approach of structural understanding.

They appreciate the visual character of the language, the limited number of symbols, and the applied design for the symbols that provides for an intuitive understanding. They also warn of the risk of overloading a drawing with symbols, as this can render it unintelligible.

About half of the students questioned go through the story of structural order first and then focus on the characteristics of structural dimensions when reading or writing a structural story. The other half do not follow this procedure.

A language for collaboration

This language is applied during structurally informed architectural design processes in design workshops with one architect (i.e. in the Tomas project, Chapter 6.3) and with several architecture students (i.e. Research Seminar 2010, Chapter 8.2). These experiences show that the language is well suited to expressing a structural engineer's conceptual design propositions during these workshops in a quick and easy manner. In turn, this language of symbols enables architects and architecture students to discern a wide variety of structural design possibilities in these conceptual design drawings. This language also facilitates a design collaboration that remains on a conceptual level, allowing the team to delay design decisions while the designers inform each other of their own design process. It focuses the collaboration on the major implications for space and form of the engineer's early design choices before any calculations or further design refinements are made.

Because this language provides (information rich) drawings, architects and students are able to consult the structural information in a presentation even after the face-to-face meeting is finished, and extract new information from them.

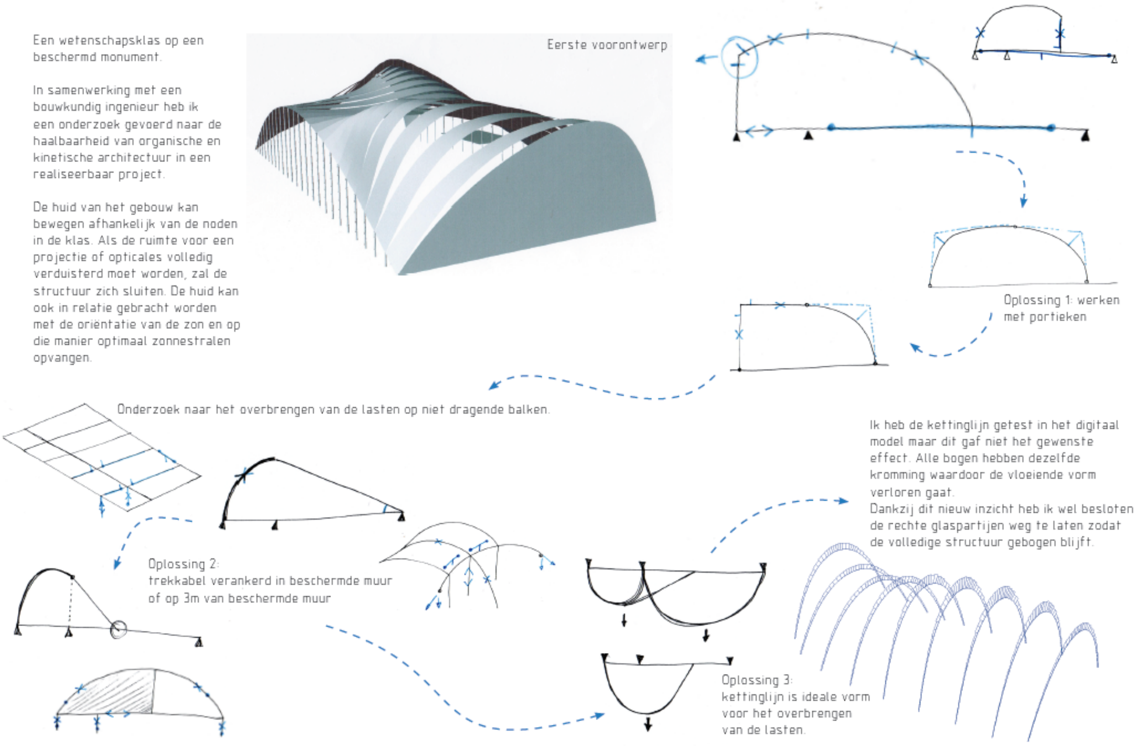


Figure 10-14. Language use in a design workshop (Research Seminar 2010). (Initial architectural shape and different conceptual designs of structures)

This language mainly suits the first phase of the design process. A more precise and detailed language of matter and dimensions is required when the design becomes less conceptual and more concrete (cf. Project Jo & Karolien, Chapter 6.2, and Research Seminar 2010, Chapter 8.2). As such, this new language can be seen as an important addition to established engineering languages that already provide for a more detailed account of structures.

