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Reinforcement in Tailor-Made Concrete Structures

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Division of Structural Engineering, Concrete Structures

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Cover:
Tailor-made concrete roofing detail, produced in the Danish research project Unikabeton (http://www.unikabeton.dk/). This structure was reinforced with conventional reinforcement, using a traditional approach. Photo: Danish Technological Institute.

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Abstract

In tailor-made concrete structures of complex geometries, the formability of concrete is an asset. To use this formability in load-bearing structures, the concrete needs to be reinforced. During the past century steel bars were used; however, in recent decades, alternative reinforcement methods have been introduced. To survey the applicability of several reinforcement methods, a literature review was made; the key findings are discussed. Despite the advantages of many of the alternative reinforcement materials, it was realised that conventional reinforcement is, in most application, the best alternative in terms of the structural integrity provided. Moreover, a major advantage of conventional reinforcement is that it is regulated in standards and design codes worldwide, which facilitates the application. The inclusion of steel fibres can provide additional structural integrity or, in some applications, replace the conventional reinforcement. As fibres do not require any concrete cover, this can be a solution for thinner sections.

The geometry of tailor-made concrete structures can deviate considerably from the standard structural idealisations, e.g. beams and slabs. Hence, two methods for the design of conventional reinforcement, based on linear finite element analyses using shell elements, were investigated in order to enable a rational design procedure. Both methods, which rely on a sandwich analogy, make it possible to calculate in a rational way the amount of reinforcement needed in unique structures.

To enable the use of steel fibre reinforcement in tailor-made concrete structures, the modelling techniques, including the non-linear behaviour of steel fibre concrete, need to be developed further. This topic was addressed in a study of fibre reinforced concrete beams, which compared experiments, FE analysis, and design according to fib Model Code 2010. Good agreement was shown when load-deflection curves from experiments were compared with FE analysis; however, the design method presented in fib Model Code 2010 underestimated the capacity of these beams. The underestimation increased with increasing fibre contents.

In addition to the investigation, future research is proposed; a rational design method is needed that should include several features not covered in the two methods discussed, e.g., the effect of inclined shear cracking, the choice of optimal reinforcement direction, optimisation for production, and the inclusion of design with steel fibre reinforcement.

Keywords: Tailor-made concrete structures, Geometrically complex structures, Reinforcement alternatives, Steel fibre reinforcement, Automated production.

Armering i skräddarsydda betongkonstruktioner
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Sammanfattning

I skräddarsydda betongkonstruktioner, dvs. betongkonstruktioner anpassade till en oregelbunden geometri, utnyttjas betongens formbarhet. I lastbärande konstruktioner måste dock betongen armeras. Under förra århundradet har armeringsstänger av stål använts. Under de senaste decennierna har flera alternativa armeringsmetoder introducerats, både i litteraturen och praktiken. För att undersöka möjligheterna med dessa metoder har en litteraturstudie utförts och de viktigaste slutsatserna presenteras i denna uppsats. Trots många fördelar med de alternativa materialen är konventionell stålarmering, i många fall, det alternativ som är bäst lämpat med avseende på konstruktionstekniska egenskaper. Ytterligare en stor fördel är att stålarmering finns reglerat i standarder och normer över hela världen, vilket underlättar användandet. I denna studie framkom även att stålfiberarmering kan förbättra de konstruktionstekniska egenskaperna, eller i vissa tillämpningar ersätta vanlig stålarmering. Eftersom stålfiberarmeringen inte kräver täckskikt, kan detta vara en tänkbar lösning i tunna sektioner.

Geometrin hos skräddarsydda betongkonstruktioner avviker i många fall från de vanligen använda konstruktionstekniska förenklingarna såsom balkar eller plattor. Därför behövs de idag använda konstruktionsmetoderna anpassas eller utökas för att uppnå ett rationellt konstruktionsförfarande. Genom att använda linjära finita elementanalyser, med skalelement, är det möjligt att beräkna erforderlig armeringsmängd. Två metoder för detta, vilka båda bygger på en sandwich-analogi, beskrivs i detta arbete.

För att kunna utnyttja stålfiberarmering i skräddarsydda betongkonstruktioner måste modelleringtekniker som också inkluderar materialets icke-linjära beteende utvecklas ytterligare. Detta har behandlats genom en studie av fiberarmerade betongbalkar, där experiment, finita element analyser och beräkningsmetoderna föreslagna i fib Model Code 2010 har jämförts. Last-deformationskurvor från finita element analyser överensstämmer väl med de som erhållits i experiment. Balkarnas kapacitet underskattas dock vid beräkning enligt fib Model Code 2010: ju större fiberinnehåll desto större underskattning

I uppsatsen föreslås även områden för framtida forskning. Det finns ett behov av rationella konstruktionsmetoder. Sådana metoder bör inkludera aspekter som inte är inkluderade i de presenterade beräkningsmetoderna såsom effekt av sneda sprickor, val av optimal armeringsriktning, optimering för produktion och inkluderandet av fiberarmering.

Nyckelord: Skräddarsydda betongkonstruktioner, Betongkonstruktioner med komplex geometri, Armeringsalternativ, Stålfiberbetong, Automatiserad betongproduktion.

"And further, by these, my son, be admonished: of making many books there is no end;
and much study is a weariness of the flesh."
Ecc. 12:12

Preface

The work in this thesis was carried out at the Division of Structural Engineering at Chalmers University of Technology from 2009 to 2011. The major part of the research was funded by the European Community's Seventh Framework Programme under grant agreement NMP2-LA-2009-228663 (TailorCrete). More information on the research project TailorCrete can be found at www.tailorcrete.com. I would like to acknowledge all project partners who made my research, resulting in this thesis, stimulating.

I deeply appreciate and respect my fantastic supervisors, Professor Karin Lundgren, Professor Kent Gylltoft and Assistant Professor Rasmus Rempling, for their endless trust, support and patience. I am also grateful to all of my other colleagues at the Division of Structural Engineering for cheering up the long corridor!

Many thanks go to my friends and family, especially my parents, for always stimulating learning without any pressure. Last, but certainly not least, I thank Ida for bearing with me for ten years! Without her it would not have been possible.

Gothenburg, November, 2011
David Fall

Thesis

The thesis consists of an extended summary and the following appended papers.

