GRADUATION REPORT

CONNECTING PREFABRICATED CONCRETE SHELL SEGMENTS

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PREFACE

This report is about my gradation in the Building Technology Master track at the Technische Universiteit in Delft. After a long bachelor, I made the choice to focus more on the technical aspects of architecture, rather than the design of buildings. This is due to my more practical approach of designs, and my interests in the production and construction of buildings.

During the electives in the master course the topic of shell structures was introduced in the Technoledge Structural Design course. The concept of designing with the aid rather than the problem of forces in structures was very appealing.

When a choice had to be made for a graduating topic, I was delighted to see that shell structures was one of the main topics in structural design. After a talk with Peter Eigenraam, I made a quick decision to focus on the prefabrication of shell structures.

During the literature research and some talks with Peter it became clear that a lot of possible topics were available within the range of prefabricating shells structures. Therefore a choice was made to look at different connection types and to design a connection for prefabricated segments of shell structures.

With this in mind a suggestion was made at the first presentation for a second mentor, Marcel Bilow. This added more expertise on connection and production techniques, which proved to be very useful during discussions and the presentations, in combination with the research already done by Peter Eigenraam.

During the graduation both mentors were very involved, and helped with organising and steering the graduation. With their help the final product is made, and the overview of the graduation was kept to avoid getting lost in time. The results lays before you, as this graduation report.

CONTENTS

INTRODUCTION

Iconic names such as Heinz Isler, Eero Saarinen, Felix Candela but also Antoni Gaudi have a thing in common: They all design buildings with the aid of natural forces, shapes and force transfers; Shell structures. Whether they used the principals of shell structure, or simply looked to nature for solutions (Gaudi), the designs they made are touching on the edge of imagination. With structures spanning 30 to 40 metres, while being only a few centimetres thick at the centre. The resulting structures are very slender, material saving, and do not require supports in the space they create. These shell structures are the result of the application of membrane forces, and designing the structures to make optimal use of these forces.

Figure 1: Sagrada Familia, design based on nature by Antoni Gaudi (Gagnon, 2009)

WHAT ARE SHELL STRUCTURES?

Shell structures are constructed systems described by three-dimensional curved surfaces, in which one dimension is significantly smaller compared to the other two. They are form-passive and resist external loads predominantly through membrane stresses. (Adriaenssens, Block, Veenendaal, & Williams, 2014)

Shells are in essentials three dimensional arches. Where arches are designed to transfer force in compression in two dimensions. Shells are designed in such a way that a third dimension is added to the

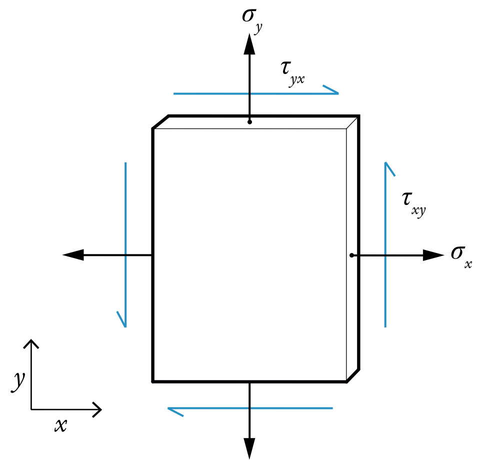


Figure 2: Plane stresses (Adriaenssens et al., 2014, p. 23)

principal, making it a three dimensional arch, transfereing forces in compression. This results in very slender structures, which support a lot of weight using only a limited amount of material.

Because of the typical force transfer in the shell, they transfer the forces in the plannar direction of the shell (figure 1), which causes shells to resist the loads through membrane stresses. Only a little of the force is transfered in the axial direction.

This makes shell structures very suitable for lower quality materials, which are very strong in compresion, but relativly weak in tension.

The most slender designs can be realised, and organic shapes can be achieved. The tension between the thickness and the span of the structures is immense, since metres of span can be achieved, with only a few centimetres of material. This results in

WHY DO WE BUILD SHELL STRUCTURES

Shell structures are used mainly to cover larger areas, with a minimal amount of material use. Not only do they cover large areas, they are also aesthetically appeasing, and mainly consist of organic forms.

Because of the shape and the design principals, shell structures transfer forces towards the foundations in compression very effectively. This means less material is needed to carry the designed weight, and make large spans. Less material means less costs, and a more sustainable building method.

In the design, no tension is present, which means cheaper materials can be used. Because designed forces and real forces might differ a bit (because of imperfections in the build structure), tension has to be taken into account while designing shells. Therefore steel reinforcement is placed, to make sure the shell can deal with tension as well as with compression.

With large structures the structural elements take a lot of space. By using shell structures, this space is reduced, and can be used for other functions (figure 3).

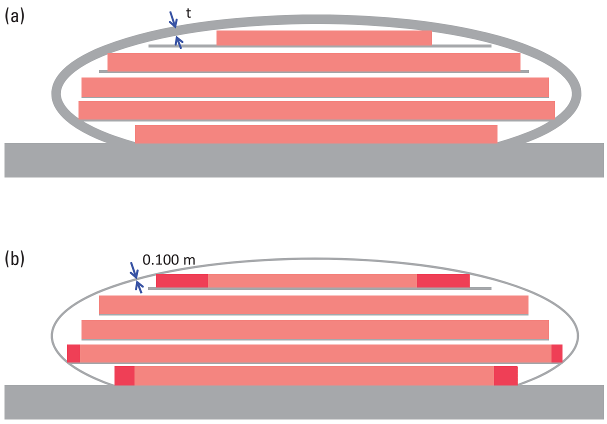


Figure 3: “Creating space“ by using Shell Structures. (Muttoni et al., 2013, p. 44)

DISADVANTAGES OF SHELL STRUCTURES

Even though shell structures wield a lot of advantages compared to regular structures, quite a few of disadvantages can be found during the build. Besides the extensive and expensive building process, the resulting shapes are determined by the present forces rather than the required spaces.

Shell structures are very often a none repetitive, unique shape, which needs to be produced on site. With the building of a manual formwork, the counter-shape of the structure is created, after which steel rebar is placed manually on the formwork. With the formwork in place, concrete is manually poured, and has to dry for at least twenty eight days. After this process, the formwork has to be removed very carefully, as to let the structure settle straight.

Because of all the manual labour on the building site, this process is very lengthy. Erecting a temporary structure, building a formwork to the specific design as well as the rebar placement and the pouring takes a lot of time and expertise. A brief overview of the time involved in the different aspects of the construction will be given in the chapter “Oceanografic Valencia”. The labourers are very expensive, and are working for a long time. Simultaneously all the time taken to build the structure no other work can be done. Even as the concrete is drying, the temporary support and formwork needs to remain in place, as the concrete has not reached its final strength.

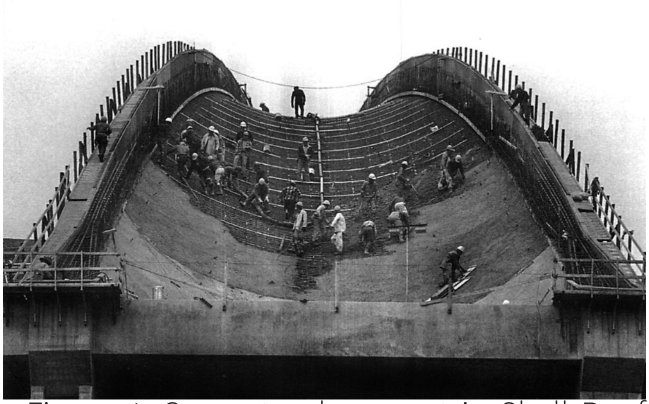


Figure 4: Concrete placement in Shell Roof (Times, 1975)

Also the design freedom of shell structures is greatly reduced when shells structures are used. While a lot of adaptations can be made, the final shape of the shell depends greatly on the forces present in the design, and the placement of supports. Also openings in the shell and specific external forces are of great influence on the design.

While the design freedom of the shell structure is limited, the advantages in material saving and force transfer can make the shell structure attractive. The only big disadvantage is the time consumed by constructing the shell structure, and the cost related to this.

TIME SAVING SOLUTION

In the previous chapter the advantages and disadvantages of shell structures were discussed. At the moment shell structures are very unattractive because of the building time and costs. The step to make shell structures more attractive to designers is to find a way to reduce the labour time on the building site, and thereby reducing the cost of the structure.

In concrete construction the main way to reduce building time on the building site is to prefabricate large parts in factories, and transport them to the building site, where they are assembled quickly. In residential housing the prefab method is used to produce large quantities of buildings cheap and quick. The only problem is that in residential housing there is a lot of repetition, and most of the surfaces in houses are flat, which makes it ideal for repetition.

Even though shell structures do not compare with residential housing in repetition and flat surfaces, prefabricating shell structures might be a good solution for saving time and money on the building site.

PREFABRICATING SHELL STRUCTURES
Because of the problems mentioned in the last chapter prefabricating shell structures seems to be a difficult task. There are a few hurdles on the way, which need to be taken before it is possible to prefabricate shell structures. A few of them are the segmentation of the shell, production of shell segments, and the assembly of the shell segments.

SEGMENTATION
The first step in prefabricating shell structures is to look at the way they have to be segmented. By looking at forces in the shell, transportation or the maximum sizes in production a segmentation of the shell has to be made. Because of the implication on the rest of the prefabricated shell, at least an assumption has to be made in this area, or an entire research has to be done.

Figure 5: Small bricks as segments (Adriaenssens et al., 2014, p. 6)

Because an entire research takes too much time to add into a graduation project, an assumption will be made upon the segmentation later on in this report. Research also has been done by Luitse (2016) in his graduation research report. By looking at forces during the construction of the shell (or in his case during the dismantling) a division of the shell has been made, which accommodates his research target of finding a way to minimize the use of temporary structures during constructions.

PRODUCTION

To make sure the determined segments of the shell structure can be produced, a production method has to be researched. Schipper and Janssen (2011) did research into the application of a flexible mould. Their research showed promising results, but needed to be expanded upon. CNC milling is another option for the production of moulds. This removes manual labour from the process, but is very material intensive, and creates a lot of left over moulds.

A lot of research has already been done into the prefabrication of doubly curved surfaces, and this also is an entire topic suitable for graduation. For this report we assume that it is possible to create doubly curved elements, which measure 3000 mm X 3000 mm.

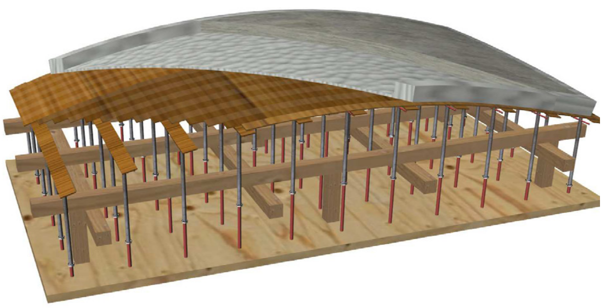


Figure 6: Curved mould (Schipper and Janssen 2011, p. 8)

ASSEMBLY

After the Shell segments are produced, and transported to the building site, the most important thing is to assemble the structure. The segments have to be lifted by cranes towards their position, and there be connected together. The lifting of large elements is not a problem, as it is done in all kinds of construction. The big issue is to connect the enormous elements together, until they form the final shell, and are working in compression.

As the order in which the elements should be assembled is already researched in the previous year (Luitse, 2016), the next topic to research is the connection of the elements. Since the connections are very different from regular prefabricated constructions, as they deal with very different forces, supports and positions. Therefore a look has to be taken into the forces which are encountered in the building process, the finished structure, and the way these structures have to be build.

In this report a research into the connection of the segments will be done. By designing, testing, analysing and discussing the different connection methods which already exist a proposal for a connection can be done, and a next step towards completing a prefabricated shell structure can be done.

RESEARCH QUESTION

With a clear idea of what needs to be done for the prefabricated shell structures to be realised, a clear research question can be defined. As a lot needs to be done, a focus will be put on the design of a method to connect the shell segments together. Since a connection is already designed, a way of judging the connection is needed. Therefore a list of criteria is made, and a method of testing and criticizing the connection needs to be devised. The main research question will be as follows:

How can we prove that a connection is suitable for use in a segmented prefabricated shell structure?

To answer this main question, a few sub questions are thought of:

- Which demands are made for a connections in a segmented prefabricated shell structure?
- How can we test the strength of a connection?
- How can we implement a connection in a digital model?

In this report these questions will be answered. The method in which these questions are answered, can be found in the next chapter.