Even though architects and students express a strong appreciation for this new language, their responses could still be positively biased for various reasons (such as the Hawthorne effect (Wikipedia contributors 2012b)). However, the design results of the various design collaborations studied show that a structurally informed architectural design took place. Because communication occurred mainly through the use of this language, these results show that appropriate and sufficient information of the structural design process is exchanged with this language to provide for a structurally informed design collaboration. The results also show that the symbols used to express structural order and dimensions bring to the fore enough essential information about structural behaviour for architects to understand a conceptual proposition in its wide range of structural design possibilities.

A language for structural design

Although this language has been developed to be used primarily in an informed collaboration process between architects and structural engineers, it can also provide an advantage in pure structural design. This new language makes it possible to express a conceptual structural proposition in one comprehensive three-dimensional drawing. This allows an engineer to create proposition drawings in order to, as Lawson writes (Lawson 2004, pp.45–49), stand back and 'have a conversation' with his or her own conceptual design. (Common current engineering language does not allow us to make the kind of rich drawings that bring to the fore the essential characteristics of the structural behaviour of a conceptual design). What is more, because these rich drawings are three-dimensional, they facilitate a three-dimensional investigation of structural design in which the third dimension might reveal more creative design possibilities than would an investigation relying on two-dimensional drawings.

The proposed language not only enables a more conceptual communication, it also takes a stance in how to experience and understand structural phenomena (cf. cognitive linguistics in Chapter 2.5). This new language has the power to train structural engineers in designing concepts by providing a vocabulary for designing conceptual design phenomena without having to go into detailed structural analysis or using structural typologies (i.e. beams, columns, ties, struts, trusses and so on). The ability to produce such descriptions based on a fundamental understanding of structural logic leads to the creation of design knowledge that can provide more conceptual building blocks of design to be used in developing structural concepts and conceptual designs. (It can even lead to the development of structural prototypes as starting points of design.) Where an engineer is currently poorly equipped to describe structural concepts, this new language can turn him or her into not only an eloquent describer, but also an adept creator of design concepts.

As this language articulates the designer's choices of load paths (i.e. structural order) and the orientations and required structural functions of each element (i.e. through symbols of structural dimensions), it brings to our attention the possibility of altering these choices and thus developing alternative conceptual designs (cf. project Tomas, chapter 7.9). This can lead to a design technique in which a symbol is consecutively attributed to different elements to explore conceptual design possibilities. (Lasseau identifies the use of such topological transformations in a scheme as part of a creative design process (Laseau 2001, p.118). This topological transformation can also be applied to the form model itself and lead to creative designs of transformed form models.)

The conceptual nature of this language and such an explorative application enable an engineer to design in breadth first without having to go into (time- and effort-consuming) details and calculations. Later in the design process, each conceptual element can be further refined, going from more articulated conceptual elements through structural typologies to materialized form, until a final design solution is reached (Figure 10-9).