Paper A	Reinforcing tailor-made concrete structures: Alternatives and challenges D. Fall, K. Lundgren, R. Rempling and K. Gylltoft. *Submitted to "Engineering Structures".*
Paper B	Steel fibres in reinforced beams: Experiments, model code and FE analyses D. Fall, R. Rempling, A. Jansson, K. Lundgren, and K. Gylltoft. *Submitted to "Journal of Advanced Concrete Technology".*
Paper C	Skräddarsydda betongkonstruktioner D. Fall, K. Lundgren and K. Gylltoft. In Swedish, published in *Bygg & Teknik*, 2010; **7**: 20-22.

The appended papers were prepared in collaboration with the co-authors. In Papers A and C the author of this thesis took the major responsibility for the planning, most of the work and the writing.

In Paper B, the author of this thesis was responsible for writing most parts and all of the modelling. However, the experimental work in this paper was carried out by Anette Jansson and the work in the section "Analysis according to fib" was mainly done and documented by Rasmus Rempling.

Paper C was published in a Swedish popular scientific journal (in Swedish) communicating research results to the building industry. The purpose of this article is to introduce the project to a broader community.

Other publications related to this thesis

In addition to the appended papers, the author of this thesis has also contributed to the following publications:

Fall, D. and Nielsen, C. (2010), Concrete reinforcement solutions, Report 2010:7, Division of Structural Engineering, Department of Civil and Environmental Engineering, Chalmers University of Technology, Gothenburg, Sweden.

Fall, D., Lundgren, K. and Gylltoft, K. (2011), Reinforcement in Tailor-Made Concrete Structures, In: Proceedings of XXI Nordic Concrete Research Symposium, June 2011, Hämeenlinna, Finland

Fall, D., Lundgren, K., Rempling, R. and Gylltoft, K. (2011), Structural Design of Reinforcement in Tailor-Made Concrete Structures, In: Proceedings of the 7th Central European Congress on Concrete Engineering, September 2011, Balatonfüred, Hungary

Contents

1 Introduction

1.1 Background

The possibility of producing concrete structures in unique shapes is one of the most attractive features of this material. However, complex geometries introduce complex and time-demanding formwork, and the result depends on good craftsmanship.

Furthermore, the tensile strength of concrete is low in relation to the compressive strength. To compensate for the low tensile strength, reinforcement is normally integrated in load carrying structures. Traditionally, reinforcement has consisted of steel bars, placed in the formwork prior the casting of concrete. Advances in material technology have made it possible to utilise a wide range of alternatives to the steel bar.

TailorCrete is a research project financed by the European Community's Seventh Framework Programme from 2009 to 2013. The project consists of 11 work packages, each dealing with a specific aspect: e.g. formwork, reinforcement, production and digital fabrication. The common aim is to make possible concrete structures that have complex geometry, i.e. tailor-made concrete structures, by combining innovative reinforcement, digital fabrication and automated production methods. In this way, greater geometric freedom can be achieved, while retaining the economic benefits of large scale automated production. Tailor-made concrete structures could be made more widely available instead of being limited to prestigious projects. The work in this thesis addresses the reinforcement of such structures.

1.2 Aim and scientific approach

This study aims to establish a platform for further research within the field of reinforcement for tailor-made concrete structures. More specifically, the aim is to choose the most suitable reinforcement solutions for concrete structures of complex geometry, based on an evaluation of available reinforcement methods with regard to their applicability to tailor-made concrete structures. Furthermore, these solutions will be investigated by addressing opportunities and problems associated with the complex geometry. Such problems could be related to the production method, the design process, standards and codes. Finally, gaps in knowledge, to which future research should give attention, are identified.

To realise the aims stated, the work was initiated with a thorough literature review of alternative reinforcement types, focusing on the criteria given in Section 2.1. It was then decided to concentrate mainly on conventional steel reinforcement and steel fibre reinforcement.

The main problems to be addressed were the design of complex concrete structures reinforced with conventional reinforcement and the modelling of steel fibre reinforced concrete. This approach was chosen to facilitate the development of a rational design method incorporating both reinforcement types in future research.

1.3 Scope and limitations

Research conducted at Chalmers University of Technology on the reinforcement of tailor-made concrete structures is the subject of this thesis. The main idea of the research project TailorCrete as a whole is provided simply as a background to facilitate contextual understanding for the research.

An overview of the available reinforcement methods, documented by the research community, is given and discussed. The discussion and evaluation of these methods concentrates on applications for buildings, although the concept could be applied to any structure.

Following the evaluation, the work is limited to the chosen reinforcement types, i.e. conventional reinforcement and steel fibre reinforcement. Moreover, the work on the modelling of steel fibre reinforcement was limited to beams.

2 Reinforcement in tailor-made concrete structures

During the past century steel bars have been used to provide concrete structures with tensile strength and ductility where the concrete itself was not sufficient. In the past 25 years several alternatives have been developed. In this chapter reinforcement alternatives are reviewed in the context of tailor-made concrete structures. A more detailed description of the described reinforcement methods can be found in Fall and Nielsen (2010).

2.1 Evaluation criteria

The properties that are considered in the evaluation of current reinforcement solutions are described in this section.

Production aspects: The keystone in the TailorCrete project is the aim to produce unique concrete structures with greater flexibility by using robotics and unconventional formwork. This radically affects the choice and design of the reinforcement. When evaluating the reinforcement solution, it is important to consider whether it can be produced in arbitrary shapes or not. Furthermore, an evaluation has to be made to determine whether the complete reinforcement solution can be produced without any manual operations.

Mechanical properties: Mechanical properties, such as tensile strength, composite toughness and composite flexural behaviour, have to be taken into account while evaluating reinforcement solutions. The tensile strength is relatively weak in the concrete itself, thus it is important that the reinforcement provide the composite with a sufficient amount. Furthermore, the composite toughness governs, to a large extent, the post-cracking behaviour. The stiffness of the composite and the bond between the reinforcing material and the concrete, will also affect the mechanical behaviour. In addition to the analytical parameters above, it is important to evaluate whether the reinforcement solution increases the load carrying capacity of the structure or simply controls the post cracking behaviour. Whether or not the reinforcement method can be used alone, or if any type of primary reinforcement is needed, also has to be assessed.

Durability: For a structural member to fulfil its expected service life, it is vital to consider two properties, namely deterioration and fatigue resistance. The resistance to deterioration depends not only on the environment it will be exposed to but also on the composition of the concrete. Fatigue resistance is not evaluated here, as fatigue problems occur mainly in structures subjected to cyclic loading, e.g. bridges, and not in buildings.

Economic properties: It would be desirable if the reinforcement solution, when widely adopted, could be produced in an economically efficient way.