METHODOLOGY

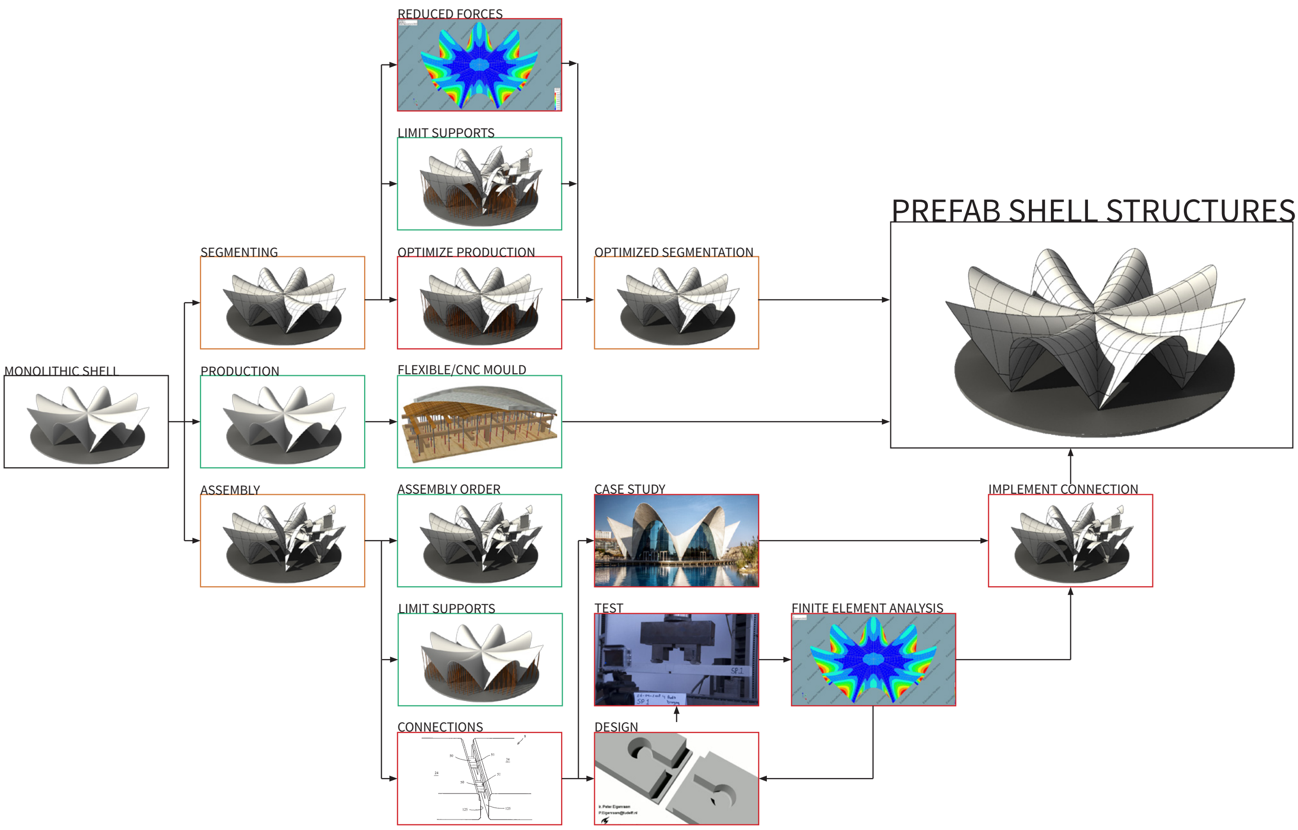


Figure 7: Flow chart of the graduation and the placement in the prefabrication of shells

In order to have a structured research into the connection of shell structures, the topic has to be clearly defined. Therefor a description of what already has been researched has been given in the last chapters. The next step is to decide how to answer the research question. In this chapter an overview of the different steps which will be taken to design a connection will be explained.

In figure 7 an overview of the directions in which the graduation will be going has been given. The first part shows three topics which are established for research, or which already have been researched (Shell segmentation, Shell production and Shell assembly). The green boxes of the chart show the topics which have been researched already. The red parst show the topics which need to be researched.

The connections will be the main research topic of this report, as only little research has been done in this area.

The research approach is split up into three different paths, which together will lead towards a connection for a prefabricated shell. These three parts are the knot design by Peter Eigenraam, the knot design by Guido van der Straten and the Case-Study of the Oceanografic in Valencia. These three researches will result into a knot, which can be used in a prefabricated shell structures.

To get a grasp on the scale of shell structures, and to clearly define the boundaries of the design, a case study is carried out. After a small search a very recent project is chosen. Because it is recent, the most advanced techniques are used in the construction, and a lot of information can be found.

The knot design by Peter Eigenraam has been commenced some time ago, as at the start of my graduation, a knot was already designed. The next step in this design process is to build a prototype. To do this formwork needs to be created, and the connection has to be established. If this has been accomplished, testing with a four point bending test can be done (figure 8). This will give results, with the strength of the knot, and the weak point in the design.

The knot design by Guido van der Straten will start with assembling a list of references, which will consist of connection from the concrete industry, but also from furniture, bridge building and other construction industries which use connections for connecting continues surfaces.

With these connections, a list of requirements, and a way to criticize the connections and rank them will be devised. These will include criteria on building time, strength, but also if the connections are easy to use.

Next a design will be made, as an improvement on the existing knot of Peter Eigenraam. The observed weaknesses will be taken into account, and an improvement will be made. Because of time restraints, no testing can be done. This improvement will be evaluated using the established criteria.

After all the testing, a value for the connection will be calculated, and put in Diana as a k-value. With these values an analysis will be run, and an observation will be made whether the connection is strong enough, to function within the shell, without weakening the shell.

This will in the end give a k-value, for which connections need to strive. This will advance the design process in such a way, that only the connection needs to be tested, and it has a minimal requirement,

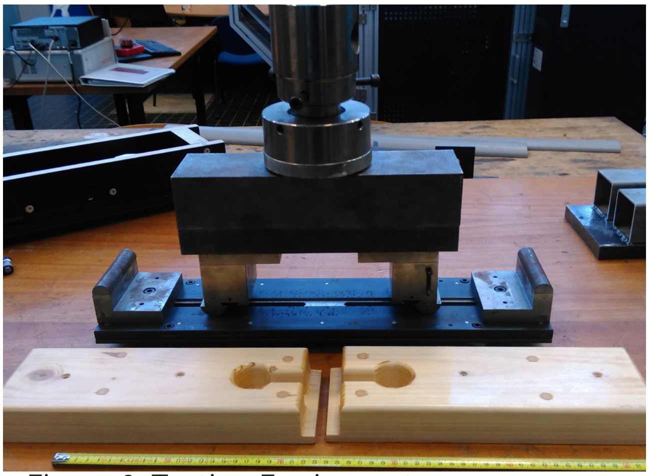


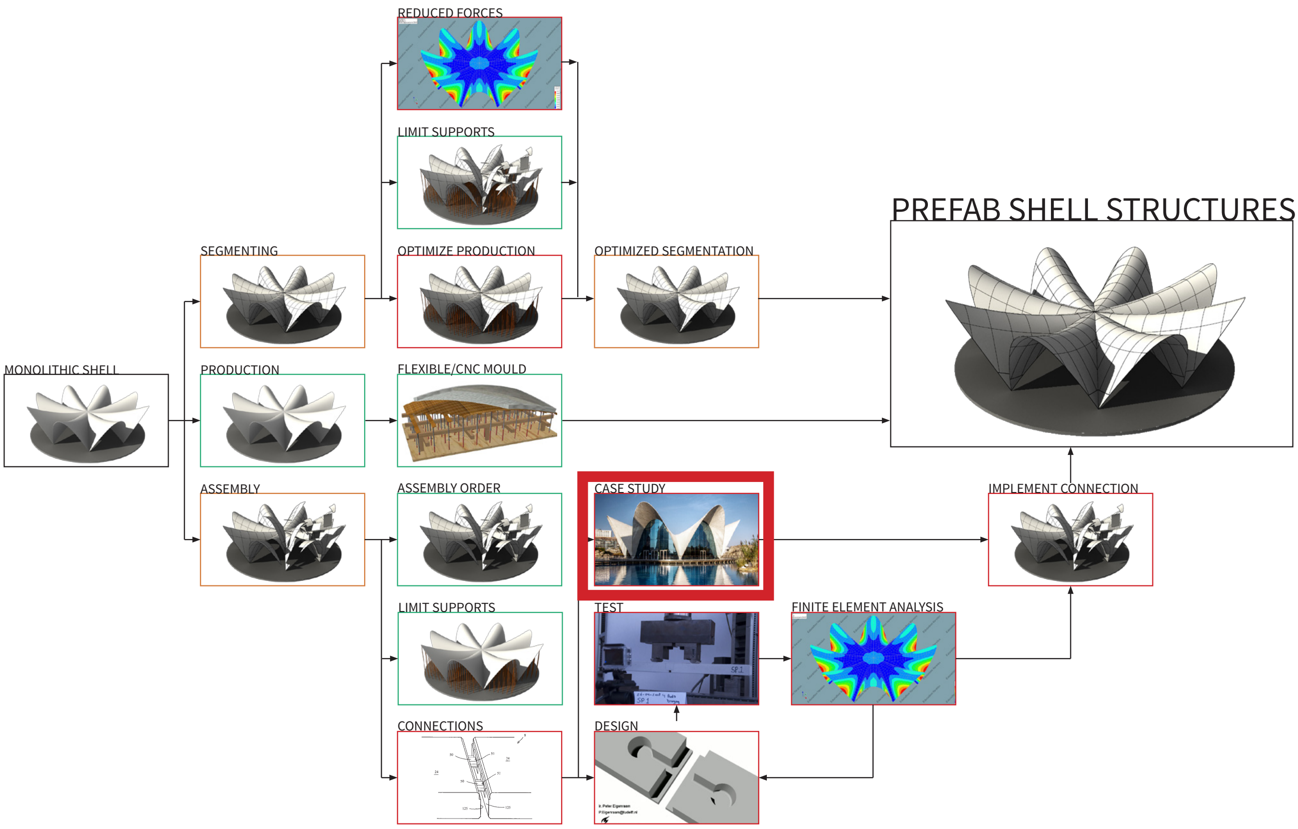
Figure 8: Testing Equipment

while it also can be criticized for assembly and production.

To verify the use of the values obtained from the four point bending test, a finite element analysis (FEA) will be performed. As early as 1975 these methods have been used and confirmed to provide information about the behaviour of structural elements. Krishnamurthy and Graddy (1975) used the FEA method to predict the 3 dimensional behaviour of bolted connections in steel structures. By comparing the results of a two dimensional analysis with the results obtained from a previous test. More recently Kulkarni, Li, and Yip (2008) analysed the behaviour of steel concrete hybrid connections. To make sure the FEA provided accurate results, it needed to be verified by comparing them to physical tests.

To make sure the results of the FEA of the counter top connector are accurate, a comparison needs to be made with the four point bending test. If the results compare, the FEA can be used to analyse the connections in a large shell structure.

CASE STUDY


REDUCED FORCES
LIMIT SUPPORTS
PREFAB SHELL STRUCTURES
SEGMENTING
OPTIMIZE PRODUCTION
OPTIMIZED SEGMENTATION
MONOLITHIC SHELL
PRODUCTION
FLEXIBLE/CNC MOULD
ASSEMBLY
ASSEMBLY ORDER
CASE STUDY
IMPLEMENT CONNECTION
LIMIT SUPPORTS
TEST
FINITE ELEMENT ANALYSIS
CONNECTIONS
DESIGN

OCEANOGRAFIC VALENCIA

Figure 9: Oceanografic (Iliff, 2007)

To start the process, first a case study is commenced. Because designing a connection for a shell structure is too wide of a topic, an existing shell structure is chosen, to find the dimensions, the forces and the aesthetic requirements for the connection.

The choice for the Oceanografic in Valencia is a very logical one. Because it was recently constructed (construction started in 2000), the most advanced techniques for designing and building a shell structure were used. The design by the renowned Felix Candela is an example of all the advantages of the shell structures, but the construction shows also all the disadvantages of shell structures.

First the general information of the building will be given. Next the construction of the shell structure of the building will be explained, and the time it took to build will be shown. Also the digital model of the building will be discussed, and the forces which are present in the shell will be discussed.

GENERAL INFORMATION

The Oceanografic is a park which exhibits sea animals. It is a large park created on a small artificial lake. It consists of multiple buildings, all housing different parts of the exhibit. One of the most remarkable building is the central building. Designed by Felix Candela, this shell structure houses the Submarine Restaurant. It is located on a concrete island, in the middle of an artificial lake.

The building is a polar array of a single shell, designed by the hyperbolic paraboloids of equation $y^2/100-x^2/4.6792=z-6$ (Barrallo, 2011, p. 70). This shape and equation has been used by Candela in many former designs. It is proven to be an ideal shape for the use as a shell structure, as it transfers all the forces in compression.

The shape also makes it possible to cover a large area, while only having 8 supports. This leaves an open area in the middle of the building, since no supports are needed to support the roof. The opening underneath the lobes is closed off by a curtain wall, which consists out of steel and glass.