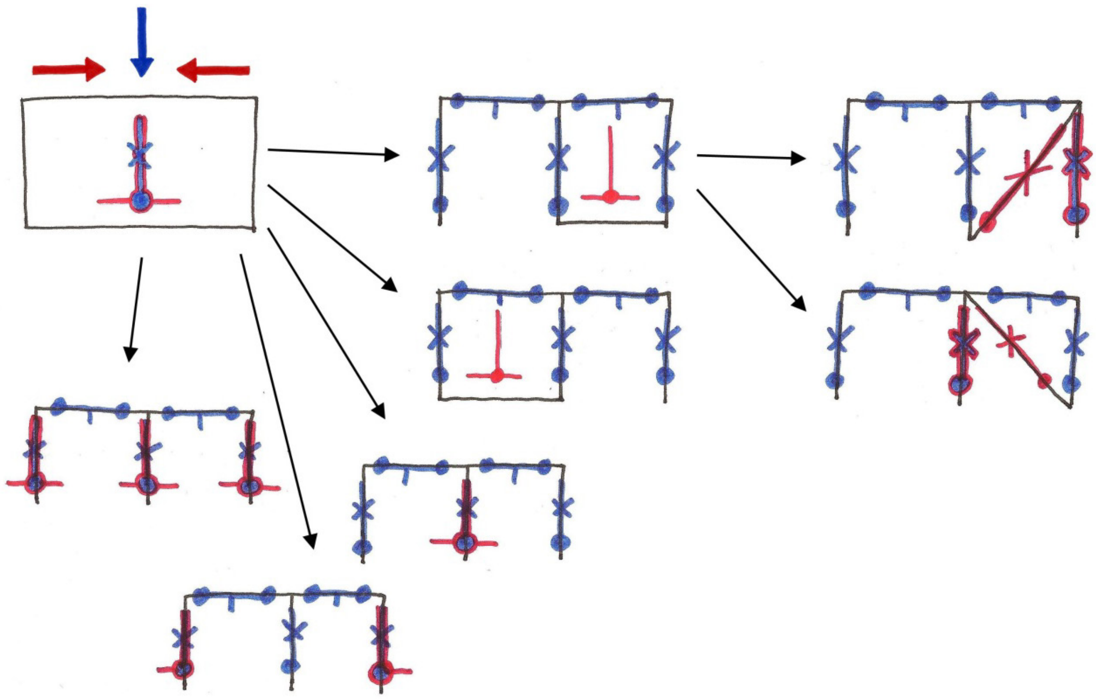


Figure 10-15. Example of element refinement with an exploration of design possibilities through a topological attribution of symbols.

A language for structural education

This language can also play an important part in structural education, as it requires a minimum of required engineering knowledge to explain how a structure functions. In the new language, the traditional diagrams of deformation, internal forces and stresses that engineers normally use to express structural function and behaviour are reduced to a few symbols that mainly express the essence of a structure's logic. The engineering storytelling of structural understanding is filtered to a narrative of structural order and structural dimensions. Most students seem to relate easily to structural order as an understanding of the structural logic of transferring loads to the supports, while the characteristics of structural dimensions appeal to a tactile, experiential understanding of structures.

As the symbols of this language are intuitively understandable, students indicate that they comprehend a structural story more easily through this proposed language then through an array of rather abstract diagrams of engineering terms like bending moments, shear forces and normal forces (cf. Chapter 8).

With the aid of the proposed language, structural education can follow the same process as design, which goes from conceptual principles to more detailed solutions. Starting from an understanding of basic structural concepts, which are closely related to structural prototypes, a wide range of structural design possibilities can be presented through a process of refinement. This is a designerly way of organizing structural knowledge, more adapted for designers than the way currently provided by the engineering sciences. This designerly organization focuses on understanding the basic structural principles before going into details and calculations, whereas in engineering science, a structural understanding is developed through a synthesis of various analyses in detail using precise structural calculations. The latter requires a profound analytical study before a structural understanding of the whole can be achieved, while the former starts from a general structural understanding of the whole before going into a more profound understanding of the details.

The more theoretical component of structural education can be linked with built reality through the use of the catalogue described earlier. Here students can find examples of various structural solutions for a conceptual element with specific characteristics of structural dimensions.

Because the proposed language has been developed for three-dimensional sketches, it can easily be applied to images of projects to explain their structural behaviour. And because the symbols of this language are easily drawn by hand, they are easy to use on blackboards when explaining structures in theory classes.