Environmental properties: It should be taken into account whether the reinforcement is produced from recycled materials. The conditions regarding the energy and carbon footprint embodied in the production of reinforcement are significant aspects of the environmental evaluation.

Regulations, standards and design rules: Design rules and building legislation govern the concrete solutions now being implemented. Therefore, one must consider whether new solutions are applicable or if they require new regulations.

Quality control: The ease of quality control is not the same for all reinforcement solutions. When structural reinforcement is considered, the various aspects of quality control should be taken into account.

2.2 Reinforcement alternatives

2.2.1 Conventional reinforcing steel

Conventional reinforcing steel can be applied either as bars, nets or rolled mats usually placed on spacers in the mould before casting. During the preparations, the steel can be formed by bending within specific limits of the radius. Reinforcement modules (e.g. cages) can be prefabricated off-site in a variety of industrial production processes. However, installing the reinforcement in the formwork is time consuming in terms of labour. During extensive research and practical use of reinforcing steel, it has become evident that durability is an issue. To cope with these problems certain requirements must be fulfilled when designing steel reinforced concrete structures, e.g. a minimum concrete cover which could restrict the geometrical freedom desired in tailor-made concrete structures.

Bjerking (1970) states that during a normal construction procedure the reinforcement bars are easily damaged in such a way that they will be dislocated from the position intended by the designing engineer. Such damage may either occur because personnel normally have to walk on the reinforcement, in order to ensure a good distribution of the fresh concrete, or due to the weight of the fresh concrete. This could cause a change of the structural capacity or a reduction in durability if the concrete cover is reduced. Furthermore, it is important that reinforcement bars are assembled with sufficient strength, by wires or welding, in order to prevent the dislocations described above.

In addition to reinforcements, steel can be utilised for prestressing for which the steel is tensioned either before (pretensioned) or after (post-tensioned) casting. The tensioned steel provides a compression stress in the concrete, which counteracts the tension stress induced by loading.

2.2.2 Fibre reinforced concrete, FRC

In recent years, the use of fibre reinforced concrete (FRC) has increased rapidly. By dispersing discontinuous fibres, of variable size and material, into the concrete mix, ductile structural members can be produced in a very labour effective manner. Here we shall consider short fibres mixed into concrete so that they constitute a randomly orientated reinforcement system. Independently of fibre material, the fibres can be produced in a great variety of shaped and lengths.

Although the first crack stress of a composite would not generally increase significantly, the post cracking behaviour is affected in a beneficial manner. Therefore, the fibre reinforcement is most commonly used as secondary reinforcement, i.e. a primary reinforcement system, providing the main structural integrity is needed. However, in some applications it has been used as the primary reinforcement with good results, as reported by Oslejs (2008). Further research is needed to extend such use of fibre reinforcement further.

Fibres can be classified according to size. Löfgren (2005) describes an approach whereby the fibres are classified as macro-fibres if they are longer than the maximum aggregate size of the concrete, their diameter is much greater than the cement grain size, and the aspect ratio (length to diameter ratio) is less than 100. Fibres with a cross-section diameter of the same order as the cement grains and a length less than the maximum aggregate size are classified as micro-fibres. Basically, macro-fibres increase the composite toughness by bridging macro-cracks, while micro-fibres increase resistance to micro-cracking prior the formation of macrocracks.

Regardless of the fibre material, the ability to control the fibre content throughout a structural member would be a breakthrough in this technology. Today, short discontinuous fibres are generally evenly distributed in all parts of a member, i.e. the fibre density is determined by the maximum tensile stress in the member. This could be optimised by using a digitally guided application of concrete with the addition of fibres in a nozzle, in combination with an FE model of the member's stress distribution, Tepfers (2008).

Reinforcing fibres can be made of steel, glass, various synthetic materials (such as coal or polymer) or organic materials.

- Steel fibres can be used as primary reinforcement, in some applications, and have good resistance to corrosion. Bentur and Mindess (2007) review several investigations of the durability of steel fibre reinforcement (SFRC). The results of these studies show generally that SFRC does not suffer degradation due to corrosion. This improvement of the corrosion resistance, compared with conventional steel reinforcement bars, is most likely due to a lower tendency to crack and the lack of electrical conductivity (short and discontinuous fibres). Furthermore, spalling of concrete, caused by rust, is avoided as the small diameter of the fibres generates only a small amount of corrosion product. Although the corrosion of steel fibre has a limited effect on structural properties, as reported by Granju and Balouch (2005), corrosion spots on the surface might affect aesthetics. Moreover, in some countries, including Sweden, the use of steel fibre reinforcement in combination with conventional steel reinforcement is restricted for some applications, due to uncertainties about whether the steel fibres will influence corrosion of the traditional reinforcement.

- Glass fibres are most commonly used in thin, nonstructural, concrete elements, e.g. façade elements. The tensile strength of glass fibres is very high; however, it is heavily influenced by deterioration. According to Bentur and Mindess (2007), the strength of a fully aged glass fibre reinforced concrete is reduced to 40% of the initial strength, while the strain capacity is reduced to about 20% of the initial capacity, if exposed to an outdoor environment. The two main mechanisms of this deterioration are chemical attack and the formation of hydration products (mainly calcium hydroxide) between the filaments; these mechanisms lead to a reduction of strength and embrittlement, respectively. The use of alkali resistant glass (AR glass) limits the effect of chemical attack but does not prevent it fully. In American Concrete Institute Committee 544 (2002) and Marikunte *et al.* (1997), it is suggested that such effects could be reduced by the addition of polymer solids or pozzolan metakaolin into the concrete mix.
- Synthetic fibres can be produced from several materials with widely differing properties, e.g. polyethylene (PE), prolypropylene (PP), acrylics (PAN), polyvinyl acetate (PVA), polyamides (PA), aramid (Kevlar), polyester (PES) or carbon. According to American Concrete Institute Committee 544 (2002), the currently widest use of synthetic fibres is in flat slab applications, where the main purpose is to control bleeding and plastic shrinkage. For such applications fibres with a relatively low modulus, such as polypropylene and polyethylene, are used and the fibre volume content would typically be only about 0.1% by volume. Fibres added for the purpose of controlling plastic cracking are normally designated micro fibres, with a diameter around 40 to 100 μm. Smaller diameters yield better performance according to Naaman *et al.* (2005).
- Natural fibres are interesting mainly due to their low cost. Wood fibres from bamboo or sugar cane can be used as well as other natural fibres such as jute, sisal or coconut fibres (coir). As the organic fibres in their natural form, contrary to many synthetic fibres, are hygroscopic, the properties of the fibres are affected more by changes in moisture content than fibres of any other material, which can cause swelling, shrinkage and rot. Depending on the fibre material, exposure to alkali environments causes varying amounts of strength degradation, ranging from 16% of the initial tensile strength (sisal) up to 50% (coir), according to Ramakrishna and Sundararajan (2005).