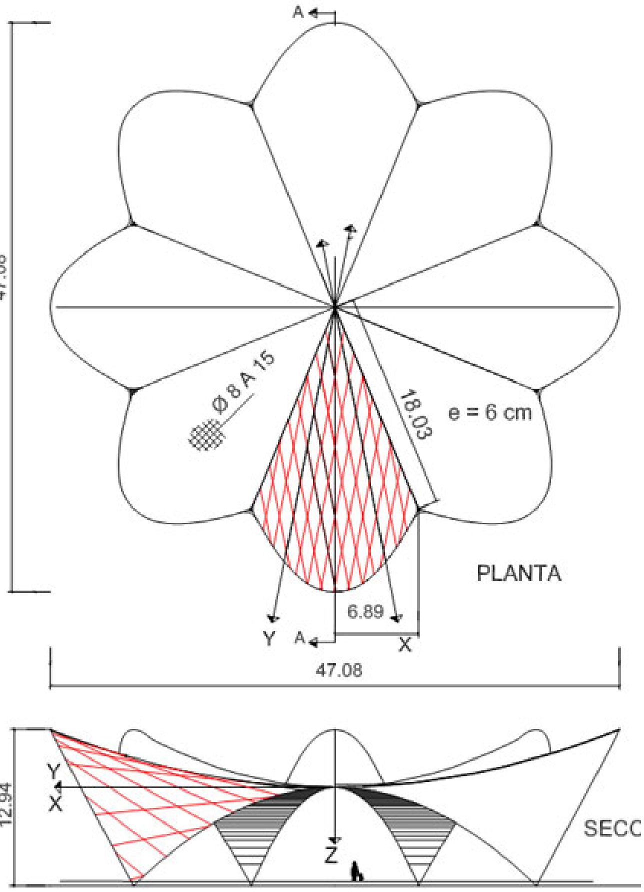


Figure 10: Dimensions of the shell Domingo et al, 2004, p. 1144)

Because the design makes use of the hyperbolic paraboloid, the shell can be made very thin. While the outer perimeters of the building are 47.080 mm by 47.080 mm, the span from support to support is at maximum distance 36.040 mm. The maximum height at the edges is 12.940 mm, and in the centre the roof reaches approximately 8.000 mm (Domingo, Lázaro, & Serna, 2004). This all while the maximum thickness of the shell does not exceed 60 mm.

CONSTRUCTION

To show the main disadvantage of shell structures, a small overview of the construction process of the restaurant will be given. From the start of the construction to the finishing of the shell, roughly 200 days passed. All the information is taken from Construction of Jchypar, a steel fibre reinforced concrete thin shell structure by Domingo et al. (2004), as they are the researchers and designers of the project.

TEMPORARY STRUCTURE

After the foundation is finished, the construction of the shell started. With the erection of a huge amount of temporary structures, the general form and support for the formwork is made. The structure consists of tubes, arranged in a grid of 1500 mm by 1500 mm by 1500 mm. With clamps at the top of the structure the formwork can be connected to the structure. It took approximately two weeks to complete the temporary structure.

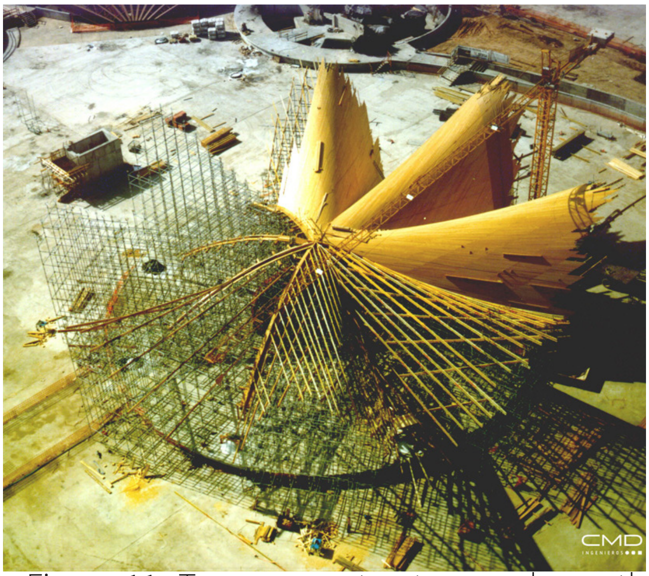


Figure 11: Temporary structure underneath the shell (CompetitionLine, 2012)

FORMWORK
On top of the temporary structure the formwork is placed. Because of the geometry, long lumber boards are placed upon a secondary wooden structure. Initially this took 15 days to completely cover 2 lobes, but because of the repetition the performance was improved, and it took 45 days to complete the total formwork. During the construction of the formwork, the mould release oil is sprayed upon the formwork, to make sure the formwork can be released without damaging the concrete.

Figure 12: Formwork on the structure Domingo et al, 2004, p. 1148)

REINFORCEMENT
The next step in the construction of the shell structure is the placement of the steel reinforcement. This is done manually, according to the design. Because of the manual placement on site, it took another 45 days to place the steel reinforcement, which is necessary to deal with the tension in the structure.

CONCRETE 'POURING'
As the formwork and the reinforcement is all in place, the next step is to start pouring the concrete. Because of the steep slopes on the shells, a method called shotcreting is used to apply the concrete on the formwork. By blasting a thick mixture of concrete on the formworks, the shell is created around the reinforcement. Because of the difficulty of pouring concrete on the slopes, the process took 60 days to complete, including the superficial finishing.

Figure 13: Construction the Los Manantiales, shell structure (skyscrappercity, 1958)

DRYING
Directly after the last concrete is poured on the formwork, the drying time started. Concrete has to settle, and it takes at least 28 days before it reaches its full strength. During this time, the temporary structure and the formwork has to stay in place.

FINISHING
After 28 days, the formwork and temporary structure can finally be removed. Because the shell structure is form-passive, any mistake in the construction can be disastrous. Therefore the formwork is removed according to a predesigned process, to monitor the deformations. Luckily the deformations where virtually nil. Because of the precision of this process, the disassembling took approximately 15 days.

CONSTRUCTION TIME
As shown in the last paragraphs, it takes quite some time to build this shell structure. Besides the inexperience of the contractors,

the manual labour on site on steep slopes and curved surfaces takes a lot of time. In total around 200 days were needed to construct the shell structure.

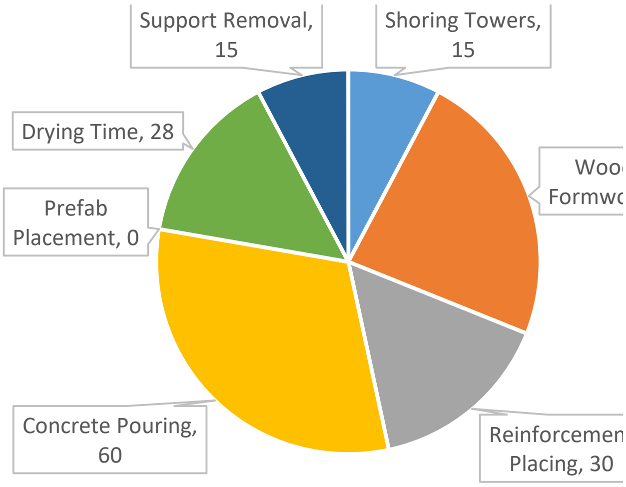


Figure 14: Amount of construction time (Own illustration)

DIGITAL MODEL

To get a grasp on the forces which are present in the shell, a digital model of the shell structure is made. With the use of the formula previously found in literature a rhino model is created. This model is exported, to be used in Diana. After the shell is modelled into Diana, an analysis is preformed, to see which forces work in the shell.

Because the formula on which the shape is based, is known, it is fairly easy to create a digital model. With a Plugin for Rhino, called MathSrf, the shell can be created easily. Because the formula only creates half of the lobe, and as a continues surface, some manual adaptations and translations are needed. By mirroring the created surface, a single lobe is created. By rotating the lobe 7 times, the shell is created. The last thing to do is to split all the surfaces with each other, so the final shape of the shell is created.

ANALYSIS

With the shell created in Rhino, an analysis can be setup in Diana. By exporting the shell as an .IGES, Diana can import the shell. After setting up the supports as not being able to translate, but being totally free in rotation as holds true for the real building (Domingo et al., 2004). The loads are besides its own weight, also the wind load is taken into account. With the analysis setup, we can run the tests, and find out how the force are transferred through the shell, and which forces are present.

RESULTS

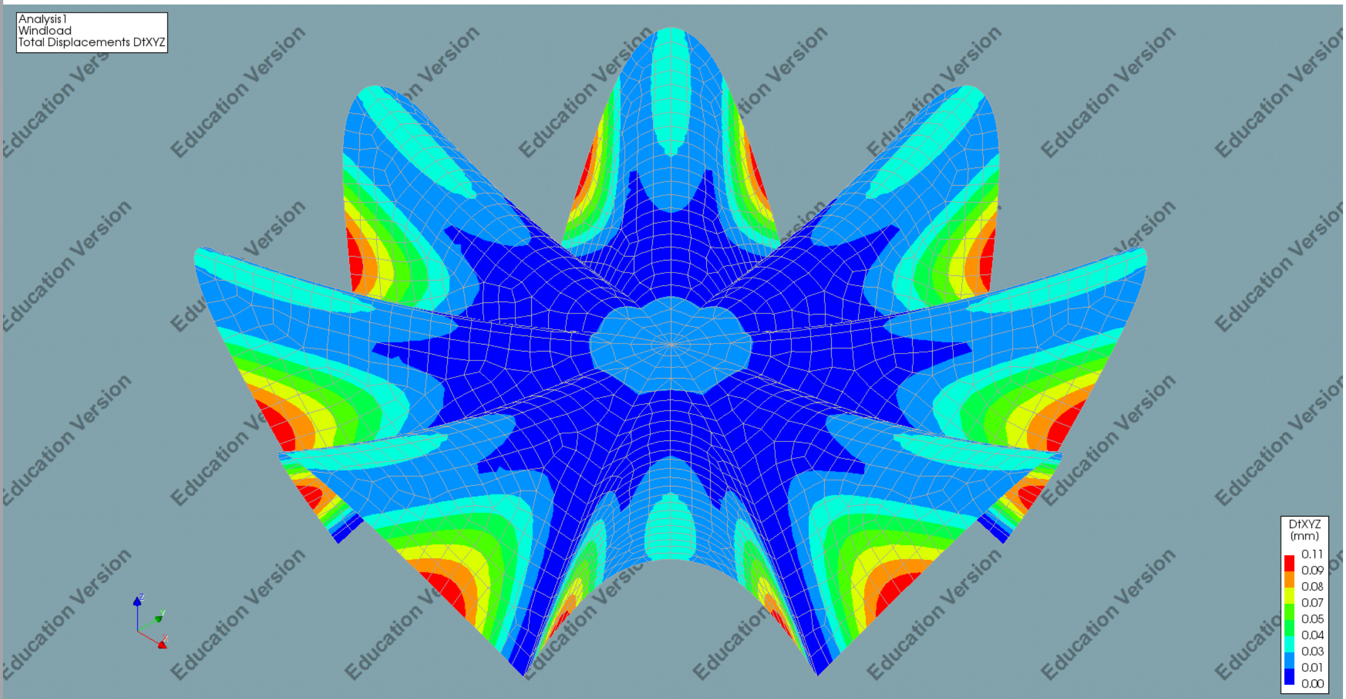
After the analysis is preformed, a few results stand out. Because of the small amount of supports, each support needs to carry a very high amount of weight, and all the forces transferred from the shell. Because of the shape of the shell, the force is not horizontal, but is tilted towards the shell.

The next thing which stands out is the bending moment. Because the shell is designed in compression, almost no bending moment is present in the entire shell. Again the foundation and supports are the place where the most bending moments are present.

With these results in place, a rough estimate of the forces which are transferred through the connection can be made.

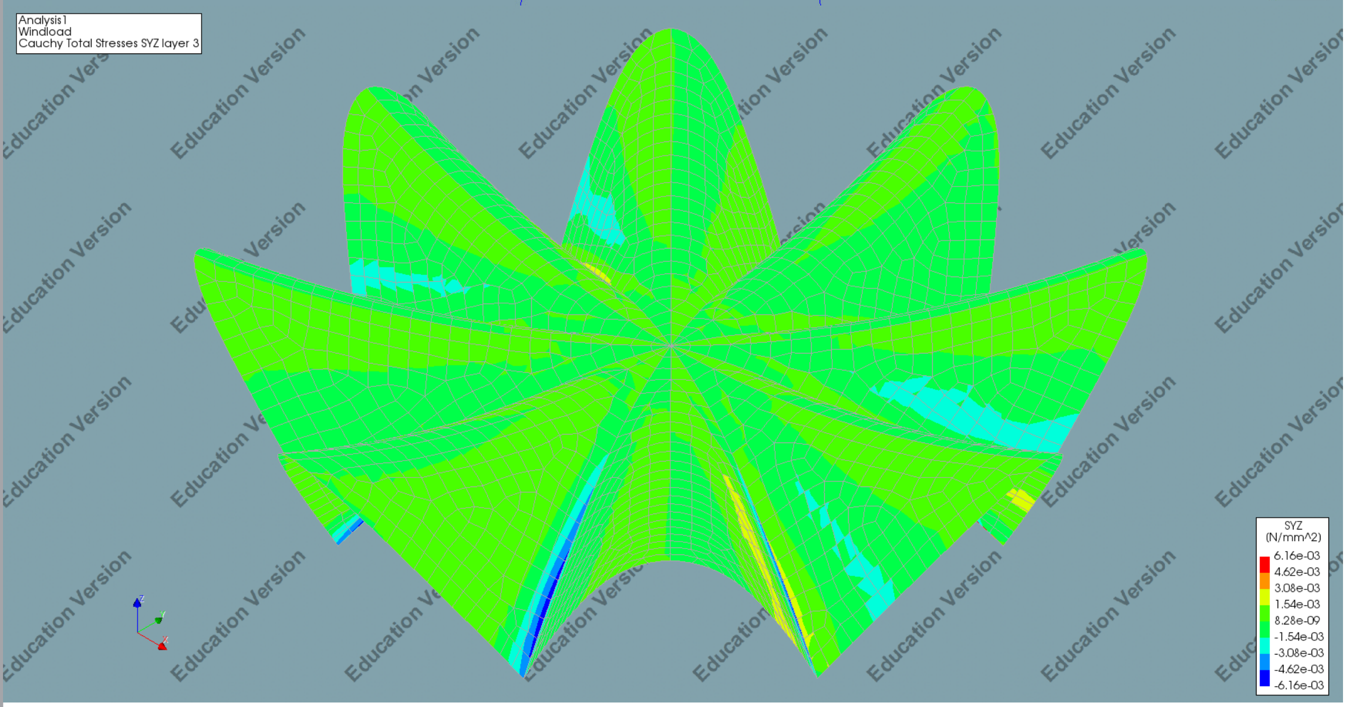
SEGMENTATION

With the forces known, the next step of this case study is to make a decision on the segmentation of the shell. Because segmentation itself is a topic which is worth a whole graduation report, a quick choice will be made on the segmentation, to know with which scale of segments we