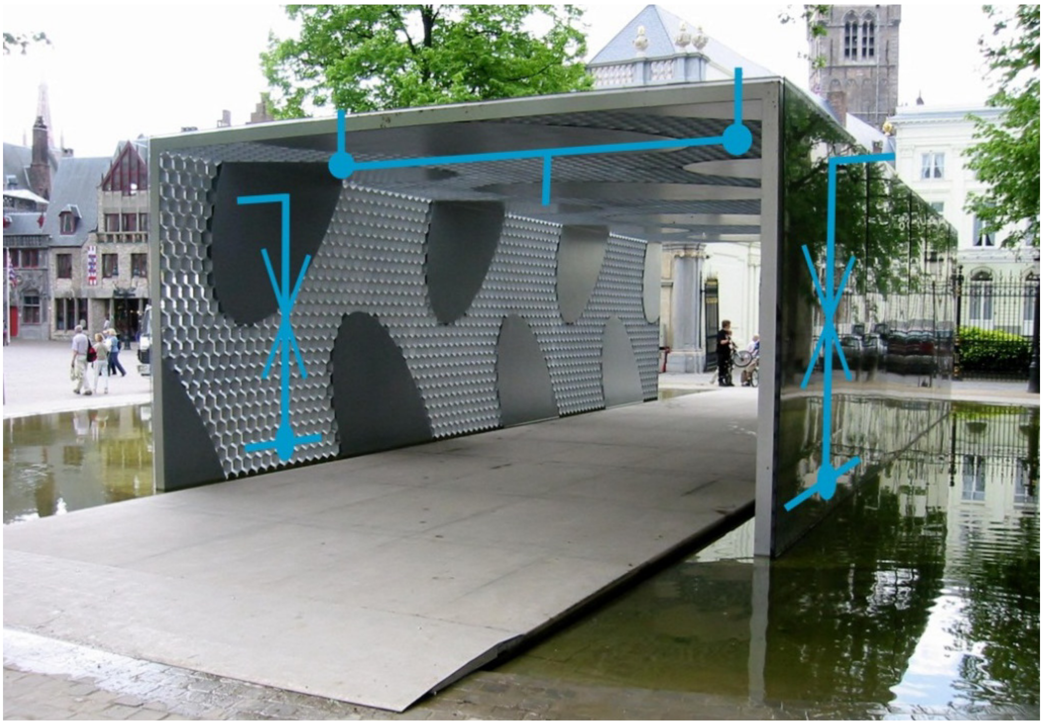


Figure 10-16. Example 1: image loaded with filtered structural information.

Figure 10-17. Example 2: image loaded with filtered structural information.

This proposed language is to be seen as an addition to the existing engineering languages and not as a replacement. It provides for a more adapted approach to structural knowledge for designers. It is my experience that from the perspective of structural education, different types of students can be identified: for example, some prefer an analytical approach in education, others a more holistic one. It is my opinion that teaching structural understanding should be multi-layered and provide for several types of pedagogical approaches. This language allows a different approach to reveal and explore structural knowledge. Some students might benefit greatly from this approach, others less so.

11. Future research

A particular characteristic of this thesis is the applied research approach as a combination of participatory action research and case study research. The various cases investigated here are derived from my practice as a structural engineer and teacher. In each case I am involved as a participating actor, which enables me to gather information from within the action, revealing more personal and interpersonal dynamics than an outside observer would. A downside to this approach is its more subjective information retrieval, which results from my biased role as an observer who is part of the investigated action. This personal character of the findings is countered by tests, inquiries of end users, and objective argumentations in order to contribute to a disciplinary knowledge production. Nevertheless, a number of relevant research projects can be undertaken to investigate which qualities of the presented findings are retained when I am not part of the action. For example, do other structural engineers experience a benefit in using the proposed language for an informed collaboration early in the design process? And do architects also profit by using this language when they are collaborating with an engineer other than myself?

Other interesting research, in my view, lies in further developing the volumetric language as a communicator of structural logic. In this language, structural form is a result of material optimization, and it expresses a different kind of structural understanding that relates to a more tactile reading of structures. Such a volumetric language gives three-dimensional form to a structural proposition, which then operates in an architectural realm. As the Jo and Karolien project shows (cf. Chapter 6.2), this more architectural expression of structural understanding can ignite interesting design inspiration for architects.

As I have experienced during a variety of design collaborations, using this more abstract language compels me to explore more structural concepts in breadth than I normally would. And the rich three-dimensional drawings this language provides inspire me to be creative with the whole of the design instead of just (planar) parts of it. This language enables me to rapidly explore different conceptual designs because it does not require me to go into details or calculations to investigate a proposition and put it on paper. Further research should establish whether this advantage of applying the language in structural design is also experienced by other structural designers.

A catalogue of built examples for various conceptual elements with specific characteristics of structural dimensions is being developed at Sint-Lucas

School of architecture. This catalogue expresses the wide variety of structural possibilities in architectural design that a conceptual element can represent. A next step is to investigate how an informed collaboration between an architect and a structural engineer can benefit from applying such a catalogue.

