CHALMERS

Efficient on site construction of small houses with concrete wall moulds

Master of Science Thesis

Erik Birgersson

Department of Product and Production Development
Chalmers University of Technology
Gothenburg, Sweden 2015

Efficient on site construction of small houses with concrete wall moulds

Master of Science Thesis

Erik Birgersson

Department of Product and Production Development
Chalmers University of Technology
Gothenburg, Sweden 2015

Efficient on site construction of small houses with concrete wall moulds.
Master of Science Thesis in Mechanical Engineering, Product Development.
Erik Birgersson

Department of Product and Production Development
Chalmers University of Technology
SE-412 96 Gothenburg, Sweden 2015

Abstract

Houses built with a solid body using materials such as concrete or bricks have many favourable properties, for example, good fire resistance, compared with wooden buildings, they are resistant and do not require intensive maintenance. Other advantageous properties of houses built with a solid body are that they provide a good indoor climate with small temperature variations during the day and they have good resistance against moisture and mildew.

Today, the most common method to accomplish a solid body or a heavy house is to use pre-fabricated wall elements or any form of bricking. It is unfortunately common that the heavy structure is isolated on both sides. The good properties of the body are then not fully utilised.
This is something that the company Incoform AB wishes to change with a new type of concrete mould for construction of small houses.

The work that is described in this master thesis was carried out together with Incoform AB. The Incoform idea is examined and developed from a principle sketch with traditional product development tools but also with methods derived from Lean product development. The result of the development is a prototype that is tested and evaluated.

Keywords:
Concrete walls, Styrofoam moulds, Insulated concrete forms, Product development, Ponti´s method, Lean product development, Heavy houses.

Preface

The master thesis ”Efficient on site construction of small houses with concrete wall moulds.” was carried out by Erik Birgersson in the department of Product and Production Development at Chalmers University of Technology, Gothenburg Sweden. The project was carried out during the spring and autumn of 2013 together with the company Incoform AB.

I, Erik Birgersson, would like to thank:
My supervisor Dr. Göran Gustafsson for his support, interesting discussions and for giving me the opportunity to take a course in Lean Product Development.
Incoform for providing the opportunity to carry out this thesis.
Mr. Kim Niskanen for the introduction to the material PUR.
Mr. Henrik Thorsén for a peppery spirit.
Byggrex for the usage of material and storage.
Pipechain for their hospitality.
Scandinavian Stage Art for the loan of camcorder and equipment.
Bisnit for providing world class computer support.
Dr. Lars Holmdahl for the introduction to Lean Product Development, and Mr. Stefan Bükk’s participation in the same course was also much appreciated.
Nordic Hangers and Oakstone AB for creative battles at the office.

Table of Contents

1 Background

The company, the problem and the delimitations are introduced in this chapter.

1.1 Problem background

A concrete wall is fireproof, solid, non-organic and gives stable indoor temperature and humidity. Unfortunately, the time spent on on-site construction of it is crucial in terms of product quality and cost efficiency. More time consumed means in general a higher cost and increased risks for damage caused by damp (both caused by high complexity and lack of error proofed systems). Regardless of great advantages, an on-site concrete cast wall is often an illustration of the problems mentioned above.

An existing solution for moulding concrete walls today is products manufactured in Styrofoam called Insulated Concrete Forms (ICF). They are moulds and insulation in one product. After curing of the concrete, the form sticks to the hard concrete and then acts as insulation. This type of wall requires another wall on the inside of the building, on which the desired surface layer is applied. This inner wall also houses the electric wiring and plumbing in the house.

Another type of wall is the one where the mould is removed after the curing. It typically takes 24 hours before the mould is removed. On the inside of the building this type of wall is ready for a surface layer but an insulation layer needs to be applied on the outside. The wall can have both electrical wires and plumbing in the concrete.

Incoform AB is developing a new kind of mould for concrete wall casting that combines the best of the two different types of moulds mentioned above. The company has an idea of how to reduce waste in construction processes through a new product for on-site concrete cast walls. It is examining if the disadvantages of traditionally made concrete walls can be reduced without reducing the advantages, to a degree where concrete walls are competitive in relation to commonly used wall types like bricks or wood.

1.2 Aim and purpose

The purpose of this master thesis is to investigate the idea initiated by Incoform and implement it in one concept. The aim is to test the concept with a 3 metre high concrete wall to investigate if it is feasible.

1.3 Incoform

Incoform AB is a new company in the construction industry with an idea of how small concrete houses can be built with higher quality and with lower total costs. The company is owned by two persons, Mr. Salekärr and Mr. Emgård. Mr. Emgård is an economist and Mr. Salekärr is a concrete worker with thorough knowledge and experience from the construction industry. Mr. Salekärr is very interested in Lean Manufacturing and this interest, applied to the construction sites, has produced an idea of how to reduce waste in the construction of small concrete houses.

The initial long term goal for Incoform was to provide an overall solution for moulding concrete walls to small houses.

1.4 Delimitations

No patent search will be conducted. All patent issues are handled by Incoform.

Economical and market research are not parts of the project. There are economic aspects in the selection of concepts, but in-depth calculations will not be performed.

In-depth economic assessments of the product versus competing products are not included in the project.

At this stage in the process the mould is intended for small houses, and walls higher than 3 metres are therefore not considered. The mould is just for outer walls so no proper development of moulds for walls on the inside of the house will be performed.

The concrete is not under development in the project. Different types of concrete will however be discussed due to the performance of the moulds that will demand special properties of the concrete.

This thesis includes only the main product components and not accessories like different kinds of in-wall installations, for example electricity components or audio components.

Detailed solutions (such as detailed CAD drawings) will not be presented. The aim of this project is to, at the concept level, develop the different parts in the moulds.

Incoform´s budget for this project is very low so no CAD program is available in-house. The budget will also limit how the solution can be constructed due to the price of the start up processes in the manufacturing.

2 Method and theory

In this chapter the method and theory are described.

2.1 BAD, Brain Aided Design

Brain Aided Design is when you make pictures or models of possible solutions in your head. This is a skill that needs to be trained in order to work in an optimal way. Factors that can influence the performance of your work are the time of the day, your location, what kind of activity you are engaging in and so on. Some people are effective in their office space, in the shower, under a pile of cushions or during some physical activity like gardening. All people are different and it is therefore important to get to know your presumption of how to be effective in this problem solving method. (Holmdahl, 2010)

2.2 PAD, Pen Aided Design

Paper and pen are the most important tools during concept development! There are two interesting aspects of making sketches when a concept is presented. To avoid lock-in effects it is important that concepts that are presented convey the idea of the concept in a way so that the creative process is not blocked by one's feeling of having a definite solution. A CAD drawing is proven to convey the feeling of a definite solution which will limit the creative process to further develop the concept. Paper and pen is therefore preferable in the development if possible. The second reason for the use of paper and pen is that the brain works automatically when the hand is working with the pen on the paper. (Holmdahl, 2010)

2.3 Benchmarking

"In the context of concept generation, benchmarking is the study of existing products with functionality similar to that of the product under development or to the sub problems on which the team is focused. Benchmarking can reveal existing concepts that have been implemented to solve a particular problem, as well as information on the strengths and weaknesses of the competition." (Page 127, Ulrich & Eppinger, 2012)
This is exactly what has been over a long period during the time that this thesis work was conducted. A set of different forums have been used, a lot of them on the Internet.

To really understand a problem, it is of major importance that you experience it with your own eyes. (The Toyota Way, 2004)

There are a lot of people who document the building of their houses. The level of detail of some of these blogs is extraordinary, and this is a good source of information for someone who is completely new to this industry. This type of information channel is of course not always totally reliable, but it is a really good tool to use in combination with the knowledge that Incoform can provide.

Visits have been conducted to sites where the work with "big forms" called Doka has been studied. Doka is used at big construction sites where for example apartment buildings are built. Construction sites are restricted areas and can be inaccessible, so a substitute has been to study different construction methods on YouTube. Nearly all manufacturers of concrete forms are presenting their products in detail, and it is possible to see the different solutions in action. As with blogs, Incoform has been a good complement to really embrace the different solutions, as all the downsides and not so good aspects of the different solutions, are obviously not presented in the videos.

In addition to videos and site visits, magazines, suppliers of material, house manufacturers, and design blogs have been studied.

2.4 MAD, Model Aided Design

Models can be built in paper, LEGO, clay etcetera. The important thing is to quickly verify the models of the concepts to increase the knowledge of the concept and to widen the understanding of the problem. The impression of a real model will be remembered much better than a computer design presented on a screen. To actually hold something in your hand and be able to look at it from different angles, put it in an environment, and try it out with other parts etcetera provides a lot of information that a picture on a screen is not able to provide. (Holmdahl, 2010)

The models can also be used to show the solutions to customers, developers or users for feedback. LEGO is a good example of a possible model in which changes can be made very quickly in comparison to making these changes on a CAD drawing.

2.5 Method

A course in Lean Product Development (LPD) was attended by the author one month into the project in order to improve product development skills. This method or approach to product development overturned the whole plan. LPD as described in the book ”Lean Product Development på svenska” rejects the classic approach to product development in which the different phases of the project are divided and where a lot of effort is put into the requirements list.

Instead of a detailed time plan and requirements list, the LPD suggestion is to avoid all the small problems in the beginning and start by solving the main problems. The workflow can be visualised as a stream of water that never stops because of obstacles in the flow.

Research is carried out when information is needed and detailed design is done when the early designs are ready. The whole process does not start with benchmarking of competitors because of the lock-in effect it will give you as an inventor when you look at how others have done. The latter part of the project was therefore conducted with the help of knowledge gaps. This is described in 2.6.1.

Information retrieval

The Incoform design idea was introduced in this phase. To really understand the concept and the conditions, a lot of knowledge about concrete and the construction industry was gained. Research was done both through books, magazines, meetings with manufacturers, site visits and through many hours of discussions with Incoform.

Concept generation and development

The methods used for concept generation were brainstorming, BAD, PAD and MAD. However, the majority of the concept generation has been conducted through discussions with Incoform. Concept generation has not been just a small phase in this project, it started on day one and has been ongoing throughout the entire process. The mentioned methods are not only those used, they are the toolbox used on a daily basis together with discussions and model building. LEGO has been the foundation in the building of models. Paper, clips, glue, tape, cardboard and toothpicks have been added to improve the LEGO models.

No concept has been eliminated in the process due to parameters other than economical or practical feasibility.

Planning, execution and evaluation of the prototype

This phase took the project from drawings and models to ordered parts. Incoform was responsible for the specification of the prototype parts, in order to facilitate future development. The goal was to have a prototype and test it at the end of the project.

A detailed plan of the prototype test was prepared when the parts were designed and ordered. The assembly of the parts was planned and evaluated together with determined responsibilities. The reason for the prototype test was analysed and the outcome of this became the questions that are answered in the evaluation of the prototype test.

The first Gantt chart was not used more than just for the initial planning of the project. To structure the product development a new method, Ponti´s method, named after the author of this thesis, was developed in which the functions, concepts and knowledge gaps were illustrated.

2.6 Ponti´s method

Instead of trying to plan the product development with gates and separate phases in the process, the main focus is to close all knowledge gaps. A knowledge gap is everything that is not known. It can be laws and regulations, design properties, manufacturing costs, competitive products etc.

A central part of the LPD process is the project room where the team gathers. There are many different aspects of how the room should be designed, but the essence in this project became that the walls should be used to visualise gathered information.

Ponti´s method is a method to keep track of a lot of concepts for a lot of sub-functions and to keep them visual to the whole team. A wall is dedicated and the goal for the project (a house in the Incoform project) is visualised at the top. Below are the sub-functions and their concepts.

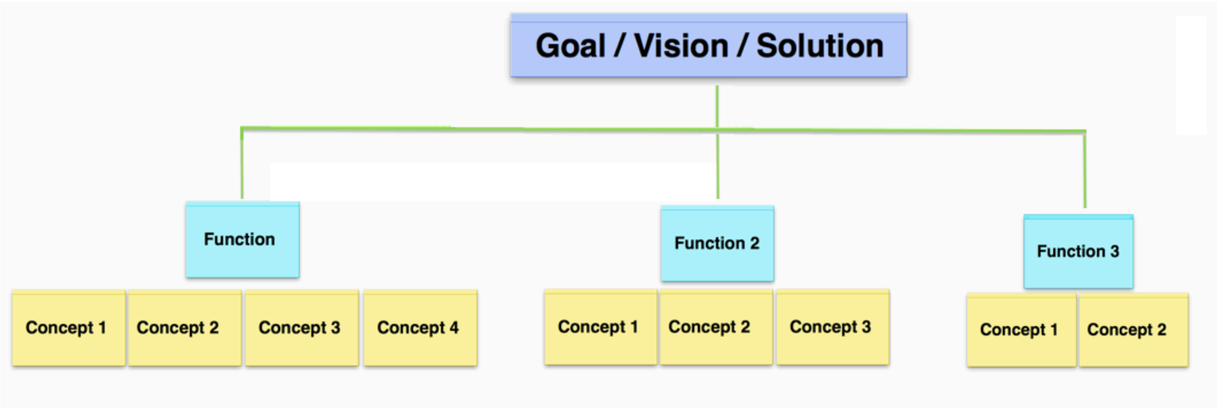

Figure 1: Ponti´s method

If a concept on the wall has a knowledge gap, put a post-it on with a short comment. This will make the current problems visual to the whole team and it is very easy to get an overview of what is needed to be done.

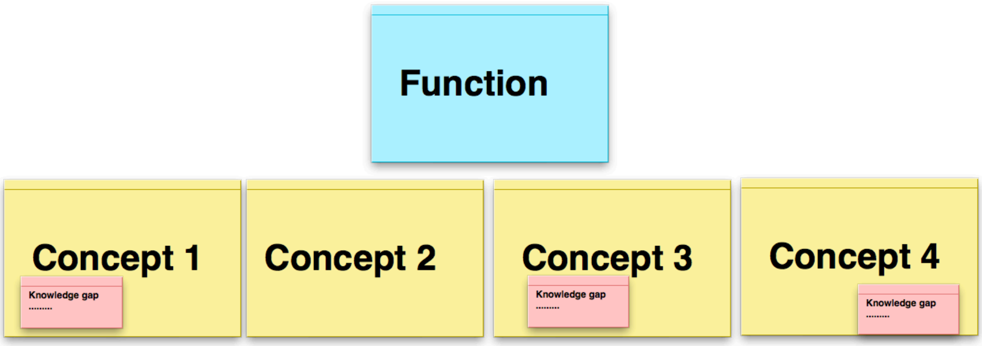

Figure 2: Ponti´s method function tree with knowledge gaps marked

When a concept is eliminated this is marked with a post-it note. The remaining concepts are moved down one step in the hierarchy under each sub-function. This gives a good overview over how the concepts are developed. Old concepts will not be forgotten, which is of big importance. You never know when old rejected concepts may become useful.