Analysis1
Windload
Total Displacements DtXYZ
DtXYZ
(mm)
0.11
0.09
0.08
0.07
0.05
0.04
0.03
0.01
0.00

Analysis1
Windload
Reaction Forces FBXYZ
(N)
190.51



Analysis1
Windload
Cauchy Total Stresses SYZ layer 3
SYZ
(N/mm^2)
6.16e-03
4.62e-03
3.08e-03
1.54e-03
8.28e-09
-1.54e-03
-3.08e-03
-4.62e-03
-6.16e-03

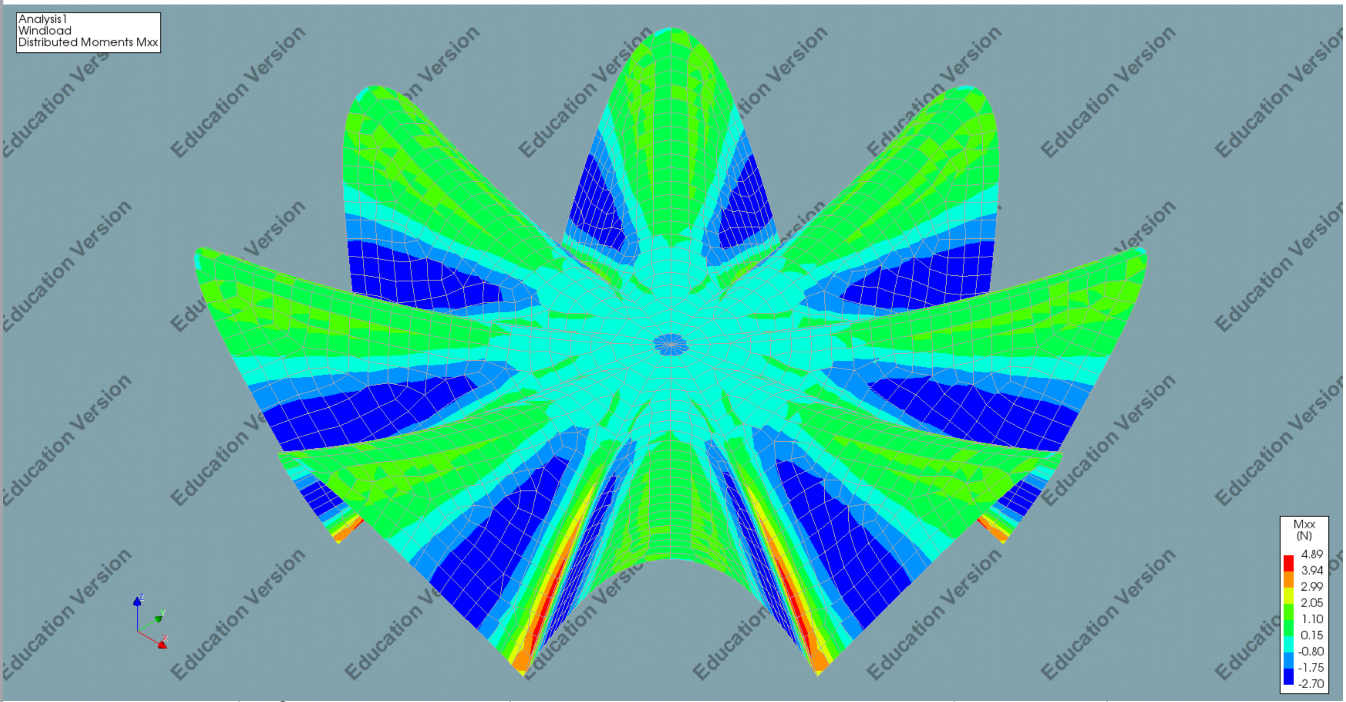
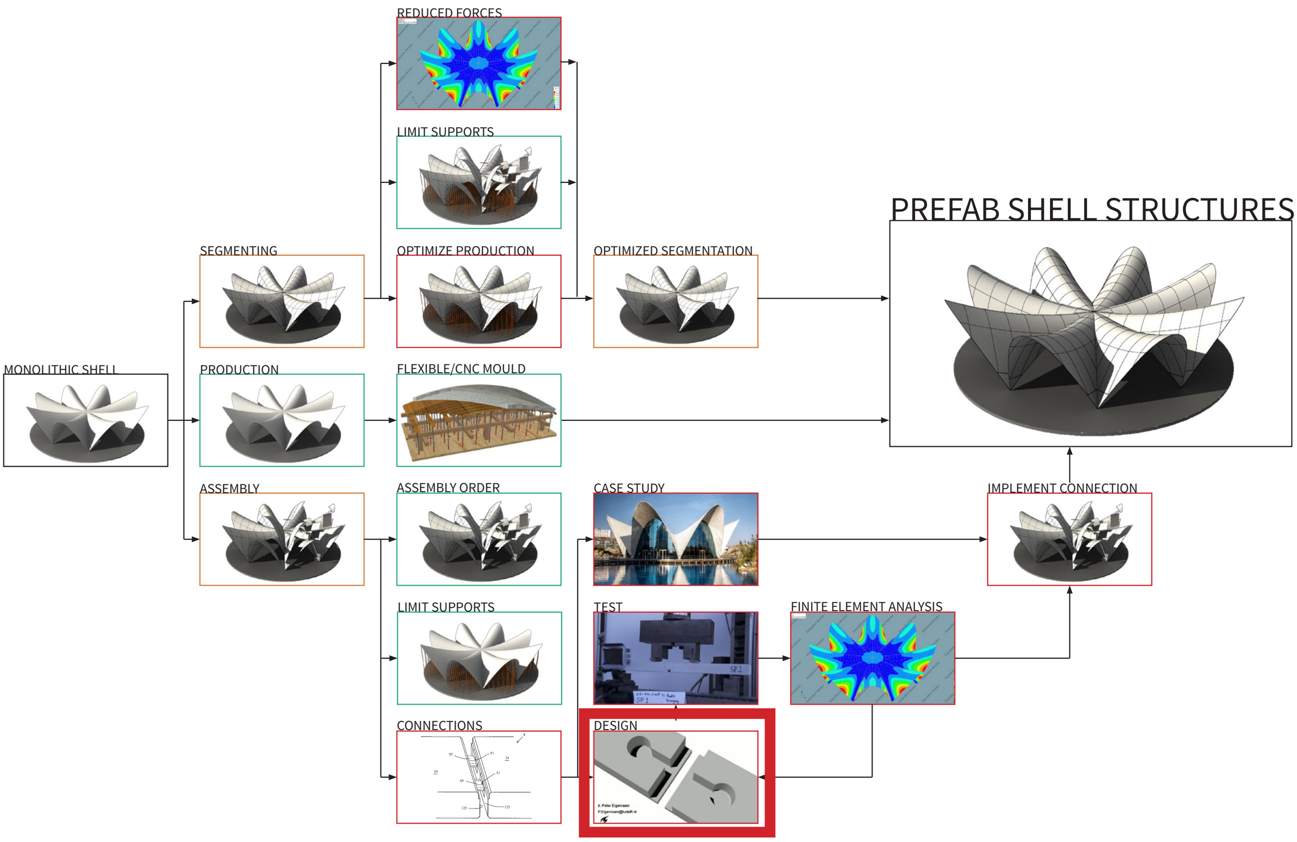


Figure 15: Results from Diana: Displacement, Reaction Forces, Total Stress and Momet

are dealing.
Because the forces in the shell do not show a clear pattern for the division of the shell, it is decided to take the production and the transportation of the different segments into account. Because of the maximum height of the road transport, which is 13,6 m x 4,0 m x 2,6 m (L x B x H), it is decided to make maximum segments of 3000 mm by 3000 mm. These can fit on trucks easily, and do not require special trailers. These sizes are also possible to produce in factories.

CONNECTION DESIGN



CONNECTION DESIGN

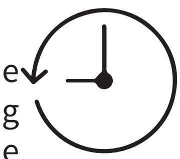
With the case study analysed an idea is formed of all the forces present in the connection, and the dimensions of the segments. With this information, an initial design for the connections can be made. But first a list of references is assembled, to see what kind of connections are present in the concrete industry, and in other industries such as the furniture industry, installation industry and carpeting industry. With the initial design for the connection, some comparisons can be made in the building time, and other criteria made for the connection.

REFERENCES

To start of the connection design, a list of references is assembled. With a wide variety in literature and the help and work of Peter Eigenraam, a large amount of connections is assembled. To get order in the chaos of all the different connections, a rough division is made into 5 main categories of connections. These five categories are Cast Connections, Bolted Connections, Welded Connections, Tension Connections and Form Connections. These connections are criticized on the time it takes to construct the shell if they are implemented in the design. All the connections can be found in Appendix A.

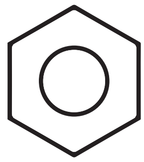
Because all the connections are suitable for prefabricated segments, most of them do not require the placement of reinforcement, nor the pouring of concrete on site. With all the connections, it is taken into mind that all this time consuming process is done in advance in factories.

POURED CONNECTIONS



In prefabricated concrete, the most used way of connecting different elements is to fix the elements in the right position, and pour concrete in-between them to fix them permanently. While the majority of the shell is produced in factories, temporary structure is still needed. Also some form of formwork is needed, although it is only needed at the seams. Because the connection needs to dry before the structure is fully able to carry the loads, it does not safe to much time.

BOLTED CONNECTIONS

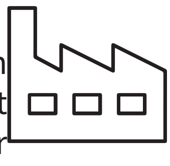


When prefabricated elements do not need to transfer forces, but need to be kept in place, bolted connections provide a suitable solution. By having bolted connections, a lot of tolerance can be applied within the structure, by using slots to make adjustments on the position of the segment. There is no drying time involved in this connection, and at the worst only a small amount of temporary structure is needed.

WELDED CONNECTIONS

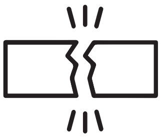
In these connections steel inserts are placed in the prefabricated segments. At the building site, the segments are lifted on their place, and welded together. This is a very time consuming method, since all the segments need to be manually welded together. And after the segments are welded together, a finishing layer of concrete has to be poured on the connections, to protect the connection, and make it watertight. The biggest advantage of this method is the fact that the temporary structure can be removed ones all the elements are welded together. Only parts of the formwork are needed, to be placed underneath the connection to prevent the concrete from dripping out at that certain point.

TENSION CONNECTIONS



If use is made of tension connections, the different elements are connected together by a steel cable, which is going through the segments, and with tension pushing the different segments together. This cable can be placed during the production of the segments, or it can be placed manually on the building site. By applying pressure on the cables, the segments are forced into their position. One of the advantages is the fact that the structure is very fit to deal with tension because of the steel cable, as well as compression because of the concrete elements.

FORM CONNECTIONS



When shapes are used to connect elements together, the segments are designed as puzzles. By making the negatives of each other, it is easy to put them together, by sliding the shapes into each other, they should instantly lock together, making further actions unnecessary to create the structure. The advantages are the quick assembly of the shell, the disadvantages are the precision needed in creating the segments. Also the directions of the force transfer in this connection are limited, due to the segments needing to slide together in one direction.

CRITERIA

With all the different connection categories organised and explained, a list of criteria for the connections can be made. By finding common ground on which to judge the different connections, a clear decision can be made on which categories of connections need to be explored further

The main criteria on which to base the choice is the assembly time. Because the exploration into prefabricated shell structures is mainly to decrease labour and construction time on the building site, it is logical to base the design on the timesaving. By comparing the amount of days it takes to construct the shell structures with each different connection, a numerical comparison can be made.

Also the forces and direction of forces which can be transferred by the connection are important. If a connection cannot transfer enough force, or does not transfer forces in a particular important direction, it is not suitable, and will not be explored further.

The production and ease of use will also be taken into account, but will not be leading in the criteria.

POURED CONNECTION

In the original building process, the pouring of the concrete and the drying time took a lot of time. While the pouring is mainly done at the factory, still a great amount of pouring is done at the building site. And after the pouring, they drying time of 28 days still needs to commence. Only after the drying time can the temporary structure and the formwork be removed. Therefore this connection is still very time consuming.