It would be interesting to investigate if a structural engineer is able to provide architects with meaningful structural input during their architectural concept creation. The research presented in this thesis investigates an informed collaboration after an architect has more or less developed an architectural concept. Structural input then occurs on the level of conceptual design propositions. Future research might investigate if it is possible for a structural engineer to structurally inform an architect in his or her personal reading of an architectural design question when developing an architectural concept. Or, what kind of meaningful input can a structural engineer deliver when no architectural form is provided and an architectural concept still needs to be designed?

In the various cases investigated here, communication during collaboration occurred mainly through sketching on paper using the proposed language. Software can be developed to produce these sketches in a virtual three-dimensional environment. The various symbols of the language should be easily attributable to different elements of a form model for an investigated load. In a collaboration, these form models could be developed by the architect as part of his or her design proposition and then loaded with structural information. These digital form models are able to contain a lot of structural input without information overload because data layers can be turned on and off, and changing the view on the three-dimensional form model would provide a better reading of the symbols through depth perception. Research can investigate the possibilities and benefits of such software in comparison with paper sketches.

The proposed language expresses the order and function of the various elements that make up a structure. Software can be developed for the language that, using the basic rules of structural stability, allows users to draw structural systems whose structural viability is verified by the software. Such software can also be used to train architects and structural engineers to alter sound structural systems while maintaining the order and functions of their elements, and even to structurally refine those elements. When these conceptual elements are linked to a catalogue of structural possibilities, this software can be used as an architectural design tool to explore structural possibilities, and as a collaboration and communication tool for architects and engineers. Research can explore the possibilities of developing such software and its qualities in different applications.

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Appendix: Structural function within systems thinking

If we consider the layer of structural function in terms of systems thinking, we can describe the 'load reception' as input, 'load transfer' as an internal operating process, and 'load discharge' as output. Presenting this structural function through systems thinking is rather unusual for the field of structural engineering science, but it emphasises the structural function that an element is required to perform. It highlights the structural engineer's role as a designer rather than a calculator: this structural function is what a structural designer requires of an element to perform as part of a designed structural system. The calculated internal forces and dimensioned material form of such an element are merely consequences of this required performance.

Figure A-1. Structural function within systems thinking.

As an example, we can make a scheme for the axial and the parallel transfer of a load force. In both cases presented here, the load is a force that is directed towards the element, and the element discharges this load at its other side (Figure A-2). The output load force is the same (in size and direction) as the input, but it is transferred to another location in the element. This is the structural function the element is required to perform, namely to process the input to the output. The load input is the load as it is applied *to* the element. The load output is the load as it is applied *by* the element (to the support, for example).

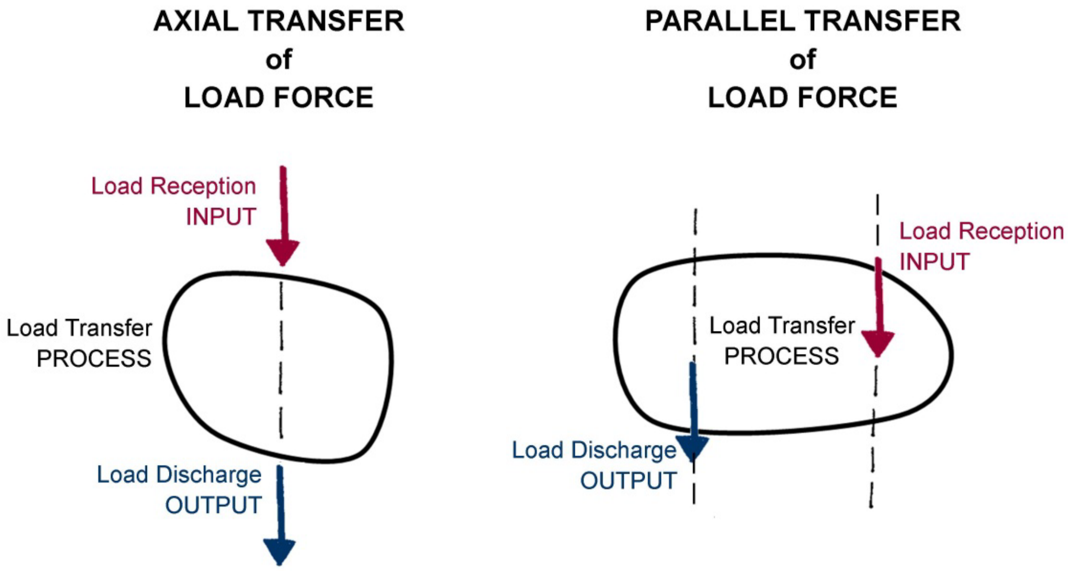

Figure A-2. Axial and parallel transfer of load force as a system.