2.2.3 Fibre reinforced polymer, FRP

In the past decade, the use of fibre reinforced polymer, FRP, has increased. By incorporating continuous fibres of aramid, carbon or glass in a polymer matrix, a reinforcing composite with unique properties can be obtained. According to Dejke (2001), the properties depend on fibre type and matrix material, but generally the composite has a lower weight, lower modulus of elasticity and higher strength than steel. The low modulus of elasticity often makes requirements in the serviceability limit state decisive, according to Svenska Betongföreningen (2002). In Benmokrane *et al.* (1995) polyester, epoxy and vinyl ester are given as examples of matrix materials.

The FRPs, in contrast to steel, do not corrode; however other degradation mechanisms could still limit the durability. Dejke (2001) mentions that a concrete pore solution might initiate deterioration. Furthermore, he also lists sea salt, de-icing salt, freeze-thaw cycles, UV light and fresh water as potential durability threats.

Dejke (2001) and Svenska Betongföreningen (2002) state that, for FRP composites with glass or carbon fibres, equal or less creep and relaxation than "low relaxation steel" have been reported. Aramid fibre composites have shown significant creep and relaxation (eg. creep of 7% after 50 years of 40% short-term strength loading).

In general FRP exhibits brittle fractures because the modulus of elasticity, according to Karlsson (1998), is approximately constant until fracture. The ultimate strain varies between 0.5 and 2% for carbon fibres, and between 2 and 4% for glass or aramid fibres. A more ductile behaviour could be obtained by combining some of these fibre materials within a composite; however the ductility is not equivalent to that of steel.

Stress corrosion can be described as a process which is the combined effect of long term stress and chemical attack. During continuous loading, micro cracks develop in the polymer matrix, which allows aggressive chemical substances to attack the fibres within the composite, ultimately leading to failure of the fibre. According to Svenska Betongföreningen (2002), glass fibre composites are the most sensitive to stress corrosion; hence, long-term loading should not exceed 25% of the short term capacity. Although, aramid fibres are more resistant to this process, stress corrosion might still occur but is preceded by large creep deformations. Carbon fibres are not prone to fail due to stress corrosion.

At elevated temperatures, different behaviours have been observed for the fibre materials. Dejke (2001) reports that glass and carbon fibres retain most of their tensile strength, while aramid fibres will have lost approximately 75% of their strength at 250°C compared with 60°C.

Fibre reinforced polymer can compete steel mainly in applications where the steel risks corrosion to a higher extent than normal. In such applications the FRP can be utilised in several product types, such as bars, cables, wraps, profiles or plates. They can be cast in the concrete or used as permanent formwork.

The FRP reinforcement bars are, according to Bakis *et al.* (2002), typically produced through pultrusion or the closely connected production method of pull-forming. Simply described the continuous fibres are impregnated with the matrix polymer and then pulled through a forming die. The FRP bar can then be bent or cut. Once the polymer material is hardened, the bar cannot be formed. The bonding between the bar and the surrounding concrete can be improved by moulding ribs in the bar, by winding one or more fibre tows around it, or by bonding a fine grained aggregate (eg. sand) on to the surface of the bar.

2.2.4 Textile reinforcement, TRC

Textile reinforced concrete (TRC) utilises multi-axial fabrics (e.g. nets or mats) in order to improve composite tensile strength and ductility. These technical textiles provide a more efficient reinforcement solution than short randomly distributed fibres; however, they are somewhat more complex to produce and install. Textile reinforcement is also a common solution for the reinforcement of plastering mortar, for example in external thermal insulation of composite façade solutions.

Typical materials used in TRC are fibres of AR glass, carbon or aramid, however thin steel wire or polymer fibres could also be used. Although fabrics can be composed in numerous ways, not all of these are suitable for use in concrete applications. Important fabric properties are displacement stability during application and a sufficiently open textile structure. Keeping these properties in mind, Brameshuber (2006) states that warp knitting with insertion of reinforcing threads is better suited as concrete reinforcement than braiding.

The technical textiles can be produced in such way that several thread systems are incorporated with different orientations in order to obtain higher strengths in multiple directions.

Special machinery (a double needle bar Raschel machine) can produce two fabrics simultaneously and link them together to form a spacer warp knit. The spacing between the fabrics can normally be between 15 and 100 mm and be varied during the production to form irregular shapes. Furthermore, the fabrics can be produced independently, i.e. different materials, mesh patterns and weft thread densities can be used.

The least complex production method of textile composites is hand-lay up. Briefly, the inside of a mould is covered by the textile prior to casting. The production method is widely used in other industries, for example in manufacturing boat hulls, wind-turbine blades or aircraft wings. The main benefit of this method in concrete applications is that a fairly high fibre volume can be obtained. One of the disadvantages is the quite labour intensive production, which requires some skill to keep the quality of the product within reasonable bounds. For fabric-cement laminate composites, the composite can be produced by pultrusion. The textile is first passed through a slurry infiltration chamber, then rolled between two rollers to press the slurry into the textile while forming the composite and removing excessive concrete. When using pultrusion the workability of the concrete-mix is crucial. It has to be fluid enough for the textile to pass through, but still dense enough to ensure that the concrete will remain on the textile. Extrusion techniques could be used to produce fabric-cement composites. The basic principle of extrusion is that the concrete is injected or compressed under pressure into a closed mould. These techniques were developed for short fibres, but they could also be applied to textile reinforcement by placing the fabric inside the mould before casting.

2.2.5 Summary and choice of reinforcement alternatives

The most distinctive properties of four reinforcement systems are presented in Table 2.1. For an evaluation of the fibre materials described see Table 2.2.

Table 2.1: Summary of the advantages and disadvantages of four reinforcement systems.

	Advantages	Disadvantages
Conventional reinforcement steel	Provides structural integrity. Widely used,i.e. easy to implement with regard to guidelines and design codes. Inexpensive.	Might be difficult to produce effectively in arbitrary geometries. Specific concrete cover needed, i.e. not suitable for very thin structures.
Fibre reinforcement	Can be added to concrete during mixing.	Rarely used as primary reinforcement.
Fibre reinforced polymer	Good durability. Can be used in thin concrete members.	Rare technology which can lead to high costs. Fixed shape once produced.
Textile reinforcement	Can be applied in arbitrary geometries.	Rare technology which can lead to high costs. Production method needs development.