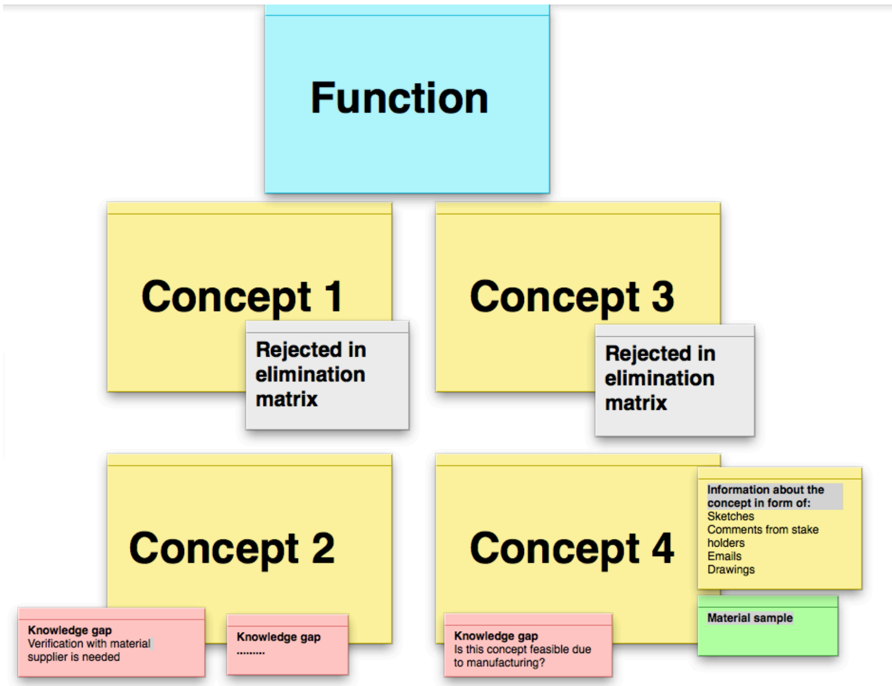

Figure 3.1: Ponti´s method function tree

Material samples, CAD drawings, emails etc. can all be sorted under each concept. Solved knowledge gaps are removed and preferably saved with a comment if needed.

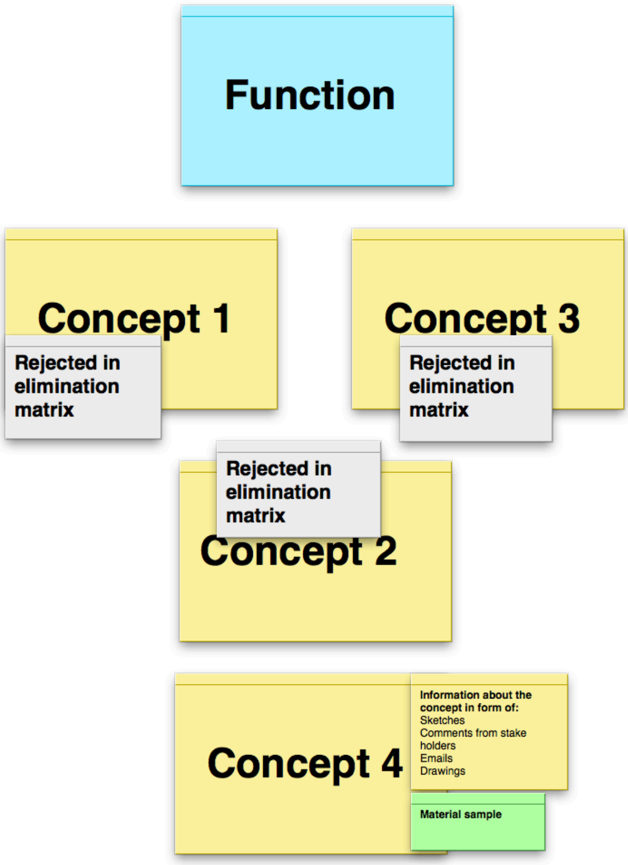

Figure 3.2: Ponti´s method with one remaining concept

3 Existing solutions

In this chapter the existing solutions are described.
To understand what the Incoform idea is about, is it crucial to understand how the construction industry builds a wall today. There exist a lot of different solutions and in this chapter a few of the main competitors are very briefly described.

3.1 Heavy concrete houses

A wall with a solid frame of masonry or cast has many advantages over a wooden wall which has traditionally been more common in Sweden. A heavy concrete wall will store energy and the indoor climate will not vary as much as in a house with for example a wooden frame. Also the humidity will be much more stable since the concrete is working as a buffer zone for moisture.

The climate will show just small temperature and humidity variations over the day. The concrete gives good fire protection, it is insensitive to moisture and mould and the wall does not require an air or vapour barrier.

Heavy walls exist in a number of variants where the most common solution is to use different types of insulated building blocks. A significant factor when building this type of wall is that it requires a high level of craftsmanship to build it properly, to do the bricklaying but especially to polishing it. Plaster is needed to make the wall airtight and to protect the brickwork.

A cast wall with Styrofoam as insulation is a good option which exists in three main variants, wooden form, “big form” and ICF (Insulated Concrete Form).

The wooden form is made on site and is a very expensive method of construction. It takes a long time to build and a lot of the material is discarded after use. This type of solution is typically used for special solutions or on uneven surfaces, such as support walls against rocks.

In large projects, ”big forms” is a very economical building system. A skilled professional team of 2 carpenters can build the form, put the concrete reinforcement in place and found up to about 50 square metres of wall during one day. The form is very expensive so it is not possible to use in small projects where the forms are used just a few times. The form is also very heavy so a crane is necessary to put the parts together at the construction site.

ICF is a Styrofoam form, the parts of which are stacked like LEGO pieces and then filled with reinforced concrete. The disadvantage with this type of wall is that the good climate characteristics of the concrete are not taken advantage of due to the fact that both sides of the concrete are covered with insulation.

When a concrete wall is cast the raise time of the concrete is a very important factor. The raise time is the rate of how the concrete rises up within the form. A high raise time will put a higher pressure on the mould than a low raise time. The raise time is calculated from tables with factors such as temperature, type of concrete and type of mould. A common raise time is 1 m/h.

3.2 *Quad-Lock*

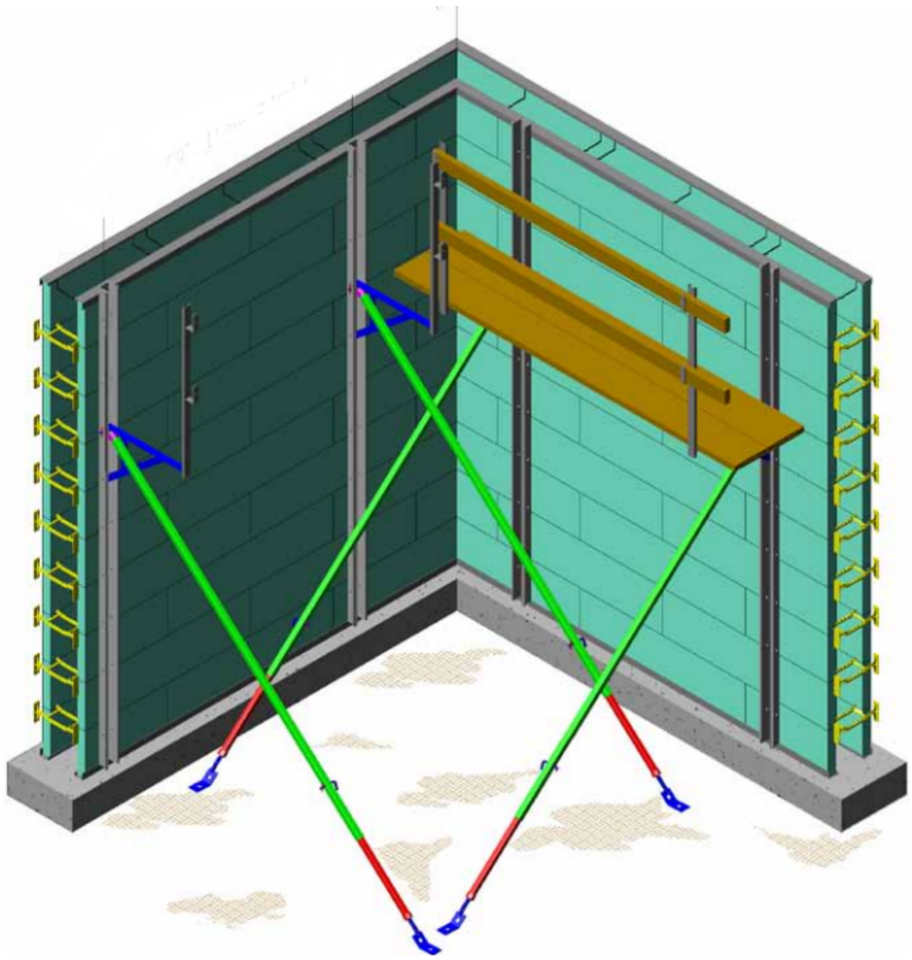

Figure 4: Quad-Lock with staging (Quadlock, 2012)

Quad-Lock is an ICF wall system that consists of panels of polystyrene, metal tracks and ties to hold the panels together. According to Quad-Lock, the polystyrene (EPS) is fire retardant. The plastic ties connect the panels and also support the armour in the construction. The metal track is used to begin and finish the walls and the metal brackets support the corners. According to Quad-Lock, additional outside bracing at corners and angles is eliminated with the brackets.

According to Incoform, the following properties are the advantages of Quad-Lock:

The construction is in many ways a good solution that is easy to handle. Quad-Lock is therefore a major possible competitor with the Incoform solution.

The time it takes from start to a sealed wall is relatively short.

A wall built with Quad-Lock is fire retardant.

The wall has limitless design options both in thickness and in geometry.

According to Incoform, the following properties are the disadvantages of Quad-Lock:

The wall system is not stable before the concrete is poured into the form.

Polystyrene is not fireproof. This should be compared with a concrete house where just the surface layer will need reparation, probably just cleaning and new paint. The concrete will not be affected by a regular fire, but in case of a fire with very high temperature under very long time the concrete reinforcement may be damaged.

A lot of work remains after the concreting before the wall is a complete inner wall and can be painted or decorated.

The good properties of the concrete (energy storage, temperature compensation and moisture-regulation) are lost when the inside is covered with Styrofoam.

3.3 Sundolitt

Sundolitt is very similar to Quad-Lock but is delivered in complete building blocks so the ties are already in place and the blocks are ready to be stacked into a wall. All parts need to be planned by the supplier of the material, which leaves no freedom to fix construction problems on site. The building blocks are assembled already at the factory, which means that the Sundolitt solution is associated with a higher transportation cost than Quad-Lock, which is assembled on site.

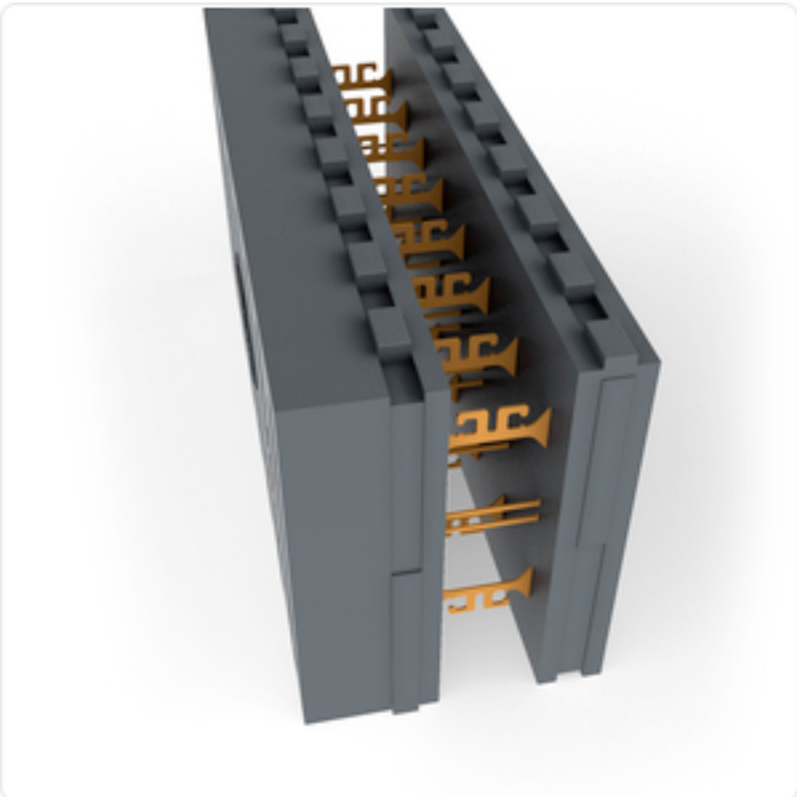

Figure 5: Sundolitt ICF (Sundolitt, 2010)

3.4 Weber Leca Isoblock

Isoblock is quite similar to a conventional brick when it comes to how the house is built. The bricks are stacked and attached to each other with mortar in between each brick. The Leca Isoblock is however bigger in size than a conventional brick and has a core of insulating polyurethane.

According to Incoform, the following properties are the advantages of Weber Leca Isoblock:

Cost efficient

Good fire protection

Not sensitive to moist

Flexible

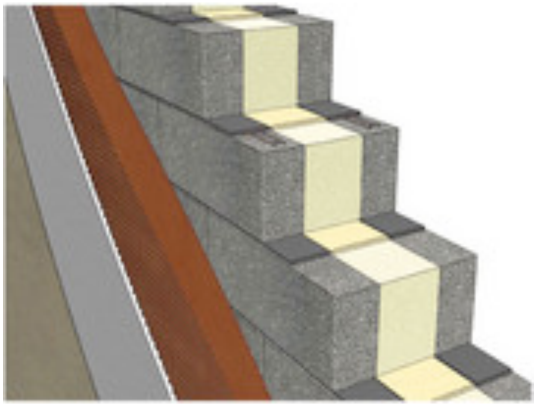

Figure 6: Weber Isoblock (Weber, 2013)

According to Incoform, the following properties are the disadvantages of Weber Leca Isoblock:

Each block needs to be put in place by hand and is heavy, around 20 kg. One square metre of wall then consists of about 200 kg of blocks for the craftsman to lift. The process is therefore very labour intensive.

The building of the house is a slow process due to the time it takes to make a good surface layer on the inside.

There are many thermal bridges in the construction due to all mortar joints between the blocks.

Installation of electrical wiring demands recesses in the wall.

The surface layer on the inside of the wall requires good craftsmanship to create.

Figure 7: House built with Weber Isoblock (Weber, 2013)

3.5 Wood stud house

A wood stud house is not a complete solution that is ordered from a factory. The house is built on site and the carpenter designs the solutions during the construction. This demands a high craftsmanship. The craftsmanship can enable a very good quality and a high flexibility but the risk of built-in errors is much higher than for a house where the construction is more a matter of assembly of parts rather than pure craftsmanship.