We can express this systems thinking in symbols provided by the newly proposed structural language as it pertains to the layer of structural dimensions. This layer is closely related to the layer of structural function as described above: it expresses structural function in relation to its implication on material form.

If we apply this systems thinking to an axial transfer of load force for tension and compression, we get schemes as shown in Figure A-3. Here the input for tension in the element is a force away from the element, and for compression in the element a force towards the element. The input force is transferred over its axis to the place of output. This output is the force that the element applies to its surroundings (e.g. support). Input and output are forces with the same size and direction.

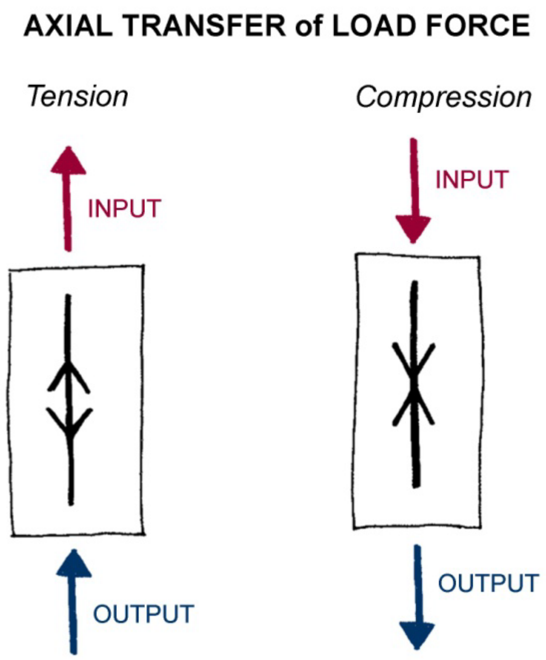

Figure A-3. Axial transfer of load force as a system.

If we apply this systems thinking to the parallel transfer of a load force, we get the scheme of Figure A-4. Here the input is a load force that is applied towards the element and then transferred parallel to its axis to the place of output (i.e. the blue solid-line arrow). This output is the same force in size and direction as the input, and is applied by the element to its surroundings. Because this element needs to be in balance, it will also induce a couple of stabilizing forces applied to its surroundings, shown here at the left (the blue dashed arrows). If the surroundings are unable to hold these stabilizing forces, the element will turn out of balance.

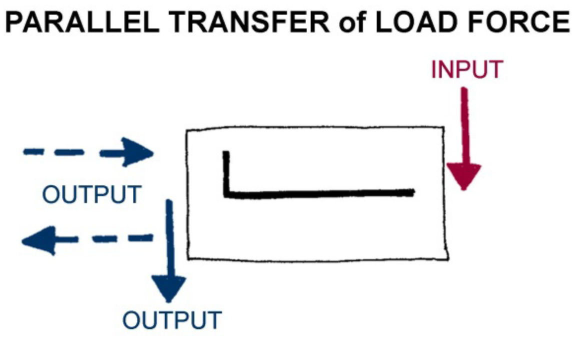

Figure A-4. Parallel transfer of load force as a system.

In this systems thinking, each element with its specific function operates as a linear and reversible process of load. The process is linear as a multiplication of the input results in an equal multiplication of the output. (Because the symbols of structural dimensions make a distinction between tension and compression in an element and thus also between positive and negative bending moments, the input cannot be inverted or multiplied by a negative factor in the presented schemes of structural dimensions. For example, if the input load of the element with axial transfer under tension (Figure A-3, left) is inverted from a load away from the element to one towards the element, the element is put in compression and another symbol of structural dimensions needs to be applied. But when only characteristics of structural function (e.g. axial transfer) are considered in the schemes (e.g. Figure A-2), input can be inverted without problems.)

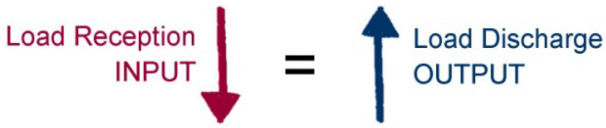

Figure A-5. Converting input to output.