Table 2.2: Summary of advantages and disadvantages with five different fibre materials.

	Advantages	Disadvantages
Steel fibre reinforcement	Good mechanical behaviour. Very well developed. Inexpensive.	Authorities in some countries (e.g. Sweden) do not allow combination with conventional steel reinforcement. Possible corrosion spotting on surfaces.
Glass fibre reinforcement	High strength.	Strength decreases with time. Sensitive to alkali attack.
Polymer fibre reinforcement	Non-corrosive.	Creep. Elevated temperature can cause problems. Low Young's modulus.
Carbon fibre reinforcement	Alkali resistant. Dimensionally stable. High strength.	Hard to obtain a good distribution in concrete mix
Natural fibre reinforcement	Available in the developing world.	Hard to ensure fibre quality. Hygroscopic. Complex to assess durability.

This study shows that conventional steel reinforcement cannot easily be set aside when designing load carrying concrete structures, as none of the other reinforcement types discussed can provide such integrity in all applications. Furthermore, including conventional reinforcement also increases the applicability of the new construction concept, devised by TailorCrete, as it is well-known and regulated in standards worldwide. However, alternative reinforcement techniques, e.g. steel fibre reinforcement, can be included to contribute additional structural integrity in terms of ductility. As previously mentioned, the production method is important to keep in mind when considering reinforcement for tailor-made concrete structures. Recent advances in automation indicate that both bending and fastening of conventional reinforcement will become possible in near future, see Cortsen *et al.* (2012).

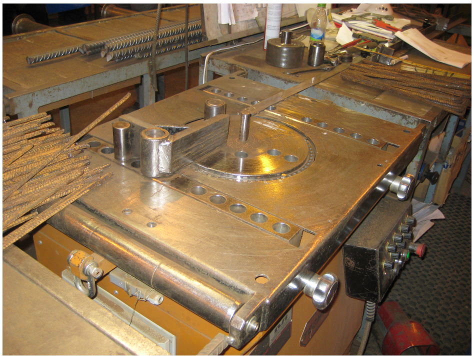
Based on the evaluation of reinforcement alternatives, it was decided to continue to develop a reinforcement solution for load-bearing tailor-made concrete structures by utilizing both conventional reinforcement and steel fibre reinforcement, separately or in combination. Textile reinforcement might be interesting; however, limitations are set by the flexibility of the textile. It may, simply put, be impossible for robots to handle such material. In structural applications where corrosion is likely to cause problems, polymer fibres should be considered as an alternative. Glass fibre would only be suitable if thin sheet elements are to be produced.

2.3 Automated production

To investigate the present level of automation in the concrete product industry, a series of production plant visits, with special focus on the production of conventional reinforcement, were carried out. The main conclusions, after two visits to Spain (Armacentro s.l, Madrid and El Caleyo, Oviedo), one to Denmark (Lemvigh-Müller DANStål, Helsinge) and two in Sweden (Scandpile, Ucklum and Kynningsrud Prefab, Uddevalla), are drawn in this section. It should also be mentioned that the author had previously visited several similar facilities in Sweden; some observations from those visits also contribute to the conclusion.

Automated production of concrete elements is a very general expression. It covers everything from machinery performing single production steps to advanced fully automated systems for the production of façade elements or concrete bricks.

Among the most frequently seen machines today, performing only parts of the production, is the reinforcement bar bending machine. This was observed during the plant visits in all three countries and in both manual and semi-automatic variations, see Figure 2.1. Furthermore, the concatenation of reinforcement was also automated for some applications in many of the plants visited. The most frequent solution to this was to use resistance welding, a solution suitable for cylindrical reinforcement, as shown in Figure 2.2.



(a) *Manual*

(b) *Semi-automatic*

Figure 2.1: *Standard machinery for bending reinforcement bars.*

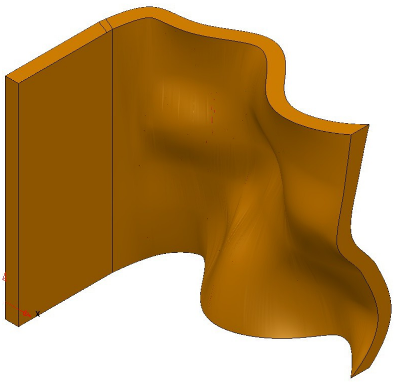
The fully automated production set-ups, observed during the visits, had the common feature that they were developed for serial production, with only limited production between each series. Among such production lines observed were systems for manufacturing stairs, foundation piles (Figure 2.2) and concrete bricks.

Figure 2.2: *Automatic production of reinforcement for concrete foundation piles using resistance welding.*

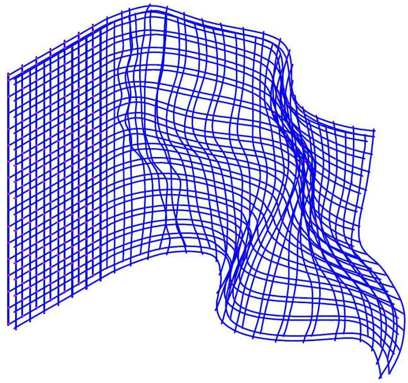
To conclude, little or no difference in the general degree of automation was observed in the three countries. None of technologies used today could be applied directly to the production of tailor-made concrete structures in TailorCrete. Consequently, a new system, using industrial robots, is being developed in TailorCrete. In this system bars are bent, placed and tied together in reinforcement modules. Although the system is still being developed, recent progress has shown that this is a promising alternative Cortsen *et al.* (2012).

3 Rational reinforcement design

Tailor-made concrete structures are intended to be produced by means of digital fabrications, ranging from conceptual design to production, see Williams *et al.* (2011). An example of such concept can be seen in Figure 3.1. However, there are several obstacles to obtain a seamless flow of information through the entire process, e.g. software incompatibilities and the need for structural model idealization.



(a) *Conceptual model*



(b) *Reinforcement model*

(c) *Manufactured (unreinforced) prototype*

Figure 3.1: *Example of two models important in the design process, and the manufactured prototype. Photo: Thomas Juul Andersen, Teknologisk Institut (Danish Technological Institute)*

As conventional steel reinforcement was chosen as one of the possible solutions for the tailor-made concrete structures in TailorCrete, a rational design method suitable for structures of complex geometry is needed. Design methods for concrete structures exist;

however, a structure of complex geometry cannot necessarily be idealised with standard structural elements. Hence, designing the reinforcement requires either long experience or a rational design method which also includes engineering knowledge, preferably implemented within a digital design tool.