A wooden structure is today built with a layer of vapour barrier on the inside. This is made out of age-resistant plastic and is a protection for the structure so that it is not damaged by moisture and vapour in the indoor air.

According to Incoform, the following properties are the advantages of Wood Stud:

Very economical solution

Very flexible design

Good availability of the material in Sweden

According to Incoform, the following properties are the disadvantages of Wood Stud:

Sadly enough there is often a lot of problems with moisture with wood stud structures. One part of the problems is moisture from the outside of the house if the surface layer malfunctions. If this happens, the core of the house will retain the moisture, which will cause problems since the moisture cannot escape.

The vapour barrier is very delicate and is easily damaged during for example, by hanging of paintings on a wall. One nail in the barrier is enough to destroy the function of the plastic. There will be no indication that the barrier is damaged before it is too late and the structure is infected by mould.

Figure 8: Wood stud house (Byggrespons, 2013)

3.6 Prefabricated walls

Prefabricated walls exist in a variety of models from wood to concrete. The risk of moisture problems in the structure with these high quality building elements is minimal thanks to the construction being carried out in a weather protected environment. Even though the houses are partly prefabricated in a factory the price is the same as for a house that is built on site from scratch. The time on site is thus very short for the mounting of a whole house.

One reason that the cost is the same as for a conventional house is that a crane is necessary to place the parts in position when they are delivered with a truck. The transportation also limits how big the wall sections can be. The mass, the length and the width put other limits on how the house can be put together.

Figure 9: Prefabricated walls (Finndomo, 2013)

3.7 Big form, Doka

The form consists of two main parts, one on the inside and one on the outside. Both are very heavy, up to 3000 kg each. The first part of the form is put in place by the construction crane and the carpenters can then mount the reinforcement bars and also put the electrical tubes and plumbing in place. When this process is completed, the outer part of the form can be put in place and connected to the inner part with a steel rod called a ”form tie”. The concrete is delivered by a concrete truck and pumped into the form. Once the form is filled with concrete, the concrete is vibrated with a ”vibre” to force all of the air bubbles to the surface. Air in the concrete will dramatically reduce the strength of the wall, so this is a crucial step.

Figure 10: Construction site with crane and concrete truck

The concrete is typically poured at the end of the day, and the next morning it is both possible and necessary to remove the Doka form. The form tie is released and the crane can lift the form parts to the next part of the wall that is going to be built.

The wall is now ready for surface preparation and a surface layer. At this stage it is not ready on the outside though. Both insulation and a surface layer need to be constructed, for which there are many different solutions to choose from.

The Big form is used on large scale construction sites, where concrete walls are built more or less daily during a long period of time. The forms are expensive, heavy and area consuming. The construction company also rents them, so it is important that they are used as much of the time as possible. This puts pressure on the construction team to really use them efficiently in order to keep the rental cost at a minimum.

Figure 11: Doka form

4 Requirements

The following requirements and needs have been identified for the Incoform wall, with the exception of the obvious fact that the wall must in certain cases must bear the required load from the rest of the building. That is a construction factor during the planning of the house and is therefore not a part of the requirement list.

No.	Requirement
1	The price for 1 m^2 finished wall with 0,30 metre insulation and 0,15 metre concrete should not exceed 2000 SEK.
2	Moisture can be devastating to the structure in the wall and the load carrying capabilities can at worst be totally damaged. The structure must withstand a relative humidity of 100%.
3	The warpage of the wall is measured with the help of a 2 metre straightedge and folding rule; the deviation of the wall cannot exceed ± 5 mm. The warpage should also meet the requirement that the deviation cannot exceed ± 2 mm with a straightedge that is 0,25 metre. This requirement is from AMA hus 11. AMA Hus is a reference book to use in the preparation of descriptions and execution of building construction. AMA Hus is published in a new edition every three years.
4	The construction must withstand rain during the mounting of the mould and the pouring of the concrete, without any malfunction.
	Needs
1	*The number of man hours* on site will affect the total price of the wall and should therefore be minimized.
2	*Time to sealed house* is the time it takes before the inside of the house is sealed from wind and rain. A shorter time will reduce the total time for the whole house to be built and reduce the risk of moisture problems in the structure and should therefore be minimized.
3	*Ergonomics,* easy to handle for the craftsman, both in terms of working conditions like weight, material and ergonomic design. After a day with mounting of the wall mould, the worker should not perceive the work as physically demanding. This is of course a subjective measurement that needs to be evaluated by experienced craftsmen.
4	*Thermal bridges* in the construction should be avoided to minimize the operating cost of the house.
5	The *risk of moisture in the construction* should be avoided, *short term.*
6	The *risk of moist in the construction* should be avoided, *long term.* Alterations or renovations of the walls must not jeopardize the long-term moisture resistance in the construction.
7	*Required craftsmanship,* should be minimized. In other terms, the construction should be so simple to mount so that incorrect assembly is impossible.
8	*Design flexibility,* the wall should be flexible in length, angles and placement of

	elements like windows and doors.
9	*Fire retardant*. The materials on the inner part of the wall should not be combustible.
10	*Total cost of house,* should be minimized.
11	*Installation complexity,* the mould should be compatible with different types of installation in the walls like plumbing and electrical wires. It should also simplify the installation and therefore lower the total price of the wall.
12	*Required additional machines,* for example a crane, should be avoided.
13	*Heavy wall properties,* the wall should be able to store energy in the structure.
14	*Operating cost,* a combination of heavy wall properties and thermal bridges.
15	*Risk of visible cracks in the surface layer,* temperature changes in the surroundings of the wall may not result in the wall moving in such a way that the surface layer is damaged.

5 The Incoform solution

This chapter gives a theoretical description of the different parts of the Incoform solution. The descriptions may differ from the conditions in the real test rig due to manufacturing changes, which will be described in the section Prototype testing.

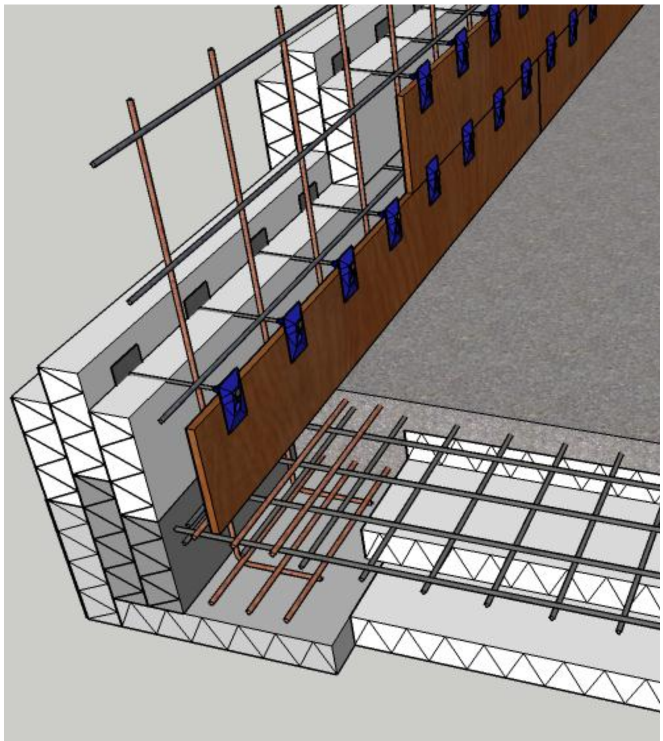

Figure 12: Incoform mould with armour

5.1 The initial idea

Incoform´s original idea is to build a wall mould that consists of stackable blocks which are each made up of 3 Styrofoam blocks glued to form one piece. This part is permanent in the construction. The other part of the mould is temporary and consists of boards of plywood. Simply explained, the solution is a combination of a wooden form and a typical insulated concrete form (ICF). The plywood is connected to the Styrofoam with a form tie that is quite similar to a conventional form tie (Figure 13) for a wood frame.

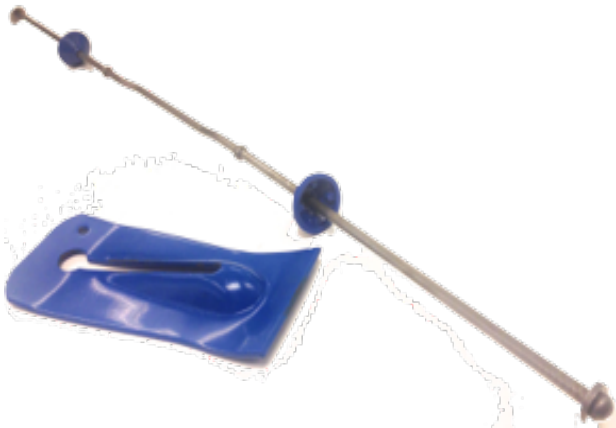

Figure 13: Form tie and conventional form lock for wooden form

The idea is to first stack the Styrofoam pieces in one layer around the house where the walls should be placed. The form ties are pressed into the Styrofoam and the next layer of Styrofoam is mounted. The process is repeated until the wall reaches the required height. The next step is to armour the wall according to present standards and regulations. When this is done, the plywood boards are mounted and locked by the form tie and its lock. The concrete is delivered to the construction site and poured down into the form from above with an estimated raise time in the form of 1 m/h. When the concrete is cured in approximately 24 hours, the form locks are removed together with the plywood boards. The form tie will stand out from the concrete but thanks to a small rim in the tie, just where the plastic cone is situated, it is possible with a few strokes of a hammer to break and remove the outer part of the tie. The plastic cone is removed from the concrete.

Figure 14: Form tie cap

The concrete filled Styrofoam blocks are permanent in the building and act as the insulation for the house. Electric boxes, ventilation, etc. are mounted to the mould boards and are therefore cast into the concrete. After the curing of the concrete the boards are dismantled. This solution provides an insulated wall with the inside ready for surface filling and coating at once after the curing of the concrete. The outside of the Styrofoam needs to be covered by an optional facade.

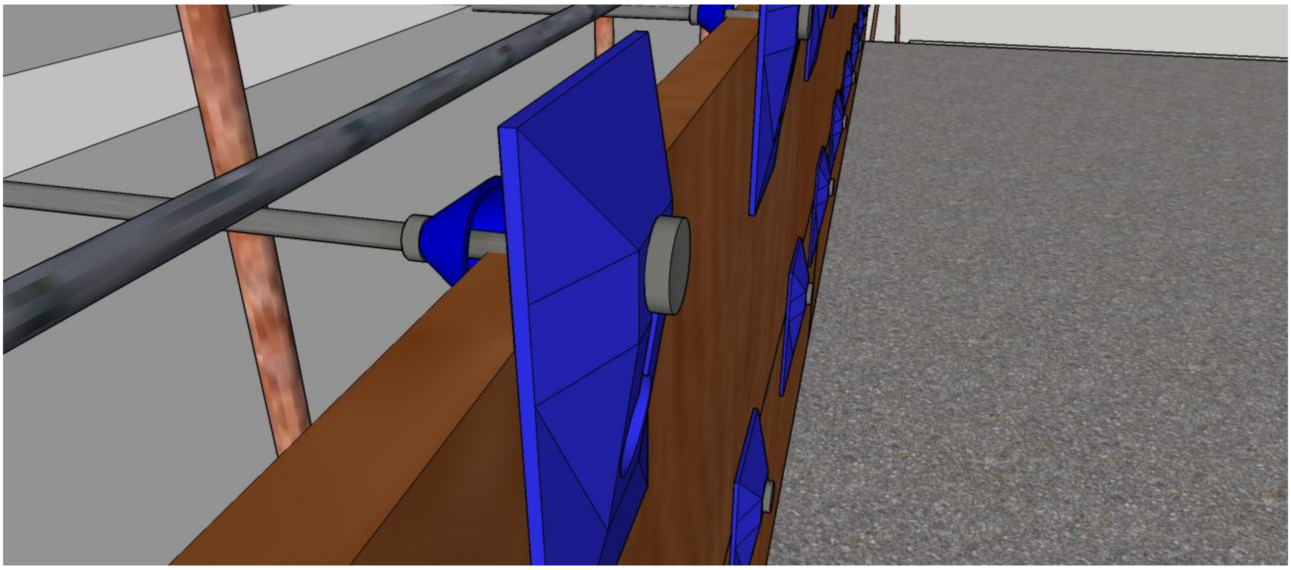

Figure 15: Form lock and form tie cap

Figure 15 shows a form tie that is locked with the blue form lock, protective armour and a wooden board. A section is 300 x 2400 mm, i.e. 0,72 m^2.

The advantages of the Incoform solution are that:

In case of a fire, a concrete wall is fireproof up to very high temperatures.

A wall that is made out of a material with a high density will ensure a stable and healthy indoor climate.

The effects on man of having oil based materials, such as a vapour barrier of plastic, in the residential environment are not yet fully investigated. Until then it is best to avoid them in the residential environment as far as possible.

The Styrofoam is in direct contact with the concrete and will stick to the cured concrete, therefore no adhesive is needed.

The solution allows for installation of all electrical wiring before the concrete is poured into the mould. This saves time and therefore saves money, in comparison to a moulded wall in which the electrical wires are installed after perforation of the concrete.

A moulded wall has from the beginning, a surface that is ready for coating. ICF solutions or a wooden wall need a second wall on the inside before the surface layer can be added. This makes the solution very interesting for the construction company, which can save a lot of money when the required time is reduced.

The low estimated mass of the Incoform solution will contribute to a good work environment for the construction workers. Prefabricated walls require a construction crane to be in place and ISO blocks can be heavy which poses a high risk to the workers. The Incoform solution can easily be stacked manually, thanks to the very low mass.

A wall with concrete and Styrofoam runs a minimal risk of becoming damaged by water. This is true both during the construction phase, when for example a wooden wall is very exposed to moisture, but also during its usage, when the concrete and Styrofoam will be undisturbed by water.