The forces which this connection is able to transfer are very high. Because a freshly poured block is put in between the different segments, the shapes is kept intact, and the same materials are used in the connections as in the segments. This provide a very strong connection, which can deal with all the different planar forces, but also with the small amount of axial forces present in the shell.

In the production of this connection, the steel reinforcement in the segments needs to be extended out a few centimetres, for the second concrete pouring to be able to attach correctly to the segments. Therefore the production is very easy, as the precision of the reinforcement does not need to be very high. Also the implementation of the connection is very easy, as it is a very well used method.

BOLTED CONNECTION.
The bolted connection is also a very quick connection. After the segments are put together, simple bolts can be inserted d into the prefabricated holes, No extra pouring of the concrete is needed. As the connection is finished after the bolts are tightened. No additional drying time is needed, and the temporary structures can be removed as soon as the last bolt is finished.

Bolted connections are designed to transfer forces in multiple directions. Because of the thread and direction of the bolt, it has a main direction in which it transfers forces. The other directions it can also transfer forces, but less compared to the main directions. Because of the main forces in the planar directions of the shell, and less forces in the axial direction of the shell, the bolted connection is very suitable for use in the shell.

WELDED CONNECTION
Because of the precision and craftsmanship of welted connecting of segments with welds is very time consuming. After the precise alignment of the segments, the steel inserts need to be precisely and very securely welded together. Besides the proficiency of the welders, they labour they provide is very expensive. And time consuming.

The production of segments with steel inserts is rather easy to do. Also the placement of the segments requires less precision, which speeds up the process.

The steel inserts which are welded together provide a very strong connection, which can transfer both axial and planar forces. By placing the concrete segments on each other, the structural continuity of the shell is guaranteed.

TENSION CONNECTION
Because of the assembly of a shell structure using tension cables or other means of tension connections, the labour on the building site takes very long. Because all the segments have to ben tensioned before they can transfer forces correctly, it is a time-consuming activity. The placement of the segments on the other hand is rather easy. Because of the continuity of the cable, all the segments are forced into place.

This connection type is very strong in the planar forces, as the concrete segments are placed into compression, but the tension cable can transfer tension in the planar direction. Axial forces are harder to transfer with this direction, but because of the shape of the shell, they should not be any problem.

FORM CONNECTION
Because form connections are very quickly assembled, they save a lot of time on the building site. With only the temporary structure, during the connecting of the elements, no drying time is involved in the connection. After the shell is finished, the structure can be removed, and the shell is finished.

Because the connection has to be moved into the right position, these connections will always have a weak direction, in which they cannot transfer forces. In the shell structure this would mean that the planar forces are easily transferred, but the axial forces are not.

Production of the form connection is a far bigger problem. Because of the precision required, it is very hard to use concrete

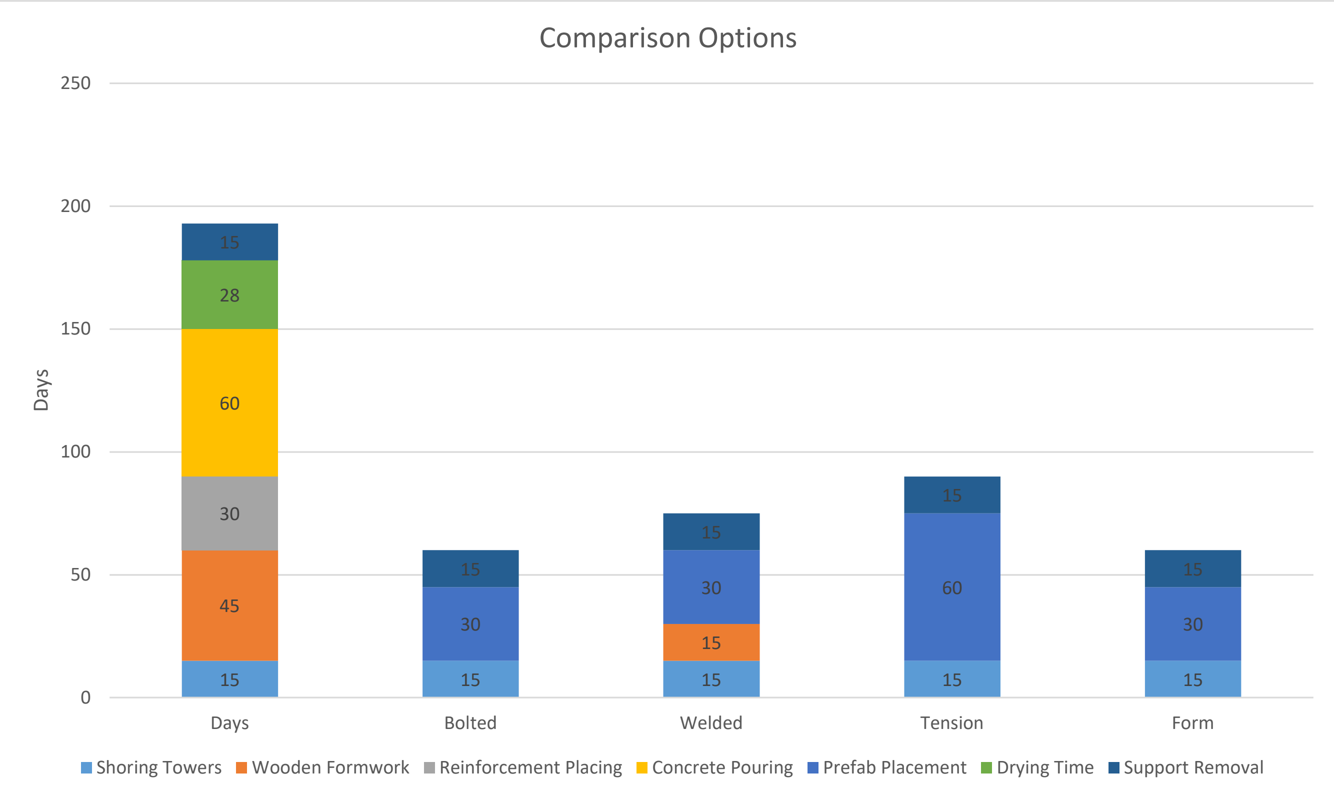


Figure 16: Comparison of the time it takes to assemble the shell with different connections (Own Illustration)

for this connection. Because of shrinkage during the drying, and the precision of the formwork some tolerance have to be taken into account.

THE DESIGN

After a quick exploration of the references, and with the different criteria in hand a decision was made to make a few design, combining strong points of each connection category. While the poured connection was disregarded because it did not eliminate all the drying time, and still had extensive formwork required.

The most promising connection is the bolted connection. Because no drying time is needed for the structure to be build, a lot of time is saved on the building site. The only problem with the connection is the precision of the placement on the building site. Therefore it is decided to combine these two connection types. With steel inserts a connection point is made for the bolt to attach the two segments together. With the shape of the concrete, the placement can be corrected to 3 mm precise. After the connections are made, and the structure is erected, a small layer of concrete is poured into the seams, to make sure the structure is watertight.

This connection speeds up the assembly by providing a quick connection, combined with a fast a secure placement of the segments. Because it is difficult to achieve watertight connections at the same time, a small sealant (concrete) is used in the connection.

Also the production can be made very precise. Because the steel plates at the edge of the concrete segments can be used as formworks, the precision can be very high.

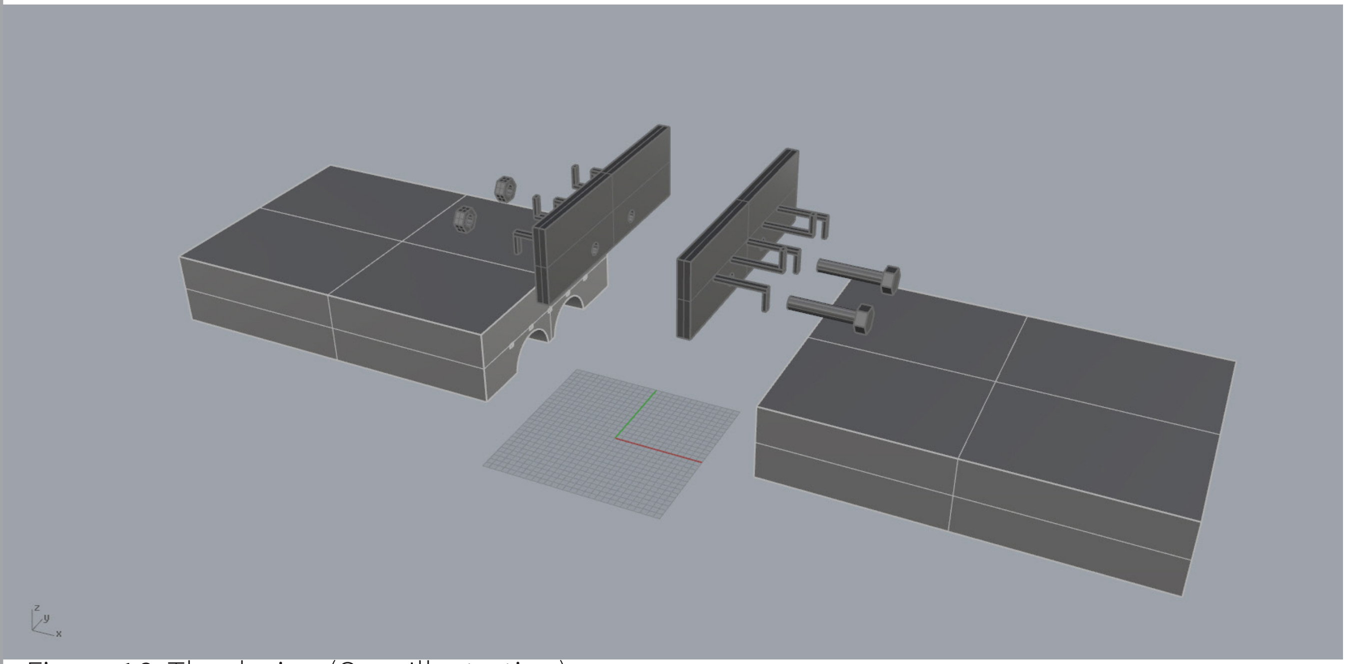
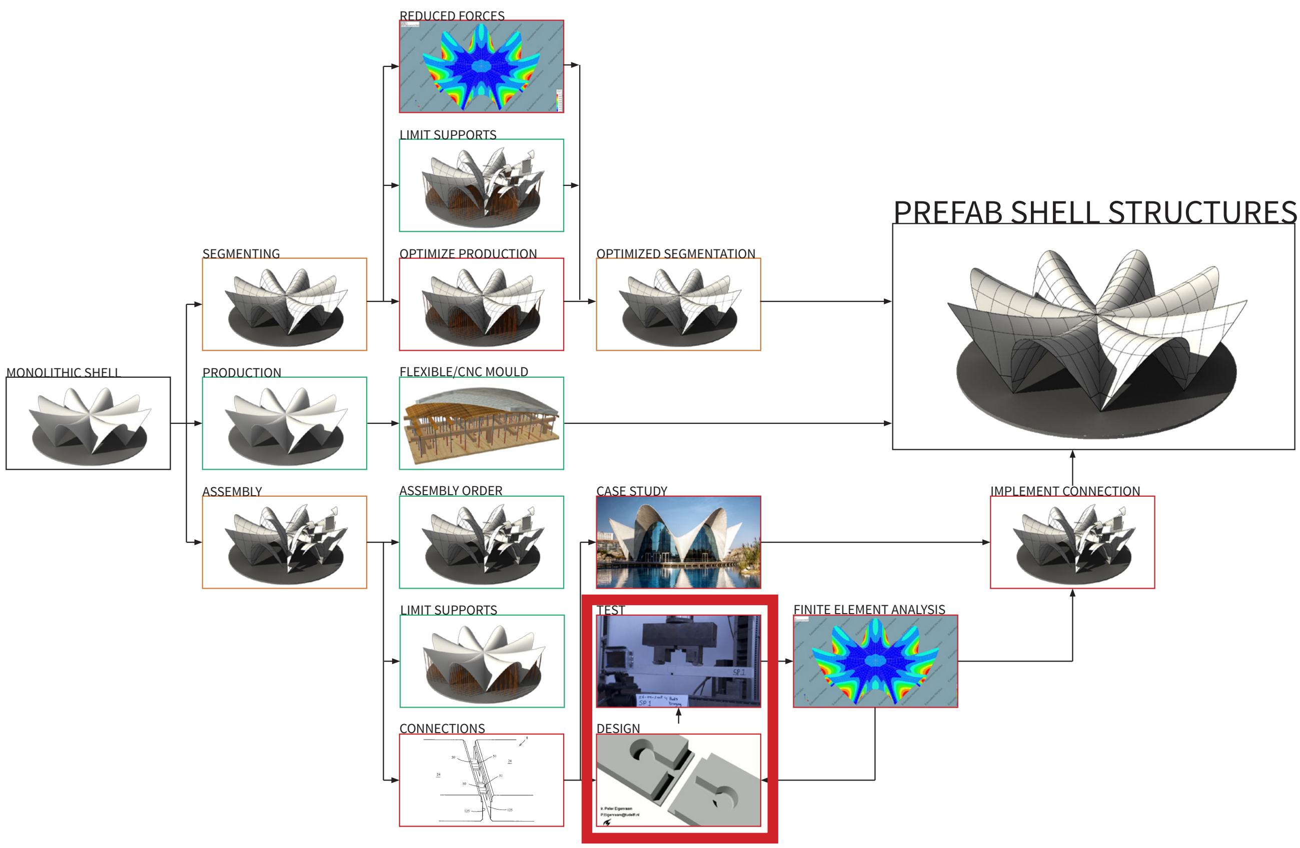


Figure 16: The design (Own Illustration)

COUNTER TOP CONNECTOR



COUNTER TOP CONNECTOR

At the start of the graduation a knot was already designed by Peter Eigenraam. This knot was inspired on the existing counter top connection, used for connecting two parts of the countertop together, on the underside of the counter. The connection works with tension, drawing the two parts towards each other by tightening the bolt (figure).