In Paper A, the foundation for rational design method is laid by means of a review of two design methods, originally formulated by Martí (1991) and Lourenco and Figueiras (1993). In both methods, the reinforcement design starts with a linear finite element analysis, using shell elements to describe the geometry. The eight independent stress components (n_x, n_y, n_{xy}, m_x, m_y, m_{xy}, ν_x, ν_y) acting in a shell element are introduced in Figure 3.2. For curved shell elements, the components usually become coupled as equilibrium conditions involve all stress resultants.

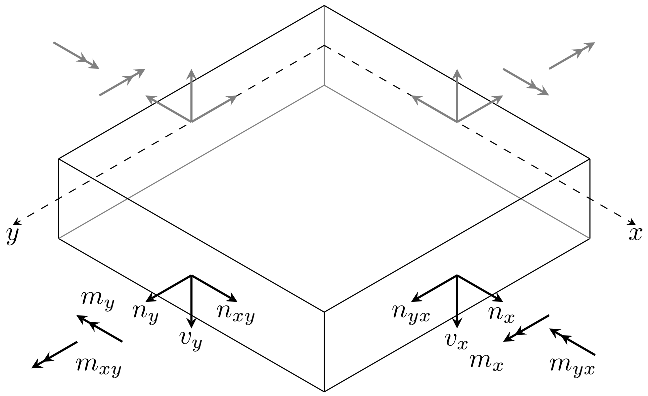


Figure 3.2: *Plane shell element with stress components: bending and membrane action.*

These methods both rely on a sandwich analogy, see Figure 3.3. For this sandwich analogy, it is assumed that membrane forces and bending moments are carried in the top and bottom layers, while the core part resists shear forces. Of the methods described, one is considerably more simplified, Martí (1991), while the other, Lourenco and Figueiras (1993), includes solving a set of six equilibrium equations, with eight unknown variables, by iteration. The simplified method relies on simplified assumptions of the lever arm and the position of the resultant steel force in the other layers, which may underestimate the lever arm, or even violate equilibrium. Hence, for future work, it would be better to use the more advanced method; using computer implementation, the simplifications of the first method are unnecessary.

By applying either of the theories described, using the results from a linear FE analysis as input, the structural engineer can calculate the amount of reinforcement needed. Such procedures relay on the theory of plastic redistributions in the cracked concrete, i.e. the linear stresses are redistributed in accordance with the reinforcement design. The solution is fulfilled provided there is enough deformation capacity (ductility). The structural behaviour can be further verified by non-linear finite element analysis, for example to obtain deformation and crack patterns, see Min and Gupta (1994) or Noh (2006).

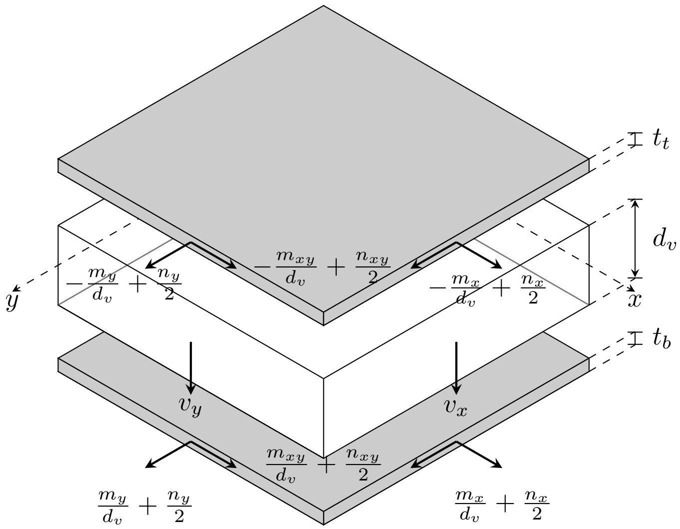


Figure 3.3: *Sandwich model with the division of the stress resultants in Fig. 3.2, see also Martí (1991).*

Several aspects need further attention in the future development of the previously mentioned digital design tool. In the design of a complex concrete structure, the best reinforcement direction is not necessarily easy to find. This means that another parameter can be adjusted to find the optimal solution. Today, optimisation usually addresses the reinforcement amount or other structural parameters, e.g. deflection. In a design tool for automated production, it can be at least as important to optimise for best possible production.

Another aspect, which is not treated in the two methods described, is the increased need for tensile force capacity to counter act inclined shear cracking. Moreover, in the design of more complex concrete structures, the increased need for tensile reinforcement due to inclined shear cracking must be included in a rational fashion.

Furthermore, it is also desirable to incorporate design methods for fibre reinforced concrete in a future algorithm for design; ideally, such an algorithm should also be able to determine areas to be reinforced using fibres only.

4 Modeling and design of fibre reinforced concrete

As steel fibre reinforcement is being used increasingly, and several design codes, standards and calculation models have been proposed. Among the most established are the models proposed in Model Code 2010, International Federation for Structural Concrete (fib) (2010), and RILEM TC 162-TDF (2003). However, there are also German, Spanish and Norwegian national recommendations. In addition to these recommendations, a Swedish proposal has been made, see Silfwerbrand (2008). The comprehensiveness of the proposals differs, but on a general level they are similar with only small variations. Larger scale beams have been studied by Noghabai (2000) and Jansson *et al.* (2010); however, there is a lack of studies on modeling and design calculations of structural components relevant to practical applications. In Paper B, three concrete beams subjected to four-point bending were studied through experiments, analyses in accordance with Model Code 2010, and finite element analyses. The experimental set-up for the beams is shown in Figure 4.1, and the three beam configurations are specified in Table 4.1.