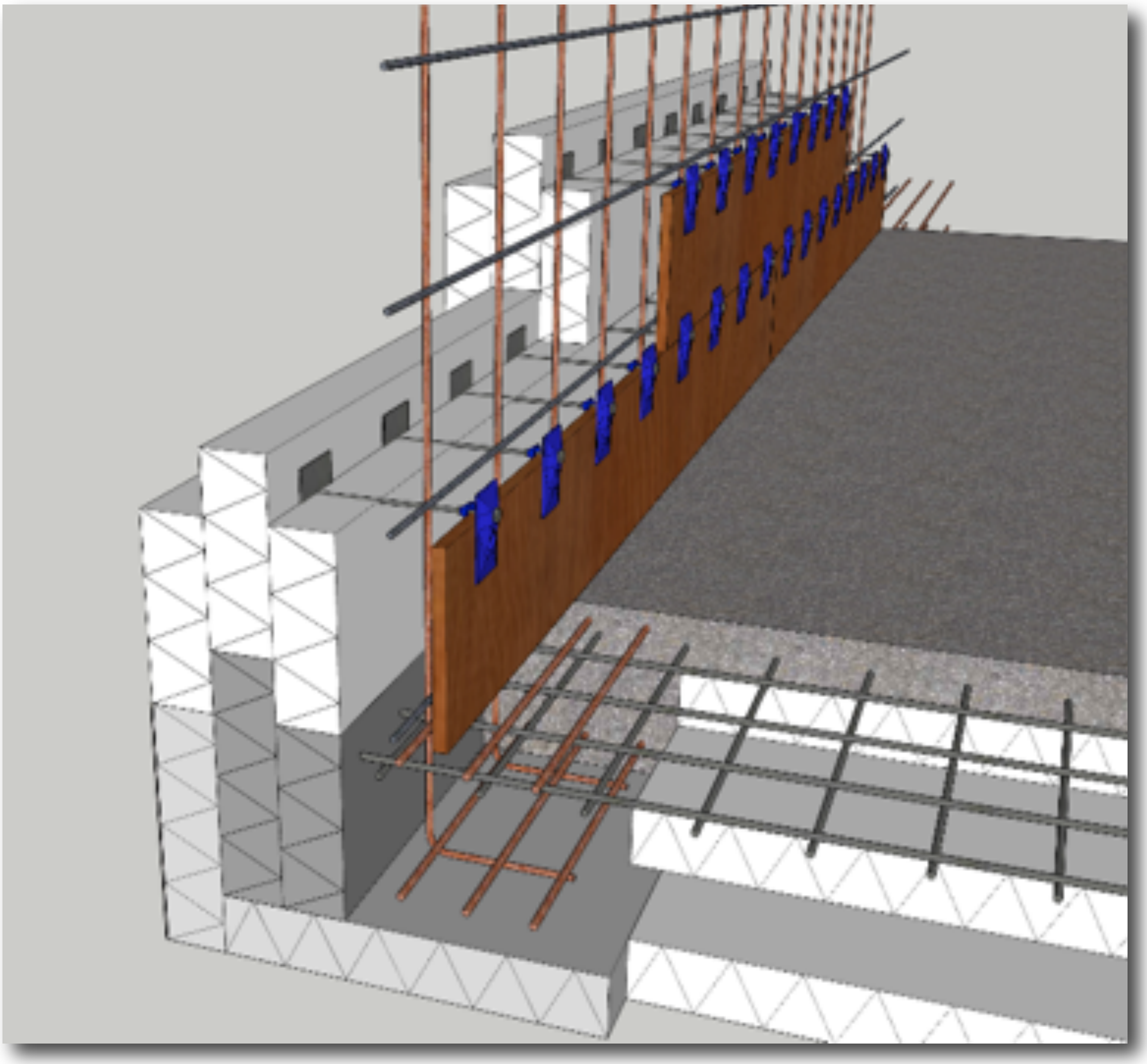

Figure 16: Incoform wall

5.2 The different parts in the Incoform solution and their concepts

The Incoform concept was initially just the idea to use an outside Styrofoam part and form boards in plywood with a connecting form tie. But these parts alone are not enough to test if the idea is feasible. This chapter describes the Incoform concept and the different concepts for each part of the overall solution.

5.2.1 Form board

The form board is a major part (see Figures 12 and 15) of the solution, and the initial idea was to use plywood for it. Plywood is common in concrete applications and is fairly inexpensive and environmentally friendly.

The form board has two important functions two fulfil. The first is to take the load from the concrete during pouring and curing without any larger deviations in the surface than 2 mm (see Requirements). The 2 mm deviation is taken from the reference tool AMA hus 11, which is used to prepare the descriptions and execution of building constructions. AMA House is published in new editions every three years and this edition is from 2011. The second very important function is that the board doesn´t stick to the concrete after the curing. Oil is sprayed onto the inside of the form to prevent sticking. The form oil also prevents metal forms from rusting.

Plywood

The most obvious material to use in the form board is plywood. It is the most common material in the building industry for form work boards. The water in the concrete is the main problem when using plywood, but rain and dew at the construction site are also difficult to handle. The plywood can have a surface layer that provides more long lasting durability through more castings than plywood without a surface layer, but the number of times it can be reused is still limited before the board is destroyed by the water in the concrete.

Figure 17: Plywood with a plastic surface

The product Sonoboard

A benchmark study was conducted in order to understand the market and existing solutions. Apart from the knowledge gained about previously presented construction methods, a new product called Sonoboard was discovered. Sonoboard is a form facing board, made of a glass fibre reinforced composite material with a thermoplastic surface that can replace the plywood board as form work in the construction industry.

According to the company Sonoform, the Sonoboard has some outstanding properties:

Can be stored outdoor and withstand any kind of weather

Is delivered cut to size and can be machined

Can be cleaned with a high pressure water jet

Nail holes will not degrade or make the board swell or rot

100 % waterproof

Very strong and light

Nail holes get filled with concrete and self-heal

The thermoplastic surface is nonstick, water-repellant and durable

Field-proven and, at the time of writing this thesis, reused 350 times.

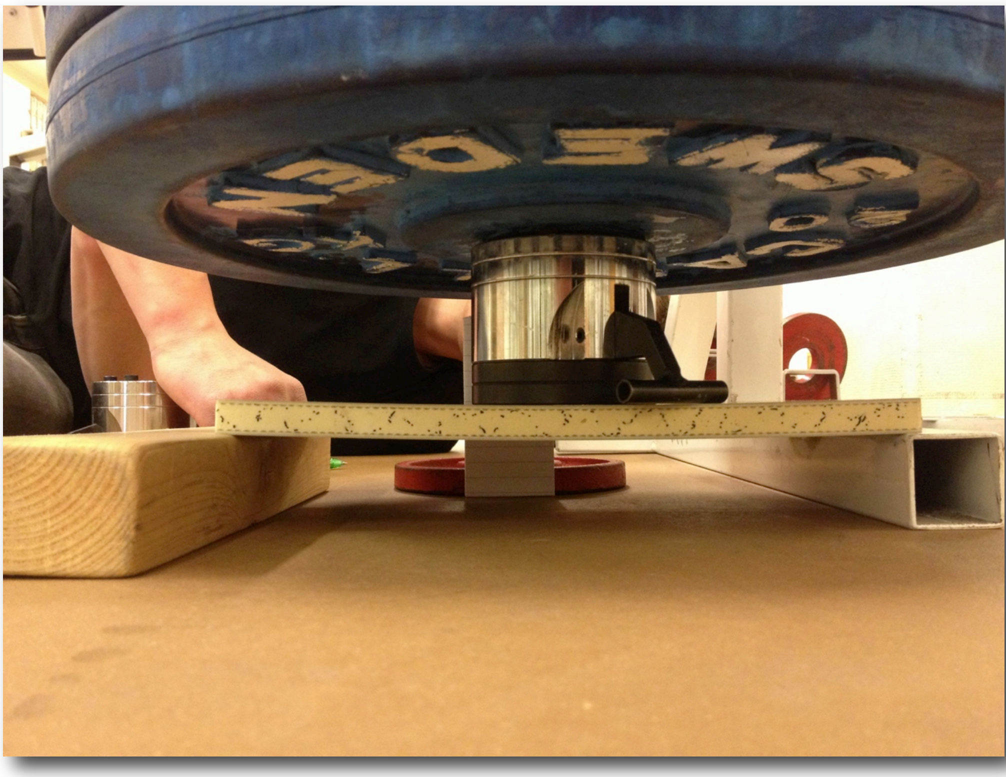

Figure 18: Load test with 85 kg on Sonoboard

A manufacturer was contacted and samples of the material ordered and tested. These boards proved to be far better than the plywood in sustainability. It was therefore an easy choice to proceed with Sonoboard and boards were ordered for the full-scale test. The Sonoboard can be reused hundreds of times compared to the plywood, which can be used one or a few times.

5.2.2 Inner corner

The Incoform solution needs to be further developed to enable the making of corners of varying angles. However, in this first stage, right-angle corners are sufficient. The Inner corner is the point of contact between the plywood boards in the corner. The corner might stay in the right position with the right angle without any additional parts, but to reduce the risk of failure during the casting, different concepts for it were developed. The corner may fail if too much concrete leaks in between the board. The construction will inevitably leak, but excess concrete is easy to remove after the curing of the concrete. A small leak is acceptable and poses no risk to the overall construction, but it is desirable to reduce the risk of a big concrete leak that makes the casting impossible.

Many different solutions have been generated in this project and two concepts, the Metal corner and the Sonoboard corner, have survived from the napkins in the lunchroom, sketches on the whiteboard and from the pile of post-its.

Concept Sonoboard corner

This concept is a combination of the different concepts for length adjustments of the wall and is a result of the benchmarking study in which the Sonoboard material was discovered. A corner is made of Sonoboard, but with two layers of material instead of one. The double layer makes the corner stiff enough to ensure that the corner will always have a right angle.

Exact dimensions and pictures will not be shown here due to a possible patent process. The special function that this corner provides is to allow the wall to be built with any preferable length without any cutting of either the form boards or Styrofoam. The Sonoboard corner was not further developed to the full-scale test stage since the metal corner was easier to manufacture in time for the test. The concept was not permanently rejected, but rather put on hold until further development after the first test.

The concept Metal corner

The concept consists of a 3 m long metal tin that stabilizes the form boards relative to each other. A board that is too short will result in a small leak and leave behind a wedge of concrete after the curing. This wedge is easily tapped away with a hammer after the disks are removed. A board that is slightly too long will not be possible to mount due to that the form ties hold the boards in the correct position.

One possible problem with the Metal corner is that its length and mass may be hard to handle when the boards are assembled. And no one knows if the board needs to be attached to the corner in order to maintain the functionality. This needs to be tested during the first casting.

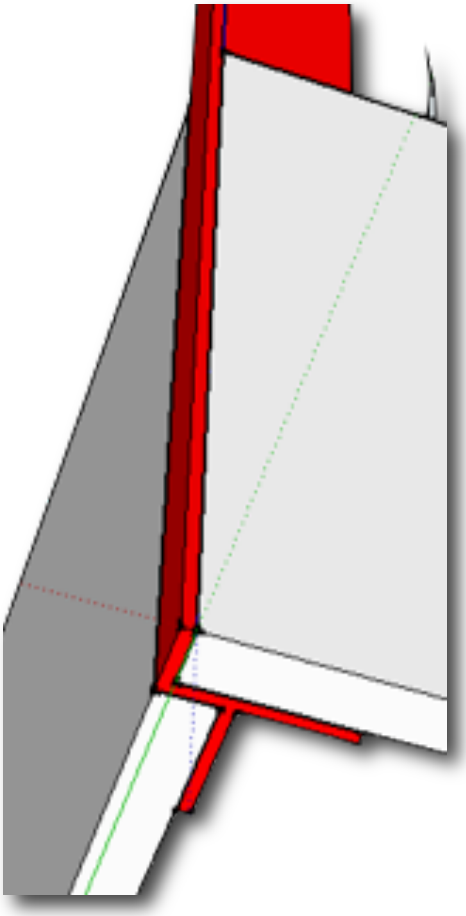

Figure 19: Metal corner and two boards

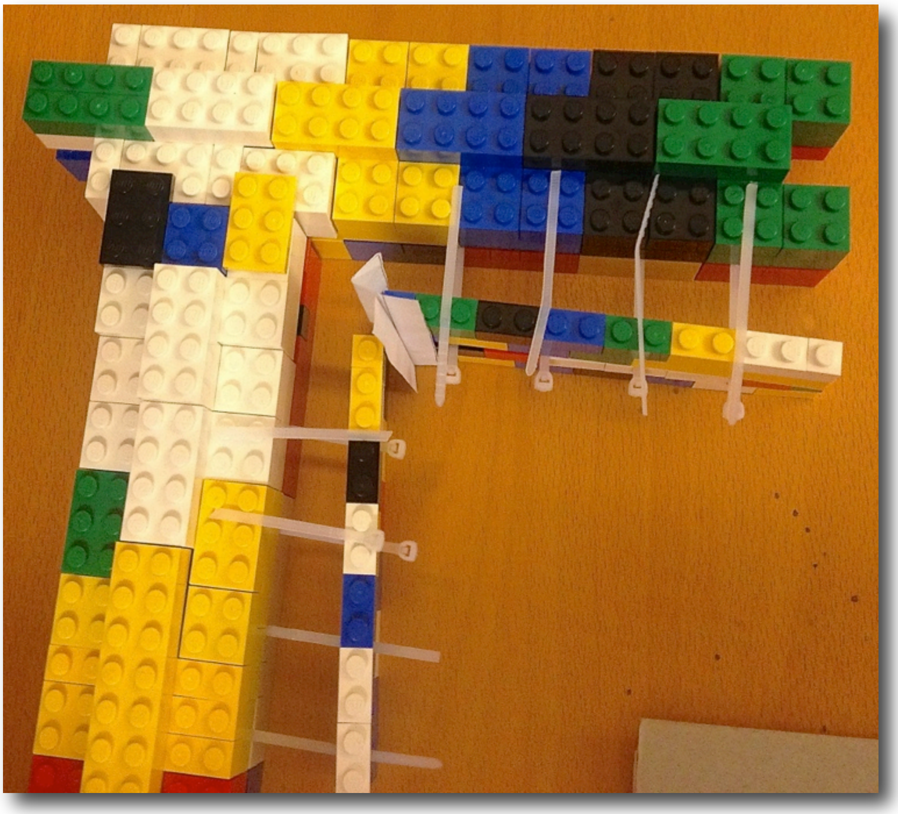

Figure 20.1: LEGO model of the solution with metal corner

5.2.3 The Outer corner

When the Styrofoam is stacked and the boards are mounted with the form ties, it shall be able to carry the load of the concrete during casting. But without support, the outer corners will not withstand the concrete but will open up.
Figure 20 shows the principle of the outer corner model. The big LEGO parts represent the Styrofoam and the clips have the function of a form tie. It is easy to see that without any support on the outside, the Styrofoam will yield to the pressure from the concrete.

Many different approaches to the problem have been discussed in this project, but only two concepts have been further considered.