By exchanging the wooden parts of the counter top with the concrete segments needed for the shell, a connection is designed. Because concrete is less precise, a concrete to concrete compression connection is difficult to make. Because of imperfections on the concrete surface, another material is needed to smoothly transfer all the forces from the one side to the other. Therefore a small concrete block is introduced in the design, which connects towards the segments using small steel plates, to transfer the force more smoothly from segment towards the small block.
To finish the connection concrete is poured in the remaining open space in-between the two segments. Because the concrete is poured in, the imperfections in the surface are no problem for the force transfer. This also seals the entire structure, making it water tight.

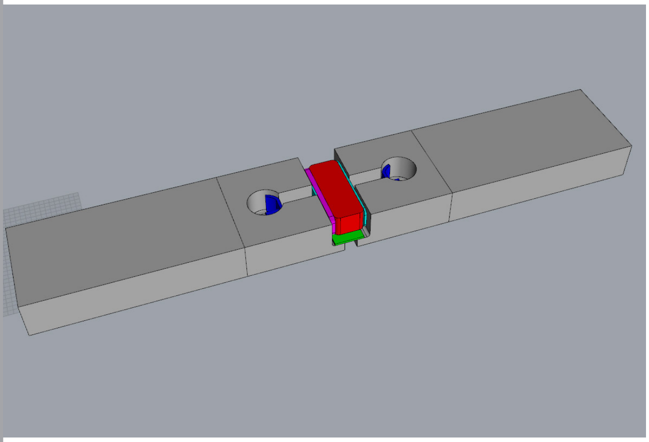


Figure 17: Counter Top Connector (Peter Eigenraam, 2018)

PRODUCTION OF THE PROTOTYPE

To test the design a prototype has to be build. Because a lot of concrete elements have to be produced, formwork is needed. These are not simple rectangular boxes, but include some inserts for the small gutter in between the two segments, and the insert for the countertop connection opening. Next the small block in between the segments needs to be made. Also the small plastic strip needs to be produced, to avoid the concrete from pouring out of the connection. The final step is to produce small steel plates, to have an optimal force transfer in the connection. In this chapter the production of the prototype will be described.

WOODEN REPLICA

First a replica of the concrete parts is made using wood and a CNC milling machine. These parts can be used to design a mould for the concrete pouring, and to establish the required length for the bolts.

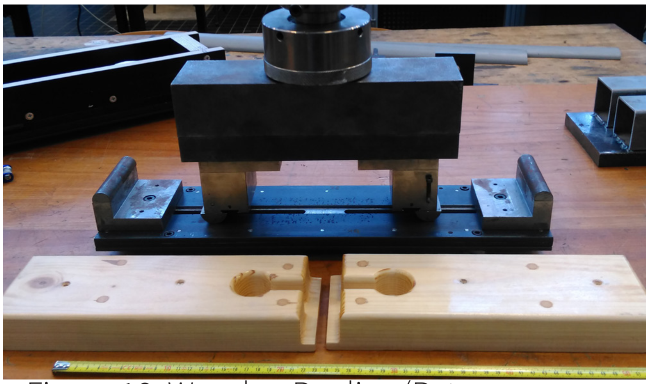


Figure 18: Wooden Replica (Peter Eigenraam, 2018)

FORMWORK SEGMENTS

Next a formwork or mould has to be created to accommodate for all these inserts. With Betonplex the rectangular boxes are created which accommodate the rough shape of the concrete segments. The rounded gutter is placed on one side.

Next the CNC milled blocks of wood are used as a mould, to fabricate the inserts for the counter top connector. These are placed over the rectangular boxes, to make sure an insert is left out.

Combining these elements results in a mould, which is able to produce the concrete segments, with all the required holes and shapes.

Figure 19: Formwork Concrete Segments (Peter Eigenraam, 2018)

FORMWORK SMALL BLOCK

For the small blocks in between the segments, a smaller formwork is needed. The details are smaller, and therefore harder to make out of wood. By hand four small wooden blocks, replicating the concrete elements are made. Because of the small scale, a vacuum machine is used, to pull VIVAC over the small wooden blocks, which creates the moulds for the concrete elements.

Because of the thin layer of VIVAC, the moulds do not hold up when the wooden blocks are pulled out. Therefore small wooden formworks are made by hand. These are more likely to hold up to the concrete pouring.

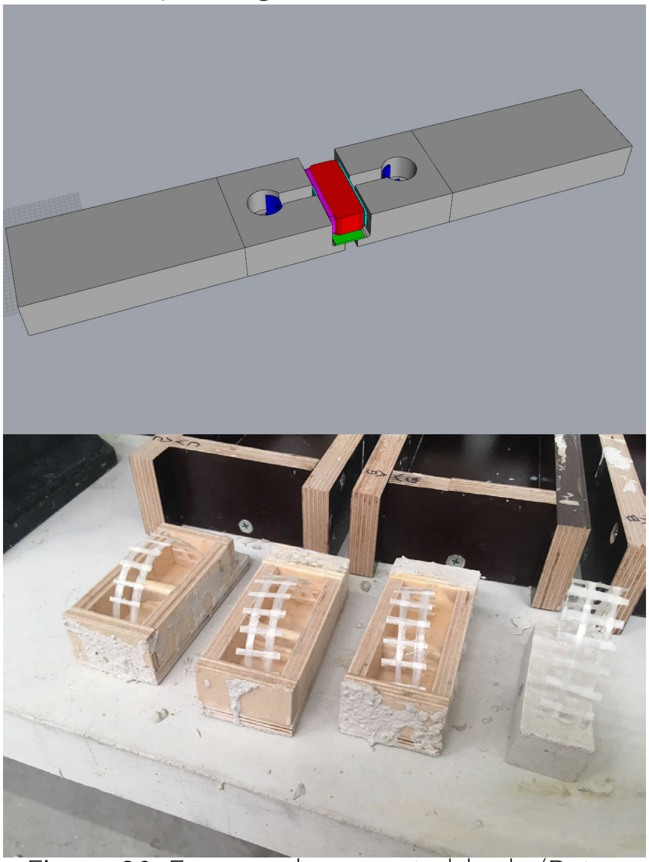


Figure 20: Formwork concrete blocks(Peter Eigenraam, 2018)

PLASTIC STRIPS

The next problem to tackle was to find a suitable material to insert over the gap between the two segments, to avoid the concrete from pouring out. In the prototype the gap is relatively small, 4 mm width, and 100 mm long. If the connection is used in an extensive shell, the length of the gap will increase significantly.

For the prototype we decided to use VIVAK plastic, since it is easy to acquire, and it suits the requirements of the strip. It is also easy to process, as scissors can be used to cut them to the desired length. If a shell is created using the connection, the VIVAK will be able to bend into the curves of the shell, making it very suitable for use in the shell.

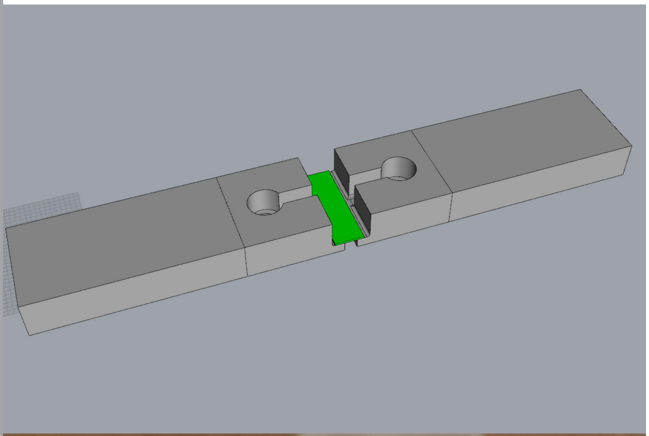


Figure 21: Plastic strips (Peter Eigenraam, 2018)

CONNECTOR

To finish producing all the parts of the connection, a bolt is required to pull the two segments together. Since the connection is inspired on the Counter Top Connector, an online order is placed for a set of Counter Top Connectors. These are ready to use, and only need a little alteration. When put together with the wooden parts, it is clear that the bolt is too long, and would prevent the connection from tightening together.

STEEL PLATES

To make sure the concrete transfers force optimal through the connection steel plates are placed in between the concrete parts, to make sure imperfections do not affect the strength of the connection.

These steel plates were designed with a slot, to be sloth over the bolt when it is in place. This way of placing the plates came with a few difficulties, besides the production.

Because of the unique slot in the steel plate, laser cutting or another mechanised way of producing was thought of. After receiving a few quotations from companies, the cheapest offer was still way to expensive. Therefor the design was changed a bit, by replacing the slot with a single hole. This had to advantages. First the production could be done at the TU Delft, with the help of Keeps at the Dream Hall. By cutting 2 mm thick steel into small plates of 80 mm by 30 mm, and next perforating them with a perforating machine. Next the plates had to be put on the bolt in advance, locking them in place in the connection. This will, opposite to sliding them in place after the bolt and concrete blocks are put in place, make it easier to put them in the correct place.

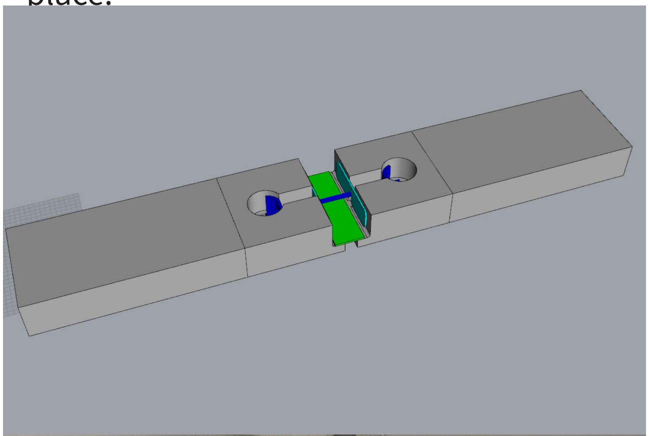


Figure 22: Steel plates (Peter Eigenraam, 2018)

TOLERANCE PLATE

Because the connection is made with two small segments, rather than two large plates hanging at a few meters high, the tolerance plate is not really necessary. But because it influence the strength of the connection, some plate has to be put in place. Therefore it is decided that the tolerance plate has the same thickness as the other steel plates, which makes them exactly the same.

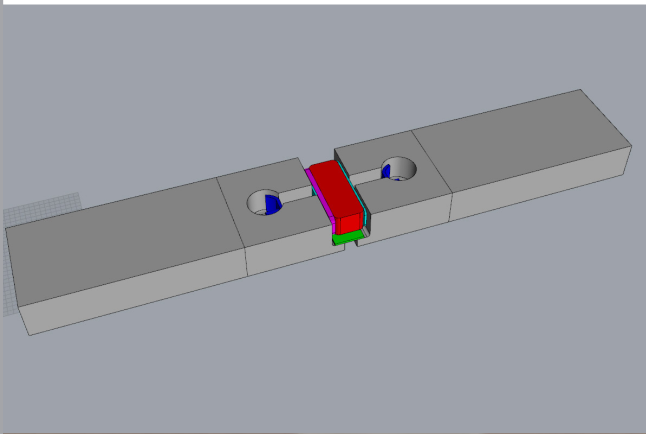


Figure 23: Steel plates with the tolerance plate and concrete (Peter Eigenraam, 2018)

CONCRETE POURING

With all the different elements prepared, the concrete parts need to be produced. For that we need a location where concrete is provided, and also space to store the framework while the concrete is settling.

The solution for this is found at MBX, a company located in Bergen op Zoom, where they produce (double) curved surfaces using wooden framework produced using a CNC milling machine. During their regular production, a bucket of concrete is given to us, to be poured into the wooden and plastic moulds. After the concrete is settled, the moulds are taken apart, leaving the parts to dry a few more days.

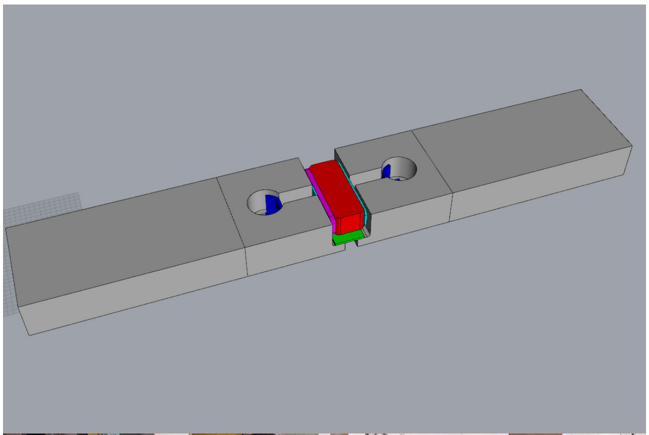


Figure 24: Pouring of the concrete (Peter Eigenraam, 2018)

ASSEMBLING

With all the parts produced and ready the connection can be made. The concrete segments have to be placed besides each other. Next the bolt has to be put in place, with the three steel plates already on it. If these are all aligned correctly, the small concrete block can be placed.