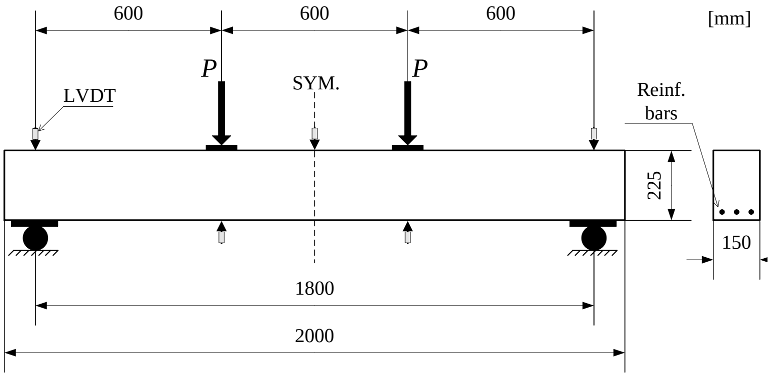
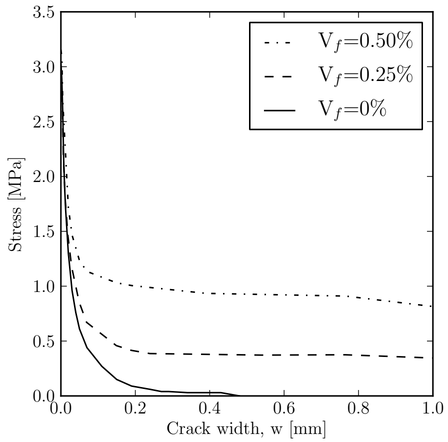


Figure 4.1: *Experimental set-up*

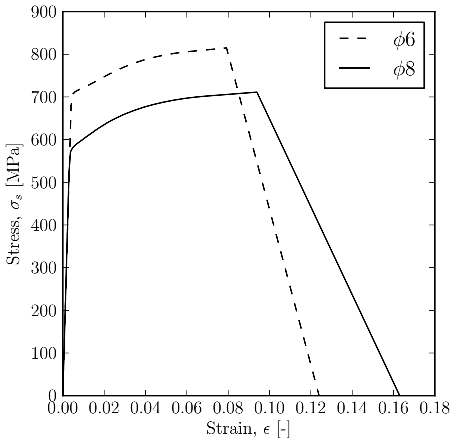
Table 4.1: Test beam configurations

Beam No.	I	II	III
V_f, nominal	–	0.25%	0.50%
V_f, actual (mean value from wash-out)	–	0.18%	0.45%
Reinforcement	$3\phi8$	$3\phi6$	$3\phi8$
$f_{ccm.28d}$	58.8 MPa	58.1 MPa	57.5 MPa
$f_{ctm.28d}$	2.9 MPa	2.7 MPa	3.0–3.1 MPa
E_{cm}	32.5 GPa	30.5 GPa	31.0 GPa

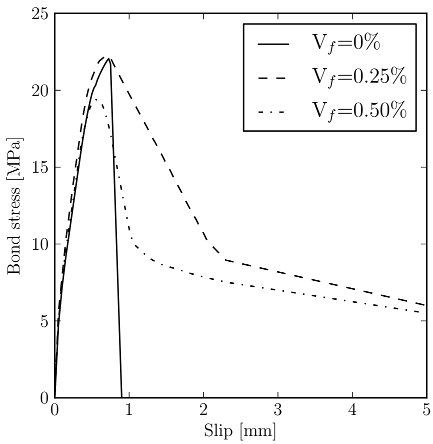
A key feature in this study (Paper B) was that all material parameters of the fibre reinforced concrete were determined by an extensive experimental programme. Other parts of the programme are given in Jansson *et al.* (2011a) and Jansson *et al.* (2011b), describing the experiments that provide material properties for concrete in tension, bond behaviour and reinforcement steel. These experimental results, somewhat idealised, were used as input for FE analysis, see Figure 4.2.



(a) *Concrete tensile behaviour (detail for crack widths up to 1 mm.)*



(b) *Reinforcement*



(c) *Bond stress versus slip*

Figure 4.2: *Material input used in modeling, based on experiments in Jansson et al. (2011a, b)*

Moreover, FE anlyses were also made with modified bond stress versus slip relation, according to Engström (1992), to include the effects of yielding reinforcement. It is reasonable to assume that the bond will decrease, not increase, once the reinforcement starts to yield, see Figure 4.3. As expected, this assumption led to more localised cracks, as no new cracks formed once yielding had occurred.

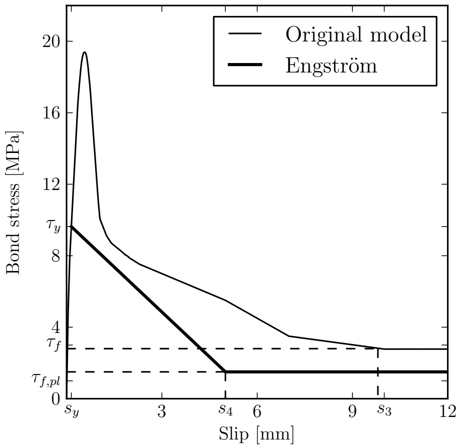


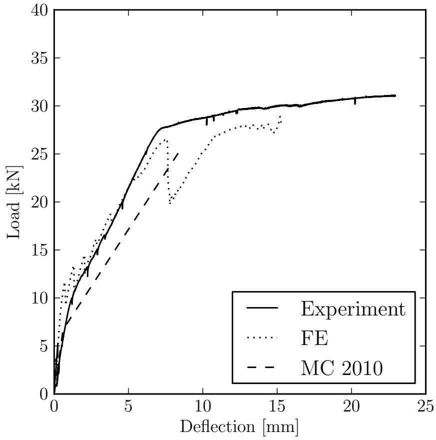
Figure 4.3: *Bond versus stress relation modified according to Engström (1992), here exemplified for the beam with* $V_f = 0.5\%$

The FE analyses were carried out using a two-dimensional model. Four-node quadrilateral isoperimetric plane stress elements arranged in a dense quadratic mesh (element size: 5mm) were used. The reinforcement was modelled by truss elements connected to two-dimensional interface elements providing the bond-slip properties. Furthermore, a smeared crack approach using rotating cracks was used. The deformation controlled analyses were made in two phases: first, the selfweight was applied, followed by incremental loading in phase two. Supports were modeled using eccentric tying, i.e. nodes representing the support plate were maintained on a straight line intersecting the plate center node.

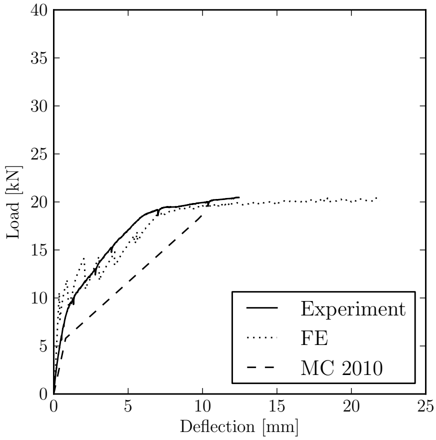
Good agreement was found when comparing experiments with FE analyses; however, calculations in accordance with MC2010 failed to represent the increased post-peak behaviour in the steel fibre reinforced concrete beams, see Figure 4.4.