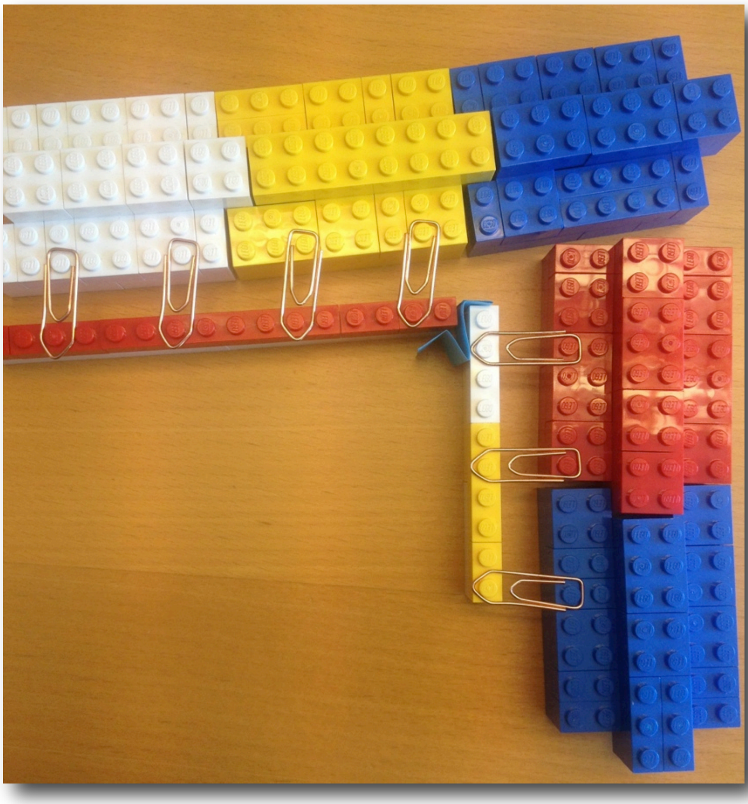

Figure 20.2: LEGO model with open corner

The concept Nail plate

The nail plate is an existing solution for assembling pieces of wood, but it can also be used for assembling Styrofoam blocks. The idea of using nail plates was to bridge each joint in the corners, i.e. to use one nail plate for each layer of Styrofoam. However, Incoform's opinion regarding this method is that the force on the Styrofoam will be so large that the nail plate will rip the Styrofoam into pieces. The concept is saved for further testing even though the idea is not fully supported by Incoform.

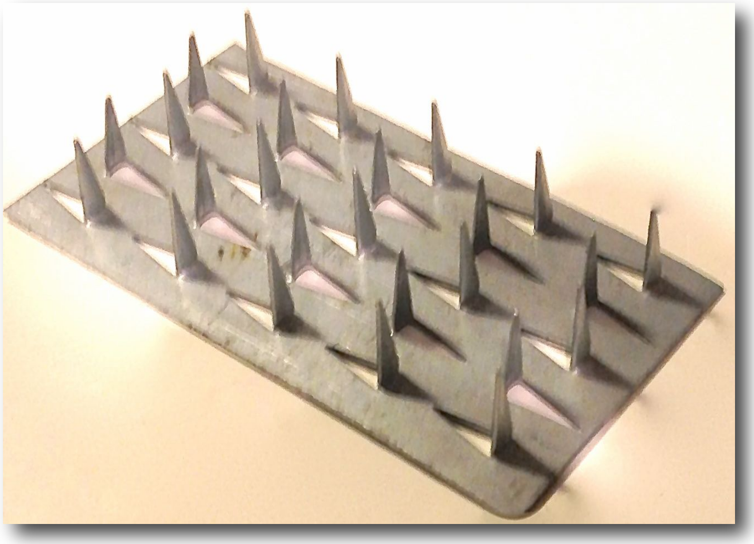

Figure 21: Nail plate

The concept “David´s corner”

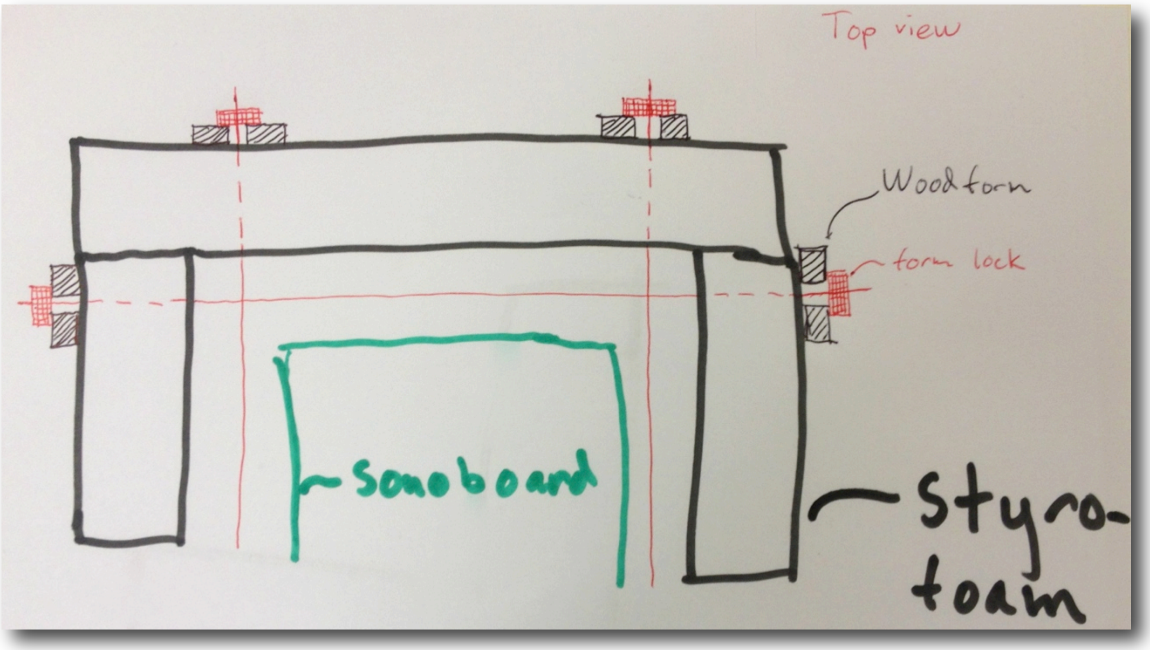

Figure 22: Sketch of “David´s corner”

This solution is derived from the wood form where the outside of the form is supported by a wooden frame and the form lock is on the outside of the form.

In this concept, at least two reinforcing bars (red lines in figure 22) are pressed through the Styrofoam (black squares) and locked on the outside with a form lock (red squares). To distribute the force over all Styrofoam pieces in the corner, a wood form (black ink) is built and placed between the form lock and the Styrofoam.

One problem with this solution is that a long wall may require a long and heavy reinforcing bar which is difficult to handle. Another issue is that it might be problematic to tighten the lock with the right tension. Too low a tension may result in movement of part of the wall, the Styrofoam, during the casting. The opposite, too high a tension, will on the other hand result in inward movement of the Styrofoam which will lead to a wall that is not completely straight.

It was rather easy to choose between these two concepts; the Nail plate and David´s corner. The Nail plate might work with a low raise time of the concrete, but David´s corner is very similar to a standard solution so the probability for a successful test casting with it seemed reasonable.

Figure 23: Form lock for wooden form

5.2.4 The Form tie

The form tie has been part of the project since day one. There are a vast number of different form ties on the market, and the initial idea was therefore to use an existing solution with a minimum of changes to minimise the cost of using this method. It is important to keep the cost low since 1 m^2 of wall contains about nine ties.

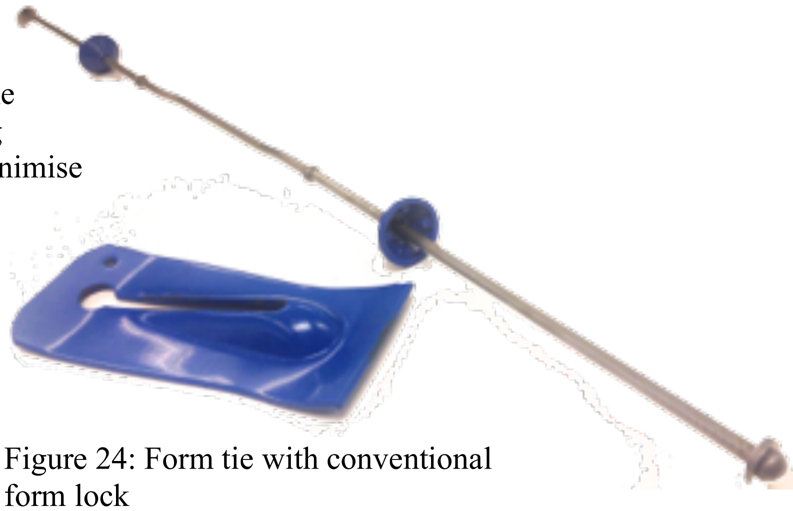

Figure 24: Form tie with conventional form lock

Different solutions have been discussed, but the only feasible one at this point in the project is to use a traditional form tie with some small changes made to it. The end of the tie that is connected to the Styrofoam has a metal plate with the dimension 100 x 100 x 3 mm, that is pressed into the Styrofoam. The other end of the tie is locked with a form lock (the blue metal part in figure 24). But for the test rig, a more flexible form lock is used that can lock at any position of the tie. A regular form lock requires that the form tie is of exact length so that the end knob fits into the lock.

A special form tie without the end knob was ordered to fit the flexible form lock:

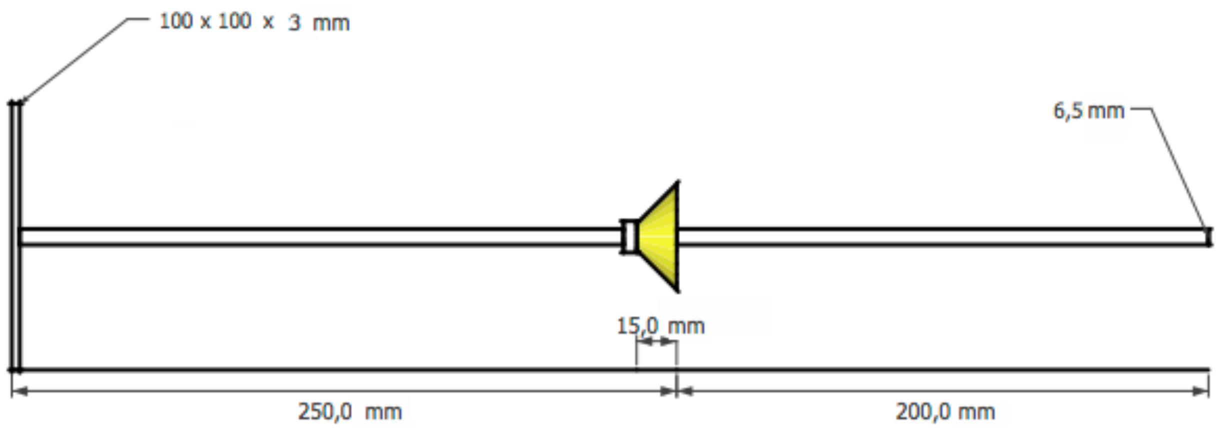

Figure 25: Form tie for the Incoform solution

5.2.5 Staging and support

When a wall is going to be constructed with concrete casting, the ground surface is very important. But even with a ground of the highest quality and totally horizontal, the wall may still begin to tilt in some direction. The wall must therefore be possible to adjust before the concrete is delivered for the casting.

There are solutions on the market for this, but for Incoform it is of interest to have their own solution. The reason for this is that when a developer rents (a lot of the construction material that is reused is rented) material or machines, it is much easier to rent from just one company that delivers a total solution.

When the higher part of the mould is mounted, some kind of platform to stand on is required. The platform is also of use when the concrete is poured into the form. The person who fills the concrete must be able to look straight down on the mould in order to be able to correctly distribute the concrete.

Figure 26 shows how it could be possible to solve both the adjustment and platform problems in the same design. This has been part of the overall product development but is not at this point a part of the test casting. During the test, pallets will be used as the platform.

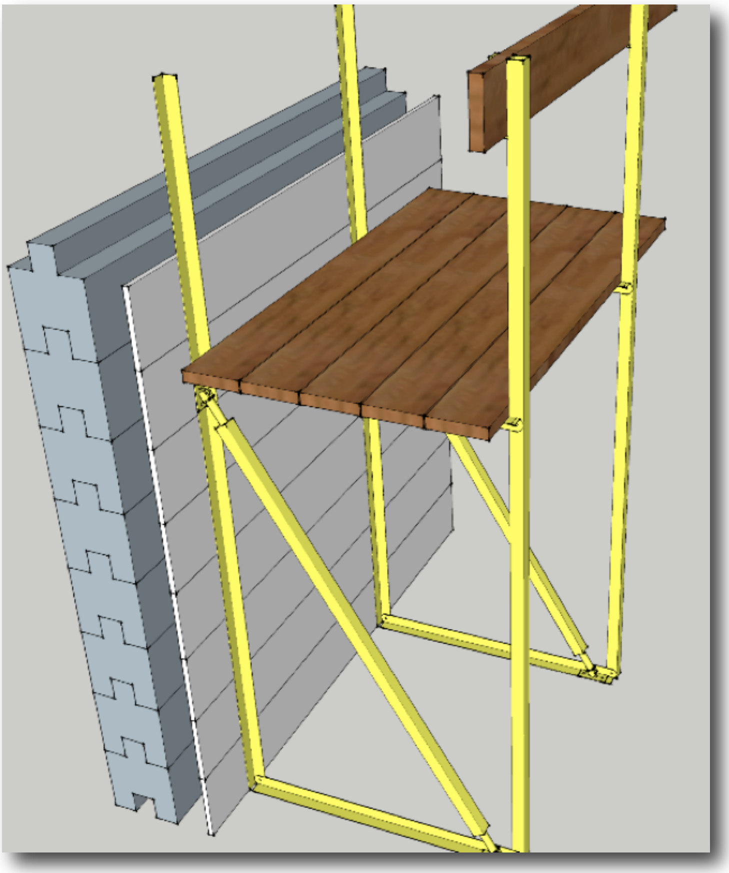

Figure 26: Concept for staging and support

5.2.6 Styrofoam blocks

The Styrofoam is the wall insulation but also the outer part of the concrete mould. It is therefore important that no concrete penetrates the slots between the blocks. Concrete there would constitute a thermal bridge in the finished construction and is highly undesirable. Since Incoform's budget is tight, the expensive manufacturing process of moulding Styrofoam is not possible to use. The Styrofoam pieces therefore were made out of flat blocks. A more complex design of the blocks would for example, simplify corners in the construction, but this is unfortunately not within reach for Incoform to finance.

Many different forms of the blocks have been discussed and examined. To represent the blocks, LEGO has been used to build prototypes. The planned thickness is a standard insulation that is 300 mm, but this can be easily changed if another insulation value is desired.