The bolt needs to be tightened, until all the different parts are in the right position, drawn together by the bolt. No torque wrench was present, so the bolt was tightened by hand, until it was stuck.

Figure 25: Assembled connection (Peter Eigenraam, 2018)

Figure 27: Backside view of the connection (Peter Eigenraam, 2018)

SECOND POURING

After the assembling is done, the second layer of concrete has to be put in. By placing two betonplex plates beside the connection, a formwork is created, in which the concrete can be poured, to secure the two segments together. After the pouring, the prototype is left to dry for 28 days.

With the formwork of the second pouring removed, the prototype is ready. In total 4 prototypes where produced in a span of 2 months. By proceeding with the second pouring of concrete before the segments where fully dried (28 days) a lot of time was saved by letting both concrete pouring dry simultaneously.

Figure 28: Final prototype (Peter Eigenraam, 2018)

Figure 26: Final prototype (Peter Eigenraam, 2018)

ANALYSIS

With the prototypes ready, the next step in the process is to determine the strength of the connection. To do this some calculations are needed. Because the beam is not a simple beam, but two separate beams, connected by a knot, we need to make use of a calculation for the k-value, which will represent the connection. Next a four point bending test will be executed on the prototypes, to determine values for the deformation and the force needed for the deformation, with which we can determine the k-value of the knot.

CALCULATIONS

Because the prototype design looks like a simple beam, the first thought is to take the equation from a simple beam, and implement a spring in the centre of the beam. This equation was found in the book Toegepaste Mechanica Deel 3: Statisch onbepaalde Constructies en Bezwijkanalyse (Hartsuijker & Welleman, 2004). But because we wanted to know the strength of the knot, two forces are chosen besides the knot, to determine the force transfer through the knot. Therefore the formula needs to be adapted to apply for the chosen setup.

We start with finding the moment in the centre of the beam. Because the two forces applied are not equally spaced, the moment in the centre is as follows:

$$M_B = R_A * x - F(x-a)$$

This moment causes the beam to deform. But because the beam has a spring in the centre, the deformation is caused by rotation at the spring, and the deformation causes rotation at the supports. Therefor the total rotation in the centre can be determined by the next formula:

$$\theta_B^{AB} + \theta_B^{BC} + \Delta\theta_B = 0$$

The rotations θ_B^{AB} and θ_B^{BC} exist out of two components, the rotation because of the bending moment, and the rotation because of the displacement. The rotation because of the displacement can be found by the next formula:

$$\theta = 2\frac{\omega_B}{l}$$

The rotation θ_B^{AB} can be found by subtracting the rotation because of the displacement with the rotation because of the bending moment:

$$\theta_B^{AB} = \frac{M_B * l}{3EI} - \theta$$
$$\theta_B^{BC} = \frac{M_B * l}{3EI} - \theta$$

The rotation in the spring can be found by the next formula:

$$\Delta\theta_B = \frac{M_B}{k}$$

Substituting all the previous found formulas in the rotational formula gives:

$$\frac{(R_A * x - F(x-a)) * l}{3EI} - 2\frac{\omega_B}{l} + \frac{(R_A * x - F(x-a)) * l}{3EI} - 2\frac{\omega_B}{l} + \frac{(R_A * x - F(x-a))}{k} = 0$$

To isolate the k-constant gives:

$$2\left(\frac{(R_A * x - F(x-a)) * l}{3EI} - \frac{2 * \omega_B}{l}\right) = -\frac{(R_A * x - F(x-a))}{k}$$

$$k = -\frac{(R_A * x - F(x-a))}{2\left(\frac{(R_A * x - F(x-a)) * l}{3EI} - 2\frac{\omega_B}{l}\right)}$$

R_A Is defined as:

$$R_A = \frac{F}{l}(l - a + b)$$

Giving the final formula for the k-constant:

$$k = -\frac{\left(\frac{F}{l}(l - a + b) * x - F(x-a)\right)}{2\left(\frac{\left(\frac{F}{l}(l - a + b) * x - F(x-a)\right) * l}{3EI} - 2\frac{\omega_B}{l}\right)}$$

In the next variables are known:
a Is the distance from the support to the applied force, 160 mm?
b Is the distance from the second applied force to the other support, 180 mm
x is the distance from the support to the investigated point, 255 mm
l is the total length of the beams, 510 mm
E is the Young's Modulus of concrete, 30.000 N/mm^2
I is the second moment of area, 3333333.333 mm^4
F is the applied force, needs to be found
$\omega_B$is the displacement, needs to be found
With this formula, a calculation for the k-constant can be determined. The next step is to find out the force needed to attain a certain deformation. Therefore the found formula is put in practice. By applying a four point bending test on the prototypes, it is possible to find the force needed to achieve a certain deformation.

ANALYSIS

At the faculty of mechanical engineering at the TU Delft in the Materials lab there are a few machine which can be used for this test. Because of the size of the prototype, it is decided to use the Static Materials Testing Machine designed by Zwick. By placing a two point support on the bottom, and a two point pressure point on the top, a four point bending test is created.

By placing the prototype with the connection in the centre, the exact same conditions are created as in the calculations. Because of a mistake in the alignment, the supports are shifted 10 mm. Therefore the calculation taken is not one of symmetry, but with a small shift.

To make sure the connection can be loaded in both directions, half of the prototypes are placed upside down. This gives two distinct results, because the connection is stronger in one direction.

We also need to find out the Young's Modulus of the concrete. Besides information of MBX a small test is performed to determine the Young's Modulus. A small four point bending test is done on two samples taken from the broken prototype. This results in the next equation:

$$\Delta\omega_{max} = \frac{\Delta F * a}{24EI} * (3L^2 - 4a^2)$$

Where:
a is 70 mm
L is 210 mm
ΔF is taken from the graph
$\Delta\omega_{max}$ is taken from the graph
I is 3333333.333 mm^4

When we fill in the formula, it results in a Young's Modulus of 6822.542 n/mm^2 and 5305.851 n/mm^2. The tests from MBX give another result. They have a result of around 30,000 n/mm^2. This is a much higher number, but it can be explained by the way the concrete dries in the factory, and our prototypes.

RESULTS

With the four prototypes, the four point bending tests are taken. These give results which need to be cleaned up, and put into the calculations.

Because the test is designed in such a way that the head (which applies the force) is able to tilt during the test, the results yield a strange beginning, which small spikes up and down. This is the head settling, and needs to be disregarded. To make sure we get the right data from the test, we need to get similar data from the test. Because it is a linear result, until the prototype starts to crack, it is possible to take the change in force needed for a certain displacement (ΔF & $\Delta\omega$) and put them in the calculation.

Visually also a few results are shown. All the prototypes are broken at the same spot. After a closer look is taken at the results, it is discovered that the prototypes all break at the same spot, besides the openings left for the counter top connector. It is seen that the concrete from the second pouring detaches intact from the concrete segments. This occurs also in the gutter between the two concrete segments. The counter top connector itself is not broken.

With these results, an interpretation can be made, to show what these results mean, and how we can advance from this point.

Figure 28: Test setup (Peter Eigenraam, 2018)

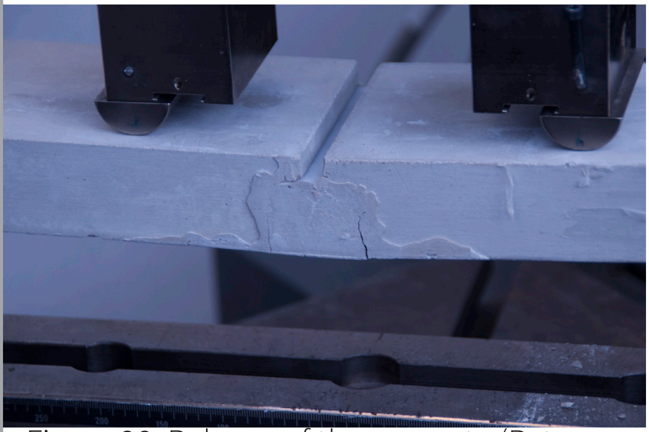


Figure 28: Release of the concrete (Peter Eigenraam, 2018)

Figure 28: Breaking point of the prototypes (Peter Eigenraam, 2018)

REFLECTION TESTING

Even though the test was thought out in advance, some small problems occurred during the test itself. Some mistakes were made in the setup, which made the calculations very difficult, but also the amount of specimens were too small, and no test samples for the testing of the

Figure 28: Test Result (Peter Eigenraam, 2018)

young's modulus of the concrete were made.

At the setup of the test, it was decided to have the specimen set up diagonal in the machine. Besides the advantage that the sample would fit in perfectly, it also provided a better view for the camera, which now could be set up perpendicular at the test sample, in this way checking the deformation and cracking in the sample. The mistake was made that the supports were not aligned correctly. The centre was 10 mm off towards the second support. Therefore the forces were not applied evenly from both supports, which resulted in the cracking of the prototypes at one side.

Besides the mistake in the setup, the amount of test samples was too low. With only four samples, of which two were turned upside down to also get results for the tension values, the amount of data could not be verified. This leads to two different results, which does not say conclusively which one is correct. But because of time restraints, one of the results needs to be chosen, and continued with.

The last problem encountered during the testing was the determination of the young's modulus. Beforehand the testing, it was considered to take the values which were determined by the factory as the young's modulus. But because we used parts of our prototypes, which did not have the same treatment as the samples made by the factory, the young's modulus might differ from the values received from the factory.

INTERPRETATION

In the next step we need to interpetate the results. To start a look will be taken at the visual results. The most obvious is to look at the breaking point. Because for all four prototypes the breaking point is the same, it seems obvious a weak point is discovered. At closer inspection, the breaking point is also at the same side of the connection. Because the forces are not applied symmetrical, the breaking occurs at one side, because the fore and bending moment are greater at that side of the connection.

When we take a closer look at the break, it is discovered that the second concrete pouring has totally detached from the segments. This indicates that the bonding of the concrete is the weakest spot. But on further inspection we see that the hole created for the counter top connector are relatively big compared to the width of the prototype. This might weaken the connection.

Both the weakness of the bonding, and the relative big hole in the segments might explain why the break occurs at the specific point. At the moment the concrete parts detach from each other, the prototype does not act as a solid beam anymore, and it cracks at the weakest point, being the opening for the counter top connector.

This result can be interpreted as the connection weakening the segment. But it might also be a problem caused by the setup of the test and the prototype. By only representing a small part of the shell in the connection, the hole created for the connection is a significant part of the tested prototype. Therefor the beam itself is weakened. But because there is no time to produce another prototype and test it, the result from this test is taken into the next step of the process.

From the graphs we can see that all the tests render similar results. While they do not give the same numbers, we can use them to find the k-value with the formula established at the beginning of this chapter. We can insert all the values in the calculation, and determine the k-value.

This results in a k-value of 10702026.94. With this k-value a next step can be made by implementing this value in a design.

IMPROVED DESIGN

From the testing a few results occurred. With these results the next step can be taken in the design process. With the k-constant as a value for the connection, further testing can be done, in analysing the knot in a bigger plate, or in the shell.

By modelling the four point bending test within Diana, the results of the test can be verified. With the k-constant inserted within the equation, it is checked that the four point bending test is reliable enough. After the test is modelled in Diana in 2D, the next step is to model 2 plates, and connect them together in a similar way.

With two plates as a representation of the shell segments forces are applied similar to those of the four point. The deformation is checked and compared to that of a monolithic shell. If the deformation exceeds the deformation in a monolithic shell, the connection does not suffices.

For further improvement of the shell, a design needs to be made, and a four point bending test has to be commenced, to determine the k-value, which can be inserted into a digital analysis, to confirm the connection strength.

CHECKING RESULTS

To make sure the right results were obtained from the four point bending test, a simulation is made in DIANA. By setting up a two dimensional analysis the results can be verified, and the first check for making digital analysis can be done. By comparing the test results to the digital analysis, the digital analysis can be found to be reliable, or unreliable.

First the setup of the four point bending test needs to be modelled in DIANA. To do this a two dimensional simulation is made. This can be done because of the linear setup of the four point bending test. By modelling the concrete segments as two straight lines, and inserting a connection in the middle, the connection can be represented (Figure29).

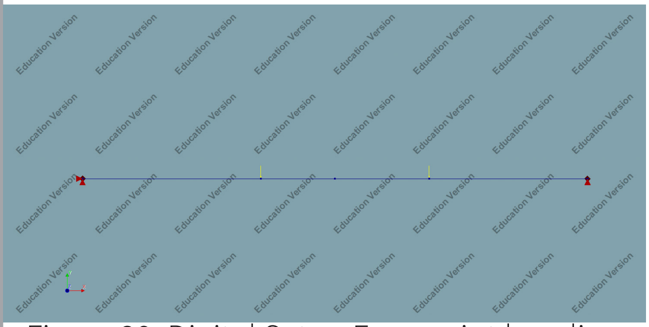


Figure 29: Digital Setup Four point bending test

This model gives the result shown in figure 30. The resutls obtained from this show that the results obtained from the bending test are reliable. The results deviate a little from the digital model (figure 31). This might be explained by flaws in the prototype, as opposite to the digital model, which is modelled as a flawless construction.