It is a reversible process of load, meaning that input load and output load can be reversed: the input load force can be changed at all times by a reversed output load (Figure A-5). For the axial transfer of load force this is obvious: it only requires turning the schemes upside down (Figure A-3).

We can even apply input forces only and no output forces, as shown in Figure A-6. These are then all the forces that are applied to the element to keep it in balance. It corresponds with the previous schemes of structural dimensions in which the symbols are introduced. These schemes that present all the input forces acting on an element are more conventional in engineering science.

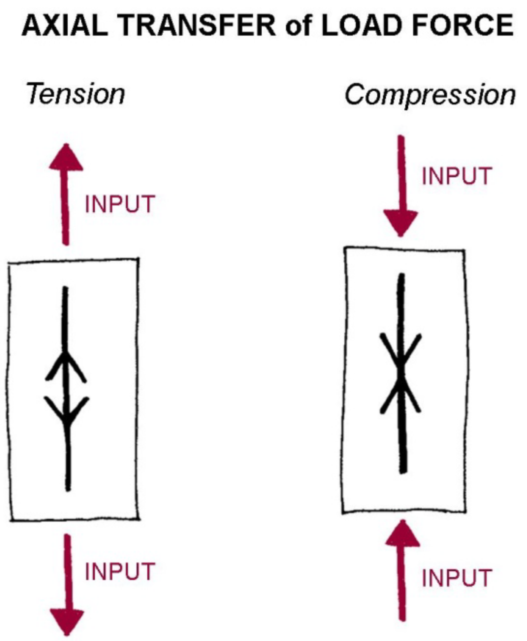

Figure A-6. Axial transfer of load force: converting output to input.

We can also apply only output forces in our scheme (Figure A-7). These are then the forces the element applies to its surroundings.

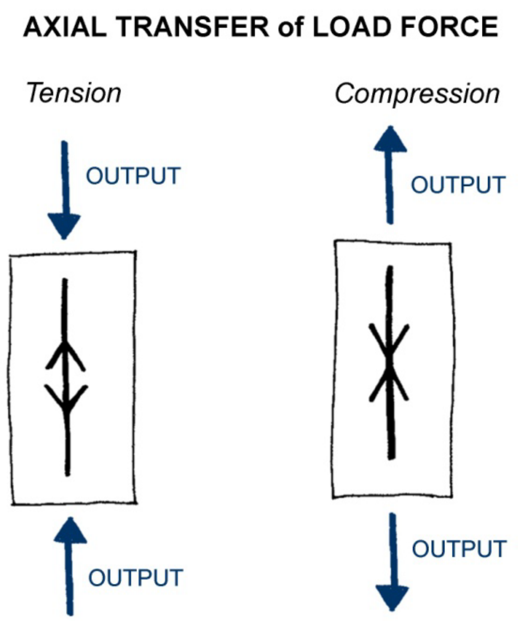

Figure A-7. Axial transfer of load force: converting input to output.

This technique can also be applied to parallel transfer schemes, in which the only input forces are the forces applied to the element and the only output forces are the forces the element applies to its surroundings (Figure A-8).

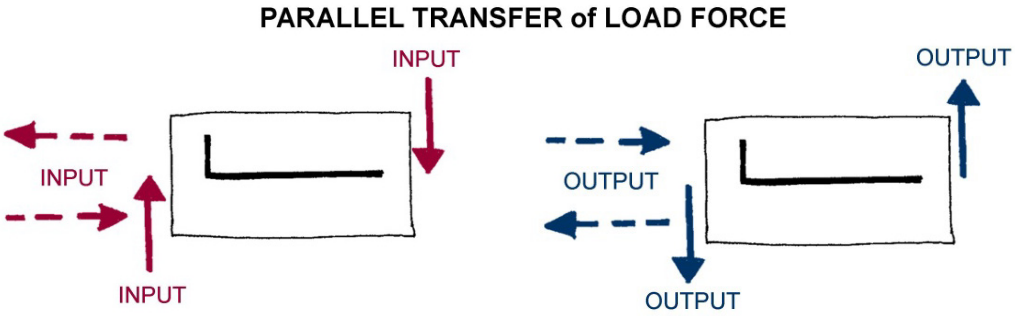

Figure A-8. Parallel transfer of load force. (Only input; only output)

This technique of replacing input forces with output forces and vice versa shows that an element dimensioned to perform a certain function, can also perform different function, but that these functions are related through this theory of systems thinking. In Figure A-9, the input load force is applied to the bottom right of the element and transferred to the upper right. This setting, in which forces are switched between input and output, compared to the above scheme of Figure A-4, leads to the same internal forces for the element to withstand and thus corresponding structural solutions. Both schemes with different functions represent the same range of structural solutions as expressed by the structural dimensions symbol and the conceptual shape of the element.