Crack patterns in experiments and from FE analysis are compared in Figure 4.5. It can be seen that the number of cracks, the total spread and crack distance roughly agree. Differences can be attributed imperfections, e.g in the sample and set-up. In Figure 4.5 half of the beams tested are displayed in order to facilitate the comparison. The omitted halves of the real beams had similar, but not exactly matching, patterns.

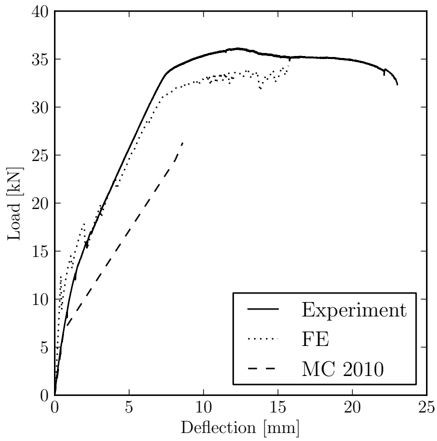
Furthermore, both in tests and in FE analyses the number of cracks tends to increase with the increasing fibre content. This relation was expected since it has been previously observed by Bischoff (2003), Jansson *et al.* (2011b) and Lawler *et al.* (2005).



(a) V_f = *0.00%, 3ϕ8*

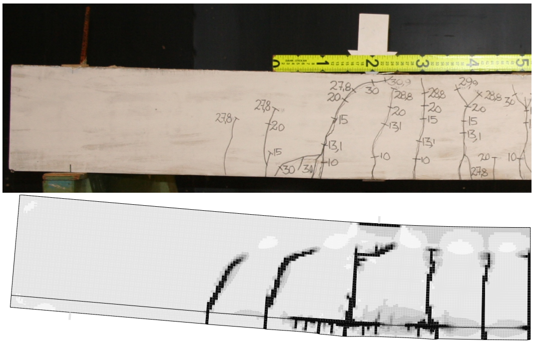


(b) V_f = *0.25%, 3ϕ6*

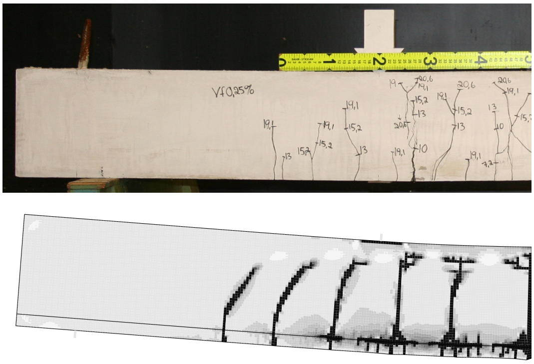


(c) V_f = *0.50%, 3ϕ8*

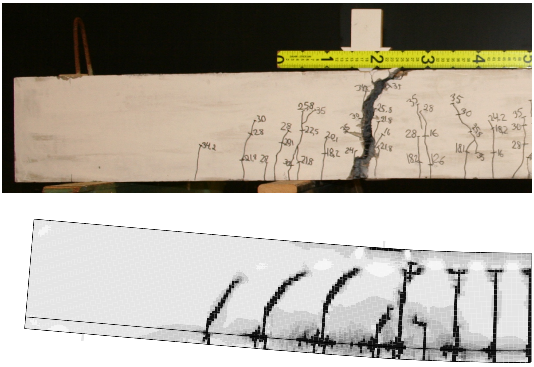
Figure 4.4: *Load (mid span) deflection behaviour: comparison between experiments, analysis according to MC 2010 and FE modeling utilizing bond model according to Engström (1992).*



(a) *Beam I, V_f = 0.00%, 3ϕ8*



(b) *Beam II, V_f = 0.25%, 3ϕ6*



(c) *Beam III, V_f = 0.50%, 3ϕ8*

Figure 4.5: *Crack patterns in experiments compared with those from FE analyses (using improved bond model). The applied deformation (in FE analyses) was 5.5 mm, 6.4 mm and 13.0 mm for V_f = 0%, V_f = 0.25% and V_f = 0.50%, respectively.*

5 Conclusions and outlook

An examination of reinforcement alternatives showed that conventional reinforcement is, in most applications, the best alternative in terms of the structural integrity provided. However, for some applications, or certain regions within a structure, fibre reinforcement can be beneficial as it could simplify the production process and allow for thinner structures.

To fully benefit from the ongoing development of production techniques, the need for a rational design method for non-standard concrete structures reinforced with conventional steel reinforcement has to be addressed. Such a design method can be based on linear finite element analyses using shell elements, and a method using sandwich analogy, such as that described by Lourenco and Figueiras (1993). Implementing this in a computer algorithm offers a basic tool for the structural designer. However, engineering experience will still be important when choosing the directions of reinforcement, placing the reinforcement (taking into account inclined cracking and overlaps, for example) and optimizing the solution with regard to aspects other than the reinforcement amount, e.g. production. Devising an algorithm that includes this engineering knowledge would generate a very powerful tool which would greatly aid in the design of tailor-made concrete structures.

Furthermore, a rational design process, to enable smooth transitions between model types and different kinds of software, thus easing the communication between architects and engineers, is needed to extend the applicability of the new technology.

For fibre reinforced concrete, the development of standards and guidelines is needed. The calculation approach suggested in Model Code 2010, International Federation for Structural Concrete (fib) (2010), does not fully reflect the benefits of steel fibres, in design. In analyses of beams with traditional reinforcement, the greater capacity provided by the addition of steel fibres was underestimated, with regard to both load and deformation capacities. The underestimation increases with increased fibre content. Furthermore, a standard allowing the use of fibres in all applications is necessary to further increase their use.

To summarise, the following suggestions for future research are listed.

- Devise an algorithm for the rational design of complex concrete structures, which includes features normally handled by engineering considerations, e.g. best reinforcement direction and factors related to production.
- Find solutions to the problems associated with boundaries between the digital formats used throughout the design process. For example, incompatibilities between architectural and structural softwares need to be bridged.
- Formulate a rational approach to the design of steel fibre reinforcement, and implement this in the algorithm suggested above.
- Further investigate and make recommendations for a more complete design code for steel fibre reinforced concrete.

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