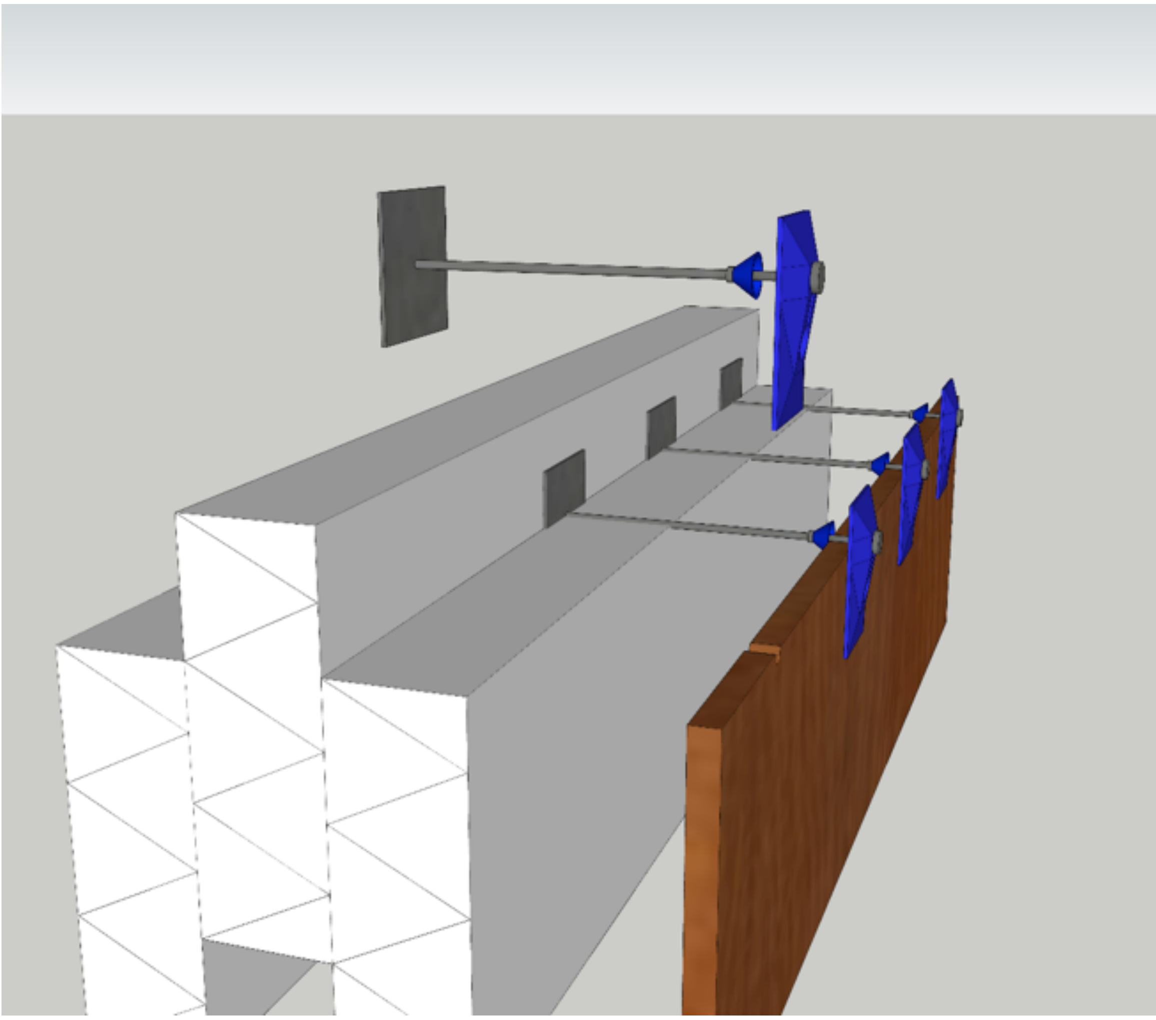

Figure 27: Styrofoam, form tie and form board

The problem with this solution is that there will be splices between the different blocks which will permit unwanted thermal bridges. Many other different solutions were therefore discussed. The solution became to have a middle part that was offset in the same way as in Figure 28.

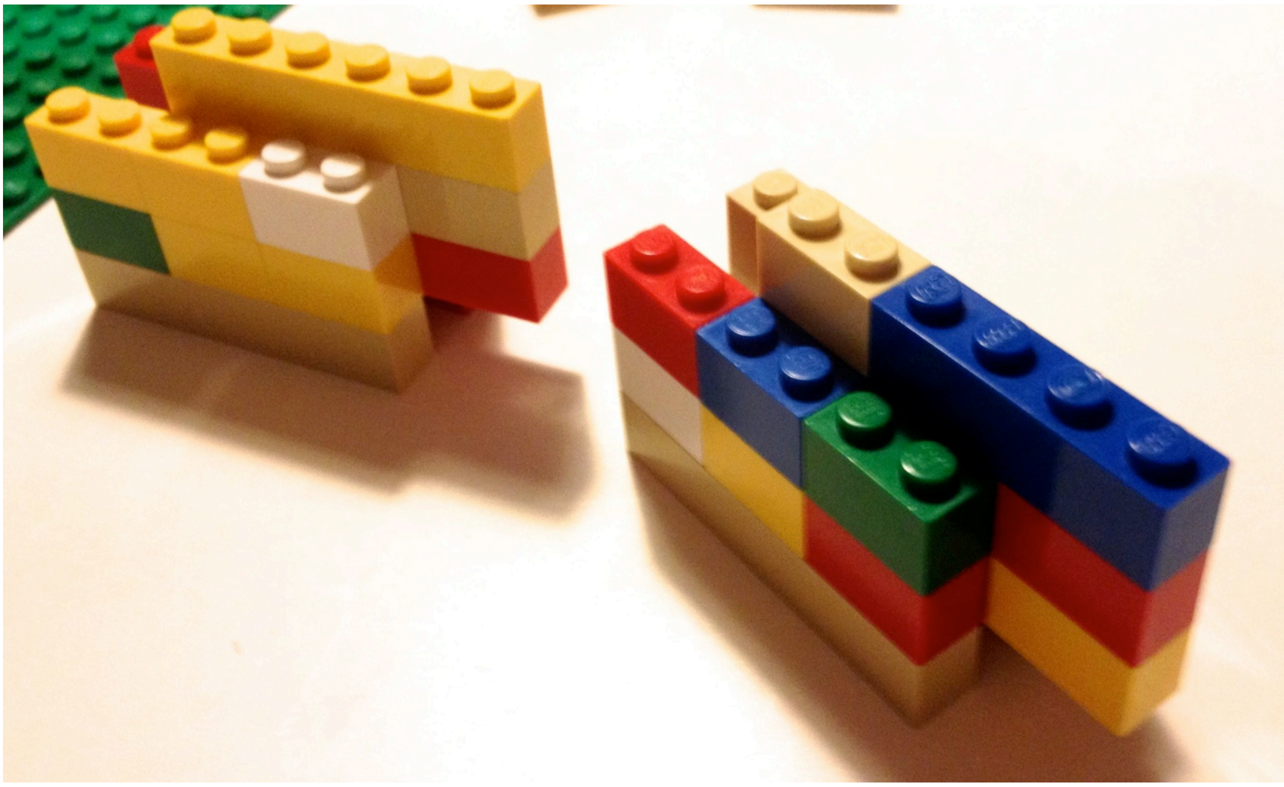

Figure 28: LEGO model of Styrofoam with offset part in the middle

The plan was to press down the form ties in the Styrofoam. The distance between each tie should be about 300 mm. A long-term plan was to make chamfers, which would allow the form ties to more easily attain the exact position.

5.2.7 Attachment of the Styrofoam to the ground

The placement of the wall corners are marked by a specialist with a laser tool. When the first layer of Styrofoam is in place, it is very important that the pieces stay in their exact places. The pieces are very light, so even a small wind gust may be enough to move them. Different solutions have been discussed on how to prevent this from happening. The feasible ones at this point are:

Glue of some type that attaches to both the concrete and the Styrofoam.

Double-sided tape

Both solutions have the disadvantage of being difficult to handle if the concrete is wet or damp. The thickness of the tape is also a negative aspect. Even a small difference in height somewhere under the first layer of Styrofoam pieces might cause the whole wall to skew in any direction.

None of the solutions is perfect, but some type of glue is probably the best solution. In the first test it is not possible to use any adhesive at all. And this is why the base plate needs to be cleaned after the test is done. Another factor to consider is that if adhesive was used, the Styrofoam would be next to impossible to remove from the concrete.

5.2.8 Length adjustment of wall

The aim during the product development work on the Incoform solution has been to keep the number of different parts to a minimum. The Sonoboards are therefore manufactured in just one size. Without a solution for the length adjustment of the wall, it is only just possible to build walls with lengths that are multiples of the length of the Sonoboards. It is possible to cut the Sonoboards, but not desirable due to the high cost of the disks. (The cost of Sonoboard is more than three times that of plywood with the same dimensions.)

To solve this problem it has been decided to use dimensions of the Sonoboard that are also available in plywood. The Sonoboard comes in two thicknesses, and the thinner one would probably work sufficiently well. However, plywood of the same thickness is too weak, so the thicker version of the Sonoboard is used anyway.

One corner solution has been developed that solves the problem of length adjustment of the wall. It cannot be tested at the first test casting though and is therefore not presented here due to a possible patent process.

5.2.9 Lower attachment of the boards, the concept Lower PUR

All boards are going to be attached both at the top and the bottom, except the first one that is placed on the ground. This board needs another type of attachment since there is no form tie below it. On the inside of the board, spikes will be attached to the concrete and provide support in the direction towards the Styrofoam. At the top of this board a form tie will be attached in the same way as in all of the other boards. To solve this problem a board with a reduced height is manufactured. The height should be the same as that of half of the form lock. These dimensions are just for the first test and will change when the cheaper version of the form lock is implemented. The function of this lower part will be exactly the same though if the test goes well. The first layer of Styrofoam blocks is obviously the same height as the first layer boards.

6 Test and verification

The development of parts ended before the summer of 2013, pending the test in the autumn. During this time, Incoform made some changes to some of the parts. This chapter describes the objective of the test, the actual parts and the result.

6.1 Verification

The Incoform idea has been twisted and turned during a long time with sketches, models and discussions with the company. To verify that the wall is performing as expected, it is necessary to have a high wall to achieve the high pressure that the concrete exerts on the mould. Most important is that the mould can withstand the pressure that results from a raise time of one metre concrete per hour. 1 m/h is the same or better than most of the ICF forms on the market today. The pressure during a casting with this mould is estimated at 40 kN/m^2 [Betong- och armeringsteknik, 2009].

The questions that needed to be verified:

Can the form withstand a raise time of 1 m/h without any visual deformation?

Can the requirement of warpage be met?

Is the Lower PUR concept reliable?
This part of the construction is the most critical due to the fact that it is placed at the very bottom of the construction. A major leak due to a malfunction of this part would lead to a total failure of the test. The pressure in the construction is highest at the bottom, so if something breaks due to the high pressure, it will be in the lower part.

Is it possible to put the Styrofoam directly on the ground without any adhesives to keep the first layer in place?

Is the Styrofoam strong enough together with the form tie, or will there be any visual deformation? The problem area could be the attachment of the form tie in the Styrofoam.

The Styrofoam exists in a variety of variants and the one that was considered for this prototype was the S200. The question that needed to be verified was if the S200 could withstand the forces during the cast and still meet the requirements?

Is it possible to use Styrofoam that is cut from standard dimensions?
Styrofoam is manufactured in blocks and the most cost effective solution would be to cut the building blocks from these standard sizes. A much more expensive but also flexible solution would be to mould the Styrofoam. A mould would enable complex design solutions but the start-up cost of a mould is very high and not possible for Incoform today.

Is it possible to use the Styrofoam without the offset part as in figure 27? The offset is displayed in Figure 28.

Is the design of the form tie reliable?

Is the Sonoboard reliable?

Is form oil necessary to use?

Form oil is used to prevent the plywood, or in this case Sonoboard, from sticking to the concrete after the curing.

Is “David´s corner” reliable?

Are there any knowledge gaps? What has not been considered? What is unknown?

The test will not evaluate the strength of the concrete wall due to the assumption that the concrete will perform in the same way as in any other wall with the same thickness. The factor to consider is if the surface of the wall corresponds to actual norms (AMA Hus 11).

6.2 Preparations

In order to gather important information about the test, an A3 report was compiled together with Incoform. The A3 report is a good tool to gather around to ensure that we agreed on the design of the test, the design of the parts and the course of action. The A3 is an internal document not intended to be read by outsiders, and it is therefore not included in this report due to the fact that it is impossible to understand. The different areas included in the report are:

- Design parameters for the different parts
- Status from manufacturers
- Dates
- List of material
- List of material to order from suppliers
- Sketch of the prototype
- To do’s
- Location and test site
- Type of concrete

The A3 report and the Ponti´s method were continuously updated by hand. The choice to write the report by hand made it more visual (not forgotten in a computer) to both parts in the project and also very simple to update when new information was discovered. Knowledge gaps were managed in the same way as the functions in the Ponti´s method, with post-it notes, marking that something needed to be considered in one way or another, or that a knowledge gap needed to be closed.

6.3 The test

In this chapter the different parts and the execution of test are described.

6.3.1 Test site

The test site was initially planned to be on a concrete slab provided by a partner to Incoform. The slab would provide a flat surface in the right material. In a real situation when a house is built the surface is a concrete slab, so this condition was perfect. A flat and horizontal surface is important in order to avoid the wall beginning to tilt. In most cases the wall will still tilt, and it is a standard procedure to support it with adjustable struts so that it can be positioned in a completely vertical position. In this case it was more interesting to see if the wall begun to tilt rather than to have a perfect vertical wall, since the aim was to identify knowledge gaps in the overall construction.

Incoform chose to change the location to a more accessible spot. The foundation there was much rougher, so a flat and horizontal surface had to be fixed. This was accomplished with shovels, rakes and a layer of plywood.

Figure 29: Test site

6.3.2 Styrofoam

The Styrofoam was ordered in just one size to minimise the cost. The blocks were initially constructed with an offset in the middle to provide a higher stability in the construction but also to reduce the number of thermal bridges. The Styrofoam blocks were ordered but at the last minute cancelled by the manufacturer. The manufacturer got a really big order from one of the giants in the industry and the consequence was that they cancelled our small order to make place for the bigger one. With the new manufacturer the offset was not possible to make with the right dimensions. The process had to go on and the offset was removed even though a small thermal bridge could occur and consequently the stability could be reduced. The dimension of the delivered Styrofoam was 300 x 400 x1200 mm.

Two different variants of the Styrofoam called S200 and S300 were ordered. The difference between them is the pressure that the material can handle during the curing of the concrete. They have different density (S200 32 kg/m^3, S300 40 kg/m^3) but nearly the same insulation properties. The reason for ordering different variants was the interest to investigate the difference in how the requirements are met between the two different variants.

The manufacturer of the Styrofoam also provided two different tolerances of the Styrofoam blocks. The height and length of the blocks were the same. The difference was in the top middle part where the first tolerance made the blocks easy to fit together when they were stacked. The second tolerance made it more difficult to fit the blocks together and a person had to jump on the blocks to get them into the correct position, Figure 38.

The first layer of Styrofoam was cut with a hand saw to get the height corresponding to the Lower PUR solution.

Figure 30: Cutting of the bottom Styrofoam part

6.3.3 Connection to the ground

The intention was to use some kind of adhesive to anchor the Styrofoam to the ground. But Incoform wanted to investigate if the construction needed to be anchored in the ground and the plan became to try without anchoring and just put the blocks directly on the plywood. This turned out to be a bad idea. It was hard to keep the blocks in a straight line and screws through the Styrofoam were therefore used. In this case it was really good that the test was not performed using the concrete slab as planned from the start.