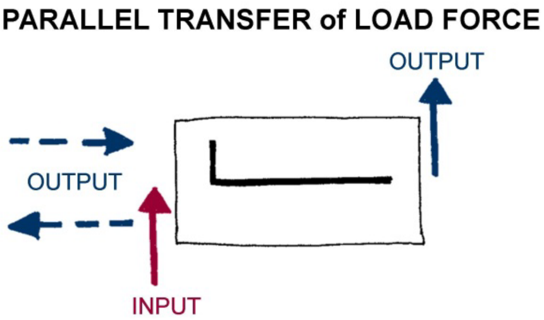

Figure A-9. Parallel transfer of load force: switching input and output load.

Different elements are combined into a structural system when the output of one element becomes the input of the adjacent element, as shown in the cantilever example (Figure A-10). Here a load is applied to the system at one end and transferred to its supports. The structural system consists of two elements, Part 1 and Part 2, where Part 1 works as a cantilever to bring the load force to Support 1. And Part 2 takes care of the couple of stabilizing forces of Part 1 by bringing this stabilizing moment to Supports 1 and 2.

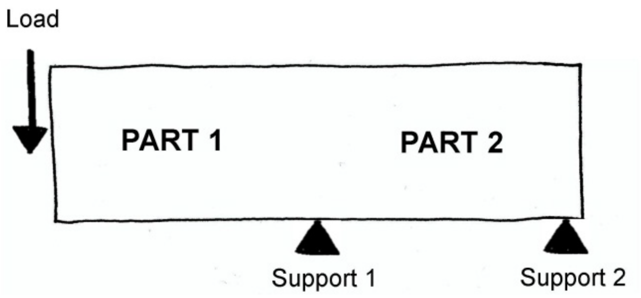

Figure A-10. Structural system as a combination of two structural elements.

We can view this structural system as a combination of two process systems (Figure A-11). The first part of the structural system transfers the input load parallel to its axis as an output load to Support 1. It will induce a bending moment with tension in the upper fibres, leading to a couple of stabilizing forces as an output of the process system. These stabilizing forces, as outputs of Part 1, then become the input of process system Part 2. This input leads to a couple of stabilizing forces as output in Supports 1 and 2. Supports 1 and 2 will have to withstand these output forces of Parts 1 and 2.

Part 1 takes care of transferring the load force to Support 1, while Part 2 only takes care of the stabilizing moment inflicted by Part 2. Both parts have the same (mirrored) structural function, as the symbol implies, but some input and output forces are switched.

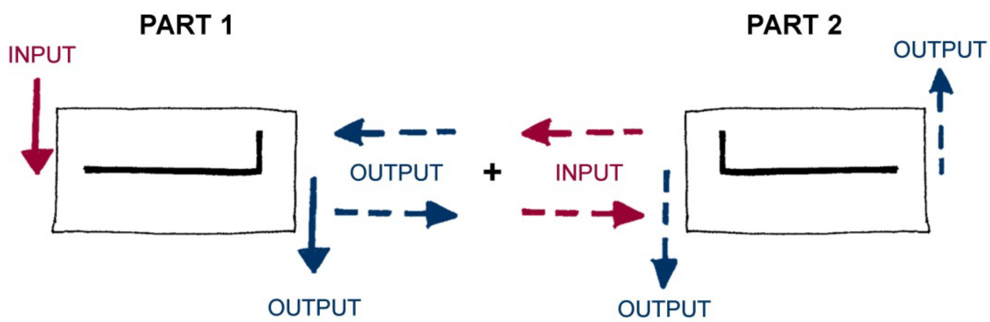

Figure A-11. Structural system decomposed into two structural elements as processes.