Figure 31: Screws through the Styrofoam into the plywood

Figure 32: Styrofoam with a height to fit the Lower PUR.

6.3.4 Form tie and form lock

Figure 33: Custom made form tie

A form tie is a standard component, but the type used in this test is custom made. It is very similar to the standard one. The difference is the metal plate that is pressed down into the Styrofoam. The distance between the ties is 300 mm and it was marked on the Styrofoam so that the ties could be mounted in the correct positions. The ties were placed on the Styrofoam and then knocked down into the material with a hammer. To reduce the stress on the joint between the plate and the tie, the Styrofoam was treated with a handsaw before the tie was knocked down at the right position. This was a really time consuming activity that must be considered in the evaluation.

Figure 34: Mounting of form tie

The form ties were ordered with an extra length that made the form ties more flexible. In fact, if something went wrong in the test and the structure had to be reinforced on the outside of the Sonoboard that was possible with the extra long form tie. The extra length made it impossible to use the first intended form lock which requires that the tie be the exact length.

The form lock that was used is not dependent on a special length of the tie. The lock is mounted on the tie and tightened with a special tool. The quality of this lock was not as expected and a few of the locks did not perform as intended. It was very hard to tighten the form locks in a good way; they were either too loose or so tight that the plastic cone on the inside of the Sonoboard was deformed. The result was that the Sonoboards did not line up properly (see Figure 36) where this occurred, and the concrete wall was uneven at these spots.

Figure 35: Mounted form lock with bad performance and the improperly aligned Sonoboards

6.3.5 The part Lower PUR

The part called Lower PUR is meant to be manufactured from the same material as the Sonoboard. To reduce the cost, it was made from plywood on the test site. The plywood had the same thickness, 15 mm, as the Sonoboard. The holes corresponded to those in the form ties.

Small spikes were placed on the inside of the plywood to keep it in the right position during the assembly of the different parts. The form ties put a substantial pressure on the plywood, so these spikes were probably redundant.

Figure 36: First layer of Styrofoam, mounted form ties and supportive spikes.

Figure 37: First layer of Styrofoam, mounted form ties and Lower PUR.

Figure 38: First layer of Styrofoam and form ties. The fit was really tight, so some parts needed to be exposed to a large force to place them in the correct positions.

Figure 39: Styrofoam with a cut groove to fit in the corner

6.3.6 Sonoboard

The material was custom made in one size boards. The material is easy to cut with a hand or electric saw, so a few pieces were cut on site. The test was constructed with a corner, and to save material the wall to the right of the corner was made a bit shorter than the left one and it was therefore necessary to cut the boards to the right sizes. The manufacturing process of the material made it possible to order any size but to reduce the cost of the test just one size was ordered.

Figure 40: Sonoboard

The top of the board is manufactured with recesses for the form ties. The form ties were put in position first and then the Sonoboard was put in place. The recesses made it really simple to get the board in the right position and even though that the form ties sat firmly in the Styrofoam there was no problem to bend them a bit to get the boards in place. According to the manufacturer the material is brittle on the edges so the parts where initially handled with care.

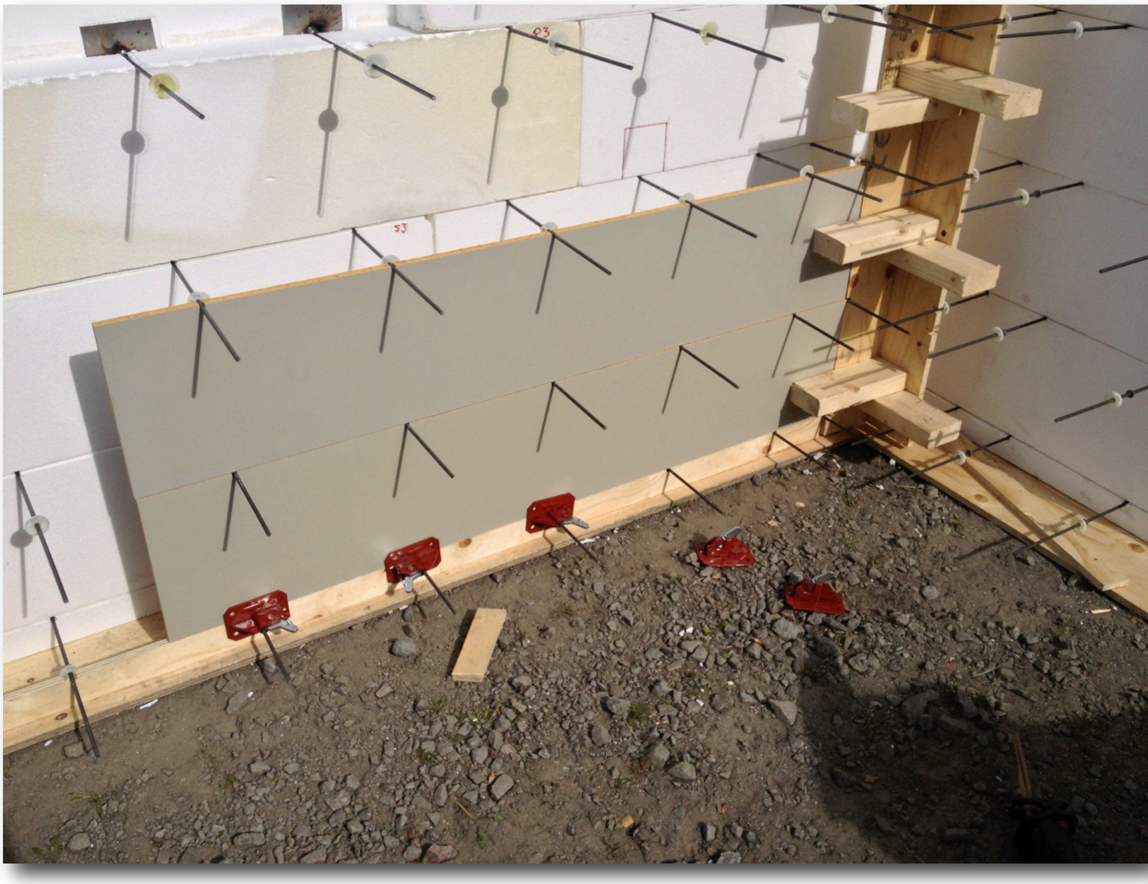

Figure 41: The first mounted Sonoboards and form locks.

The planned metal corners were not delivered to the test, so an on-site quick fix was created using with an earlier concept as a model. The corner is made of 15 mm plywood and supportive wood pieces. See Figures 41 and 42.

Figure 42: Test rig with corner solution and the wood stud that closes the right side of the mould.

6.3.7 "David´s corner"

"David's corner" is a solution for two problems. The first problem is that the stacked Styrofoam in the corners cannot withstand the pressure from the concrete without deformation of the corner. The other problem to solve is that the end part that consists of three wood studs must be kept in the correct position during the casting. The solution for this is to place a wood stud on the outside of the corner with a pervading rebar that is pushed through the Styrofoam into the mould and also pervading the wood stop in the end of the mould. A conventional form lock is used in this solution to lock the wood studs towards the rebar. In Figure 44, the left wood stud is shown with the three form locks.

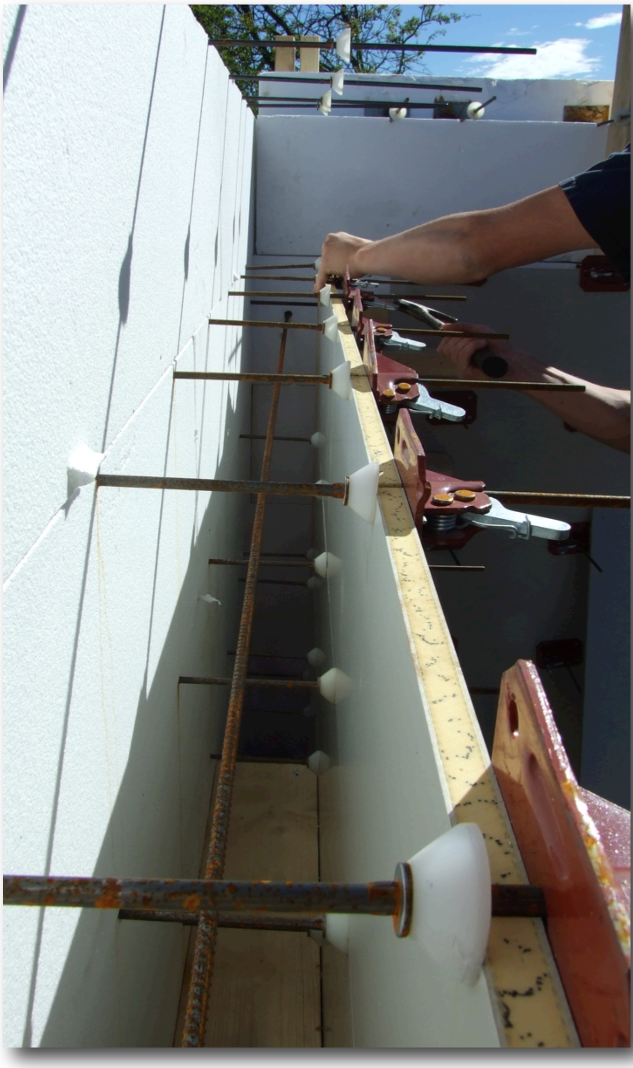

Figure 43: The pervading rebar on the inside of the mould.

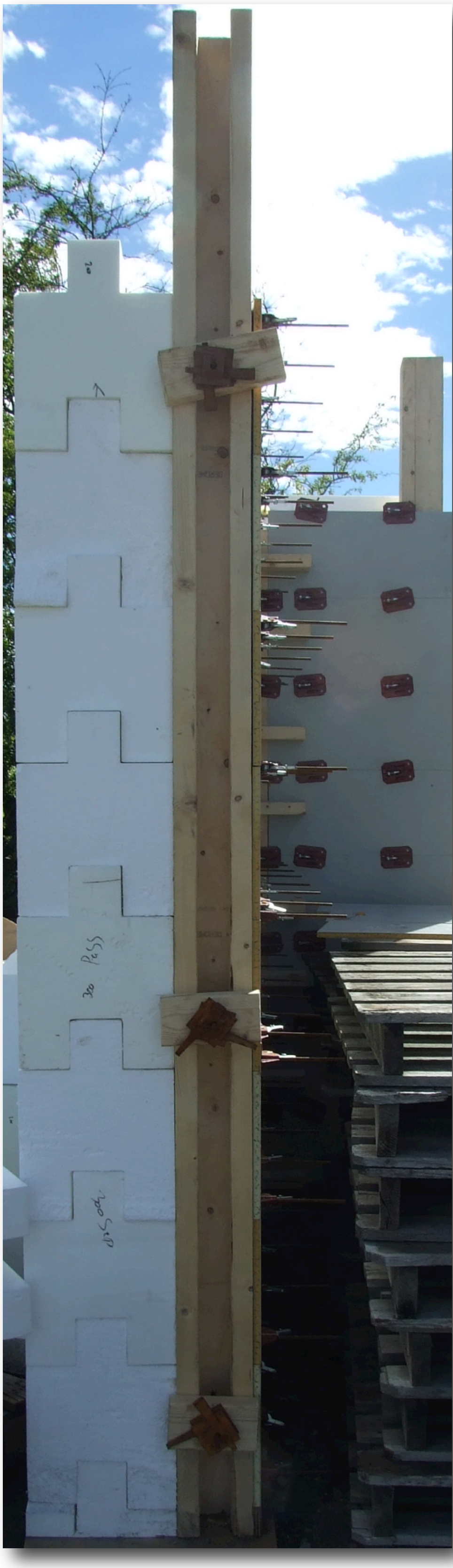

Figure 44: Wood stud with form locks.

Figure 45: Wood studs on the back of the mould, each with 3 form locks that lock the 6 rebars on the inside of the mould.

Figure 46: Mounting of the last form locks

6.3.8 Concrete and vibrator

When concrete is poured into a mould it is not assumed that the distribution of the concrete is even through the mould. To even out the concrete a vibrator is immersed into the fresh concrete and the result is that air in the concrete is pressed to the surface and the concrete is distributed and packed. An ICF is a bit brittle and therefore a vibrator is not used in these moulds due to the risk that the vibrator will burst the form. Instead self-compacting concrete (in Sweden known as SKB) is used where a vibrator is redundant. The plan was to use SKB for the test but when Incoform placed the order for the concrete the supplier could not deliver SKB in such a small quantity. The strength of the cured concrete was not of interest and therefore the supplier could ignore the quality of the concrete and just deliver a concrete with a loose texture similar to an SKB.

The concrete was delivered in two rounds. In an ordinary situation the concrete truck would be filled with a few cubic metres of concrete but when the form is in this small size, it is not possible to fill up the mould in the required speed before the concrete in the truck starts to become slow flowing. Therefore the truck was just half filled so that the right raise time of the mould could be achieved (1 m/h).

Figure 47: Pouring of concrete

After the casting of the concrete into the form Mr. Salekärr, who is a skilled concrete worker, was not satisfied with the distribution of the concrete in the mould. A vibrator was then immediately rented. As mentioned before an ICF is not rigid enough to be exposed to the vibrator. But this mould was perceived as very stable and rigid so the risk that the vibrator would ruin the mould seemed very low. The assumptions turned out to be right. No damage was seen.

Figure 48: The vibrator is lowered into the form

6.3.9 Material cost for the test

Concrete with delivery: SEK 8350
Plywood, wood boards, spikes, screws, electric cord etc: SEK 2490
Form locks: SEK 3775
Form ties: SEK 3312
Sonoboard 1500 x 300 mm: SEK 6500
Styrofoam: SEK 6800
Shipping costs: SEK 3523

In total: SEK 34.750 excluding sales tax.

This price might seem high for less than 8 m^2 of wall. But it is important to keep in mind that the Sonoboards can be used again together with the form locks. And all parts were custom made, so in a big project, the prices of the different parts would be reduced.

Figure 49: The mould right after the pouring of the concrete

6.4 Removal of the Sonoboards

The form locks opened up with a few hammer strikes and could easily be removed. Even if the procedure is easy, it is quite time consuming to remove all of the locks.

The most common procedure after a concrete casting is to remove the form the following day. A longer time between the casting and the removal of the form, will increase the work that will be necessary to remove the form from the concrete due to that the material gets stuck to the concrete. In this case it was impossible to meet up with Incoform for the removal the day after and a few days went by before we could remove the Sonoboards. Even though a few days went by the Sonoboards were very easy to remove and not a single part had stuck to the concrete. Noteworthy is that no form oil was used and this reduces the number of operations and also the mounting time for the form. After some cleaning, the surface of the Sonoboard was as good as new.

Figure 50: The mould before removal of the Sonoboards

The ”Lower PUR” solution with a plywood board was not easily removed. It was obvious due to the colour of the wood that it had absorbed water and as expected it stuck to the concrete. The adhesion to the concrete was so strong that it was impossible to remove the wood in one piece so compared to this the performance of the Sonoboard was really outstanding.

When the form ties were ordered from the manufacturer by Incoform, the design feature with a small deformation of the metal where the small plastic cone is situated, was forgotten. This small jag makes it possible to bend and break the form tie inside of the small plastic cone. Not a big issue, all form ties were removed with a grinder instead.

When all form ties and Sonoboards were removed, the concrete surface was studied. The areas where the form ties had malfunctioned were as expected not good enough to fulfil the requirements for warpage. The warpage is measured with the help of a straightedge (2 m) and folding ruler, the deviation cannot exceed ± 5 mm. The warpage should also meet the requirement with a deviation smaller than ± 2 mm, with a straightedge that is 0,25 m. This was not met due to the malfunctioning form locks. No deviations could be detected on the areas where the form locks had been functional.

Figure 51: Malfunction form lock and deviating Sonoboards

Figure 52: Verification with straight edge

Figure 53: Finished wall with opening for window

Figure 54: Close up of one hole, where the plastic cone was situated. The form tie was removed with a grinder.

6.5 Answers to the verification questions

Can the form withstand a raise time of 1 m/h without any visual deformation?
Yes. No deformation was noticed.

Is the Lower PUR a solution that is reliable?
Yes. With another type of form-lock this part will be adjusted in height to fit to the lock but the concept works properly without any changes.

Is it possible to put the Styrofoam directly on the ground without any adhesives to keep the first layer in place?
No! It is very hard to put the parts in the correct position and keep them there. A small correction on one piece will move the other parts and some adhesive is necessary. In this case were screws were used which would be impossible in a real situation where the foundation is concrete and not plywood as in this test.

Is the Styrofoam strong enough together with the form tie or will there be any visual deformation?
Yes, it is strong enough! No visual deformation could be seen.

The Styrofoam exists in a variety of variants and the one that was considered for this prototype was the one called S200. And the question that needed to be answered was if the S200 could withstand the forces during the cast and still meet the requirements?
Yes, the S200 is good enough. The problem with warpage of the wall was not due to the quality of the Styrofoam.

Styrofoam is manufactured in blocks and the most cost effective solution would be to cut the building blocks from these standard sizes. A much more expensive but also flexible solution would be to mould the Styrofoam. A mould would enable complex design solutions but the startup cost of a mould is very high and not possible for Incoform today. Is it possible to use Styrofoam that is cut from standard dimension blocks?
Yes it is probably possible, but due to the fact that the form ties need some type of design feature to fit, without on-site-fix, it is more realistic to plan for Styrofoam that is made with a mould. It would probably be possible to manufacture with standard dimensions but then it is necessary to add a station at the factory where the extra design features are manufactured. Incoform has a solution of how this could be done but it is not realistic to implement this solution before this type of product is manufactured in a big scale.

Is it possible to use the Styrofoam without the offset part?
Yes. The stability of the wall is very good thanks to the offset part in the bottom and the top of the Styrofoam. When the pieces were put together we climbed up and sat and on top of the Styrofoam and it was very rigid. It is for stability reasons, not necessary to have the offset to the right and left in the blocks. However, this must be further investigated due to the fact that without the offset, a thermal bridge will appear between the Styrofoam parts.

Is the design of the form tie reliable?
Yes!

Is the Sonoboard reliable?
Yes! The manufacturer claimed that the Sonoboard was brittle. At first the boards were handled with care but as the test proceeded the boards were subjected to more and more violence. In the end the boards were really tested and the conclusion are that the Sonoboard can withstand much more force and rugged handling than plywood can ever withstand.

Is form oil necessary to use?
No. Form oil is used to prevent the plywood or in this case Sonoboard, from sticking to the concrete after the curing. But in this case form oil is not necessary at all. The Sonoboard did not stick to the concrete even though that the form was not removed the following day as would be the normal procedure.

Is “David’s corner” reliable?
Yes, it worked as expected.

Are there any knowledge gaps? What has not been considered? What is unknown?

It was not expected that the form locks would have such bad performance as they did. A malfunction in the form lock with today’s solution will result in a defect of the wall on the spot of the malfunctioning form lock. One solution to prevent this is to make Sonoboards with some kind of a groove or fold so that the boards connect to each other (similar to the Styrofoam with an offset). The boards then dock in to the right position and also prevent the boards from moving out of position in the case of a not fully functional form lock. This kind of solution-was considered together with Incoform but for the first prototype it was desirable to keep the complexity at a very minimum, both to minimise the cost and to investigate how elemental the construction can be.

The requirements were not achieved. But this was obvious already during the mounting of the mould when the form locks not were fully functional. When the form locks were not fully functional the Sonoboard was not correctly positioned and an edge was created in the concrete.

The first manufacturer of the Styrofoam parts promised tolerances in the range of 0.1 mm deviation. When this company cancelled the order another company was contacted and in that process the tolerances were forgotten. When the parts arrived there were large big deviations from the ordered dimensions. All Styrofoam parts were around 7 mm shorter and 2 mm higher than what was originally specified to the manufacturer. The test had to stop when the wall was 2,77 m due to the fact that the Styrofoam did not meet up to the expected tolerances. The Styrofoam part of the wall was so much higher than the Sonoboard part that it was impossible to fit the form ties on the top of the mould.

There are two ways to hammer down the form ties in the Styrofoam, the first is to hit on the metal square. This was way too hard to accomplish without smashing the Styrofoam. The other way would be to hammer directly on the tie but one thing that we realised was that this would expose the weld to forces that might reduce its strength. The solution on site was to use a saw to cut out gaps where the form tie could fit. This solution was too time consuming to be a future way to handle the construction. The result of this is presented in Chapter 7, Conclusions.

6.6 Comparison of existing solutions with Incoform

To illustrate the competitiveness of the Incoform concept towards existing solutions a method called Pugh matrix was used. The various concepts were compared with 15 different criteria. Those criteria are based on the requirements and needs in section 4.2.

One wall solution is chosen as reference and the others are compared against this reference on all criterion. For each criteria the alternative concept can score +1 (better than the reference), 0 (same as the reference) or -1 (worse than the reference). When all concepts are compared to the reference the net value is summed up and the different concepts can be ranked. For this project the matrix was used to illustrate that the Incoform concept could be competitive on the market. To ensure that the ranking is correct three different solutions were used as reference separately.

Incoform's experience from the industry was the knowledge base for the scoring in the matrix.

Issued by: Erik Birgersson	Pugh Matrix					Created: 130401 Modified: 131127
Criteria	**Alternatives**					
	Ref: Prefab Concrete	**Wood stud**	**Incoform**	**Prefab Wood**	**Quad-Lock**	**Weber Leca Isoblock**
Man hours on site	0	-	-	0	-	-
Time to sealed house	0	-	-	0	-	-
Ergonomics	0	-	0	0	0	-
Thermal bridges	0	-	+	-	+	-
Risk of moisture in the construction, short term	0	-	0	-	0	0
Risk of moisture in the construction, long term	0	-	0	-	0	0
Required craftsmanship	0	-	0	0	-	-
Design flexibility	0	+	+	+	+	+
Fire retardant	0	-	0	-	-	0
Total cost of house	0	+	+	+	-	-
Installation complexity (electric and ventilation)	0	+	+	+	+	+
Required additional machines (for example crane)	0	+	+	0	+	+
Heavy wall properties	0	-	+	-	-	0
Operating cost	0	-	+	-	-	0
Risk of visible cracks in the surface layer	0	0	+	0	0	+
Number of +	0	4	8	3	4	4
Number of 0	15	1	5	6	4	5
Number of -.	0	10	2	6	7	6
Net value	0	-6	6	3	-3	-2
Ranking	3	6	**1**	2	5	4

Issued by: Erik Birgersson	**Pugh Matrix**			Created: 130401 Modified: 131127		
Criteria	**Alternatives**					
	Ref: Quad-Lock	**Wood stud**	**Prefab Concrete**	**Prefab Wood**	**Incoform**	**Weber Leca Isoblock**
Man hours on site	0	-	+	+	+	-
Time to sealed house	0	-	+	+	0	-
Ergonomics	0	-	0	0	0	-
Thermal bridges	0	-	-	-	0	-
Risk of moisture in the construction, short term	0	-	0	-	0	0
Risk of moisture in the construction, long term	0	-	0	-	0	0
Required craftsmanship	0	-	+	+	0	-
Design flexibility	0	+	-	+	0	0
Fire retardant	0	-	+	-	+	+
Total cost of house	0	+	-	+	+	-
Installation complexity (electric and ventilation)	0	+	0	+	+	-
Required additional machines (for example crane)	0	0	-	-	0	0
Heavy wall properties	0	-	+	-	+	+
Operating cost	0	-	+	-	+	+
Risk of visible cracks in the surface layer	0	0	0	0	+	+
Number of +	0	3	6	6	7	4
Number of 0	15	2	5	2	8	4
Number of -.	0	10	4	7	0	7
Net value	0	-7	2	-1	7	-3
Ranking	3	6	2	4	**1**	5

Issued by: Erik Birgersson, David Salekärr	Pugh matrix		Created: 130401 Modified: 131127			
Criteria	**Alternatives**					
	Ref: Incoform	**Wood stud**	**Prefab Concrete**	**Prefab Wood**	**Quad-Lock**	**Weber Leca Isoblock**
Man hours on site	0	-	+	+	-	-
Time to sealed house	0	-	+	+	0	-
Ergonomics	0	-	0	0	0	-
Thermal bridges	0	-	0	-	0	-
Risk of moist in the construction, short term	0	-	0	-	0	0
Risk of moist in the construction, long term	0	-	0	-	0	0
Required craftsmanship	0	-	+	+	0	-
Design flexibility	0	+	-	+	0	0
Fire retardant	0	-	0	-	-	0
Total cost of house	0	0	-	0	-	-
Installation complexity (electric and ventilation)	0	+	-	0	0	-
Required additional machines (for example crane)	0	0	-	-	0	0
Heavy wall properties	0	-	0	-	-	0
Operating cost	0	-	0	-	-	0
Risk of visible cracks in the surface layer	0	-	-	-	-	0
Number of +	0	2	3	4	0	0
Number of 0	15	2	7	3	9	8
Number of -.	0	11	5	8	6	7
Net value	0	-9	-2	-4	-6	-7
Ranking	**1**	6	2	3	4	5

To further differentiate the different solutions the matrix could be supplemented with weight functions on the different criteria. However, this would not be possible in a fair manner between all stakeholders when several criteria are contradictory. For example, the craftsman wants good ergonomics which is not related to the end- users. The contractor does not want to minimize the number of construction hours which is in direct conflict with the end-users who want a house built with as little work as possible to keep down the total cost. Who is the most important of the various stakeholders also varies from project to project. The value is therefore absolute for all stakeholders or projects. Much more interesting to note is that Incoform is the winner in all three comparisons, and has only a total of 2 minus (marked with pink in the first matrix.)

When measuring man hours on site, it is not so strange that it is higher than construction using prefabricated concrete walls that are finished when they are delivered to the construction site. This is therefore difficult to compete with.

Time to sealed house is the second criterion where Incoform is worse than prefabricated concrete walls. Although this criterion is hard to beat it should be noted that the time before the house is sealed is not particularly critical for Incoform´s concept as opposed to wood stud, due to the fact that the Incoform mould is not sensitive to moisture.

7 Discussion

The aim with this master thesis was to test the conceptual idea with a 3 metre high concrete wall to investigate if the concept is feasible. Even though the height of the wall did not reach the set target, it could be proven that the concept is feasible with some adjustments.

One goal for Incoform has been to remove as much as possible of the craftsmanship in the construction and replace it with clean assembly work. The part where the form ties were knocked down into the Styrofoam demanded a lot of time consuming work that is not assembly work. This makes it impossible to use the Styrofoam that is cut from one piece which then means that the manufacturing method which remains are moulding of Styrofoam.

The idea of making a mould the Incoform way, is a really good idea with big benefits in a residential environment. The time it will take to build a house with this solution will probably be shorter than with an existing ICF solution due to the fact that the wall is ready for surface layering on the inside after the curing of the concrete. This removes the step of building a wall on the inside of the ICF which will reduce a lot of time and material. The time and material savings will in turn lead to a lower total cost of the house. This is of course just assumptions at this point in the development, but any other calculation is hard to do when the product is still at a concept stage.

The patent is now pending for the idea with Styrofoam and form boards connected with form ties.

8 Conclusions

8.1 Further Development of the concept

There remains a lot of work to reach the point where Incoform can provide a full scale design solution. But the design features that need to be further developed for the concept are:

The Styrofoam needs to have insertion so that the form ties can be mounted without any modification of the Styrofoam on site.

When the manufacturing process is set for the Styrofoam, the Sonoboards can be adjusted in height to perfectly match the height of the Styrofoam due to the very flexible manufacturing process that is provided by the Sonoboard manufacturer.

Change the design of the form ties so they fit to a conventional form lock.

Change the height of the Lower PUR so it fits to the conventional form lock.

Investigate the solution with a groove or fold to the Sonoboard so that the boards are perfectly aligned even with a broken form lock.

Construct a solution for corners with angles other than 90 degrees.

Investigate and further develop the solution for length adjustment of the wall.

8.2 Recommendations

It has been proven that the Incoform solution can be realized, but a lot of work is still needed to further develop the product before it can be introduced on the market. After more than 6 months of work together with Incoform, the author can conclude that this will not happen without external investors. The recommendation to Incoform is to pause all further development, save the concept wall and focus all efforts on finding investors that are willing to finance the patent.

9 References

Holmdahl, L. (2010) Lean Product Development på svenska, Digitaltryck Nu, Gothenburg.

Ulrich, K. & Eppinger, S. (2012) Product Design and Development, 5th edition, New York; McGraw-Hill.

Liker, J. K. (2004) The Toyota Way. 14 Management Principles from the World´s Greatest Manufacturer, McGraw-Hill.

Quadlock (2011), Quad-Lock Product Manual, access date 16 May 2013, http://www.quadlock.com/technical_library/manual/Quad-Lock_Product_Manual_LowRes.pdf

Sundolitt (2010), Byggsystem-Sundolitt KUB, access date 20 June 2013, http://www.sundolitt.se/sundolitt/produkter/kub/kub-017

Byggrespons.se, Picture, access date 20 June 2013, http://www.byggrespons.se/images/Galleri/Sanda/Sanda5.jpg

Weber.se, Picture, access date 20 June 2013, http://www.weber.se/typo3temp/pics/4b4cf97a9a.jpg

Weber.se, Picture, access date 20 June 2013, http://www.weber.se/lecareg-produkter/raad-anvisningar/referenser-lecareg/villa-eken-billdal-goeteborg.html

Finndomo.com, Picture, access date 20 June 2013, http://www.finndomo.com/uploads/RTEmagicC_0027.jpg.jpg

Byggentreprenörerna (2009), Betong- och armeringsteknik, Sveriges byggindustrier, Borås/Göteborg. (In Swedish.)