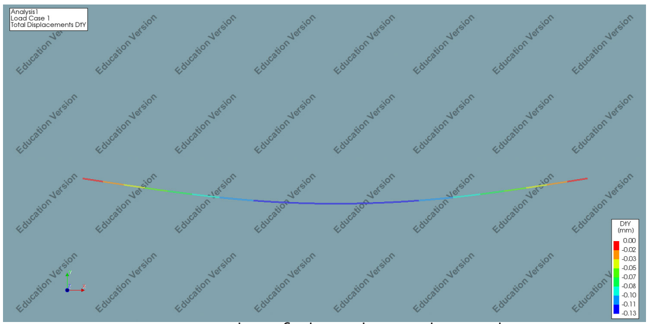


Figure 30: Result of the digital analysis

By comparing the results of the four point bending test with a digital modelled analysis, we can determine whether the value inherited from the test is viable for modelling large scale structures. By showing that the results of both the test an analysis compare, the value is viable and can be used in large scale modelling.

	Test 1	Test 2	DIANA
Applied Force	200.7787	200.092	200.347
Deformation	0.143249	0.192506	0.13104

Figure 31: Comparison of the test results and the digital analysis

IMPLEMENTING RESULTS

After a result is obtained from the four point bending test, and the values are verified, the results can be tested in a larger setup. By modelling two or more segments we can see whether the connection holds up on large scale, and how it compares with a monolithic shell.

With the existing digital model of the monolithic shell structure a start is made. By splitting the shell into segments, using the criteria established at the start of this

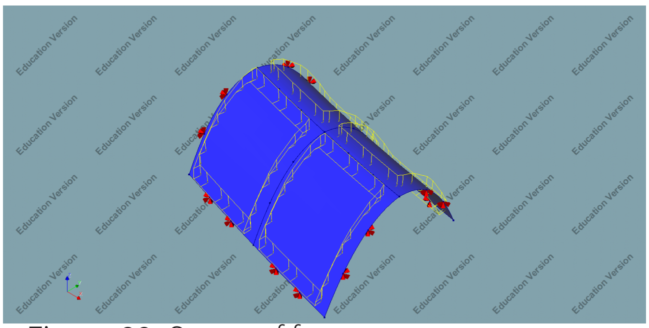


Figure 32: Setup of four segments

graduation, the different segments of the shell are created. By attaching points to the edges of the segments, an anchor point for the connections is made. By modelling a small gap of 1 millimetre in between it is made sure that the segments are not connected by default, but can be connected by the connections (Figure 32 &33).

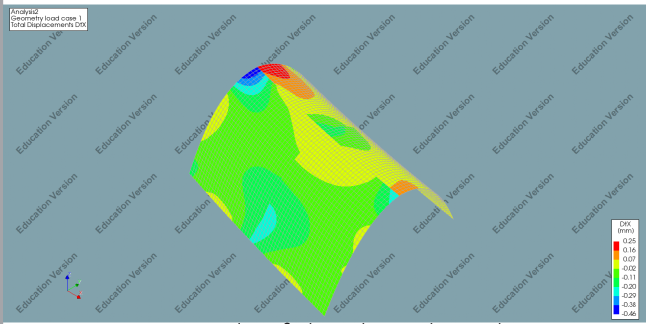


Figure 33: Result of the digital analysis

Next the digital model is imported into Diana, and connections are programmed in between the points. To make sure the setup works, at first only four segments are put into DIANA, to see how the connection behaves in a three dimensional setup.

After the connections are put in place, and the rest of the model is modelled (Shell thickness, loads, supports, material, see figure 33). After the analysis, the model shows only small deformations, and only small amounts of moments in the connections and shell. The digital model shows that the connections are sufficient for all the forces within the shell.

This shows that connections can be digitally tested for use in shells. By setting up a digital model of the structure, the connection can be tested by determining the k-value of the connection retrieved from the physical testing.

Next a start is made into modelling the entire shell, but this is found to be very labour intensive, as modelling a single lobe

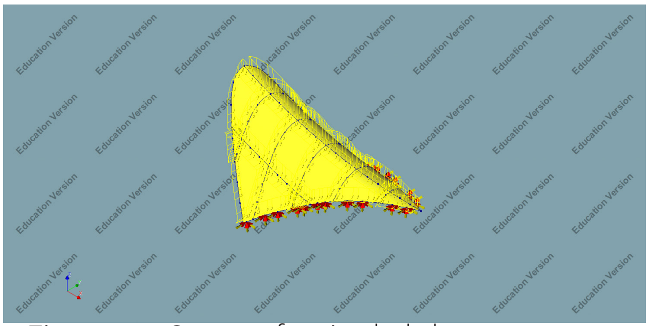


Figure 34: Setup of a single lobe

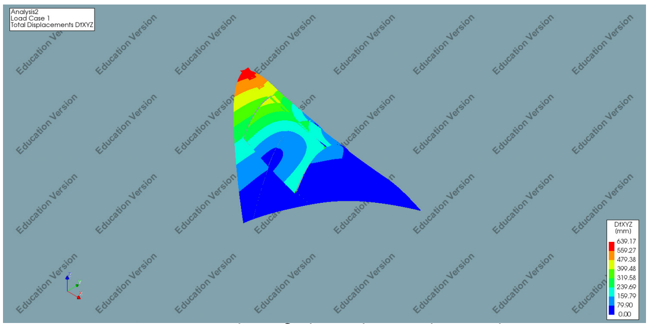


Figure 35: Result of the digital analysis

takes around 2 days. After completion of the model, an analysis is performed. This shows large deformations in the tip of the lobe, which can be prevented by attaching more connections.

The analysis shows that the model is reliable, and can be used for implementing connections in a segmented shell structure.

CONCLUSION

CONNECTION DESIGN

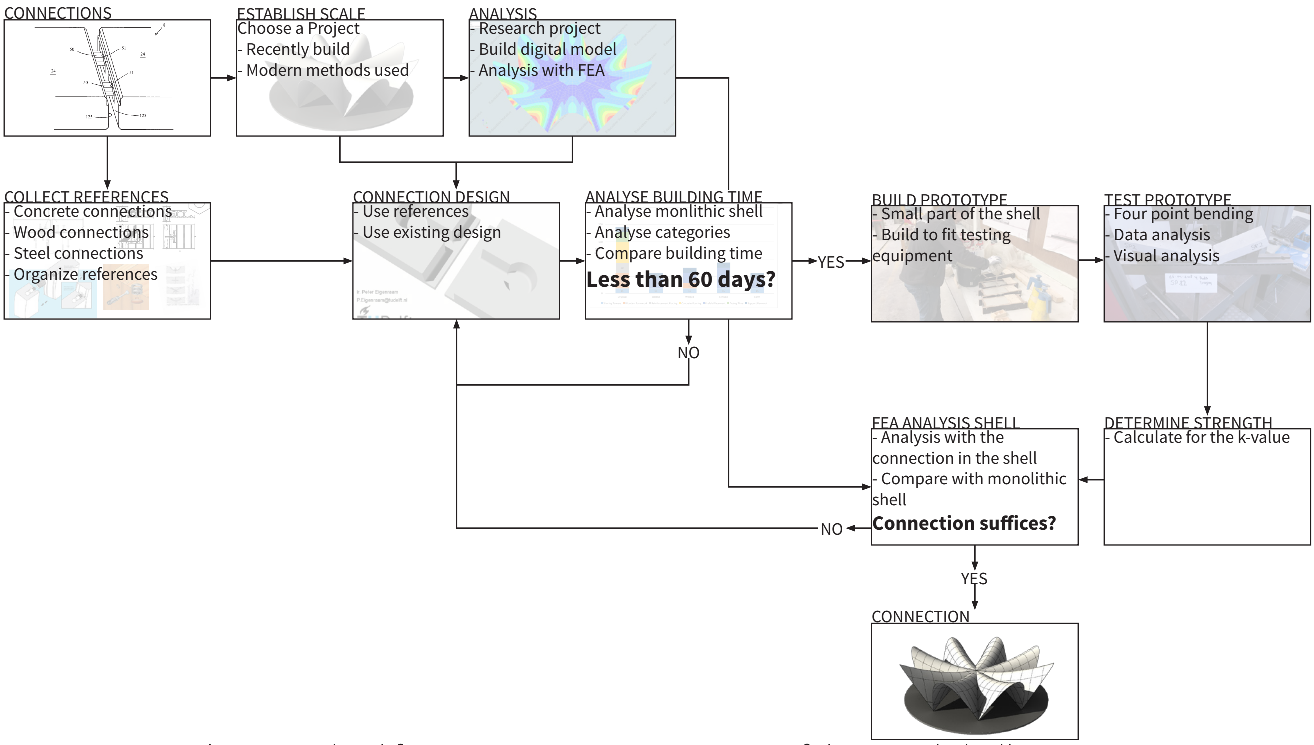


Figure 36: Resulting method for testing connections in prefabricated shell structures

In this graduation report an insight is given into the process in which a testing method is designed to criticize and chose the best connection. By looking at methods to design and criticize connections, a method is created with which a connection can be checked whether it suffices within the design.

After an early attempt on designing a connection, the criteria and demands were found to be unclear. With finding references, a clearer picture of connections and the different categories within connections can be made. But even with these categories a way of comparing different connections is still not clear. Therefore a framework was designed, in which the demands are determined.

To set a standard, a case study is made, to find out the different times which are involved in the construction of an existing shell. In the Oceanografic in Valencia, these times were found to be very extensive, as it takes 200 days to build the shell structure.

By determining the amount of time it takes to assemble the structure, a comparison with other methods can be made, and a ranking for the different connections can be made. As the starting point of this report is the prefabrication of the shell, the drying time of the concrete is generally avoided on the building site, speeding up the construction in general. Still there are subtle differences within the different categories, which make a big difference in the construction time.

To check if the connection is strong enough within the structure, a four point bending test is commenced. With the results of the test, a k-value is calculated, which can be used in the model of the shell structure. Also a visual result is observed. These results show weaknesses in the connection. These weaknesses can be taken into account during the improvement of the connection. In this way a validation can be made, and a minimum value for the connection can be found.

To improve upon the connection, these results can be taken into account, and the weak points can be tackled. Improvement on these points can be made, and a new prototype needs to be produced for a four point bending test. By repeating the production, testing, analysing and improving, the connection design can be improved, until the connection satisfies all the needs.

The resulting method is shown in figure 36. This gives an insight in the steps which need to be taken to design an prove the strength of connections for prefabricated shell structures. The method has been proven in this report, and can be used to prove the design of a connection.

REFLECTION

With a method deviced, it is time to analyse the strength of the connection designed by Peter Eigenraam. By running the connection through the different steps of the method, a verdict is given on the connection.

BUILDING TIME
By analysing the different aspects of the connection design, a quick verdict can be made. Because the connection at this point still needs an additional drying time, it takes more than 60 days to assemble the structure. Eventhough the construction time is halved already, it can be improved further.

With the connection failing at the first point, a new design step should be made. Because of time restrictions, we still take the next steps in the method, to show the working of the method.

PROTOTYPE BUILDING
The prototype building already gave insights in the connection. Because the small concrete blocks are very small, the moulds are very difficult to produce.

Also the connecting steel plates were changed during the production, as holes are easier to make, instead of an incision. It also secures the plates better, as it cannot move away from the bolt.

TESTING
During testing a few problems were show, of which the gap for the connection seems to be the biggest one. Because the opening is relatively large compared to the width of the prototype, the cracking occured at that point of the prototype, showing that the connection might be stronger than found during testing.

ANALYSIS
With the connection produced and tested, an analysis can be made. By building a digital model, it is shown that eventhough the connection weakens the shell a bit, it is strong enough to be used in prefabricated shell structures.

This shows that the method can be used, and that the connection needs redesign, and testing without the second pouring, to achieve the criteria set in the method.

GRADUATION REFLECTION
What started out as a design for a connection, transitioned gradually into a list of demands, and further on into a method for checking and developing a connection. This change made the position of the graduation somewhat different compared to the aim at the start of the project. Even though the research did fit in the general research program into prefabricating shell structures. The framework designed for checking the connection did contribute towards the next step in prefabricating shell structures, which will result in the saving of unsustainable material such as concrete.

At the start of the graduation, the aim was to aid the development of prefabricated shell structures by designing or improving the design of a connection in the prefabricated shell. By aiding Peter Eigenraam in building the counter top connector, and testing the connection, it was thought that an own connection could be designed, aimed at the results gathered from the test. With the designed connection a next prototype would be created, which henceforth could be tested again, and be the final result of the graduation.

With the production of the connection taking seriously longer than anticipated, the realisation came that designing and building an own connection would take too long. Therefore the focus was shifted towards finding criteria with which the connections could be tested and ranked. Even though this does not provide a big advance in the design of a connection, it provides a framework on which connections can be checked. The next step in the topic of prefabricated shell structures is to improve the connection, and test the connection on a larger scale, in an entire shells structure.

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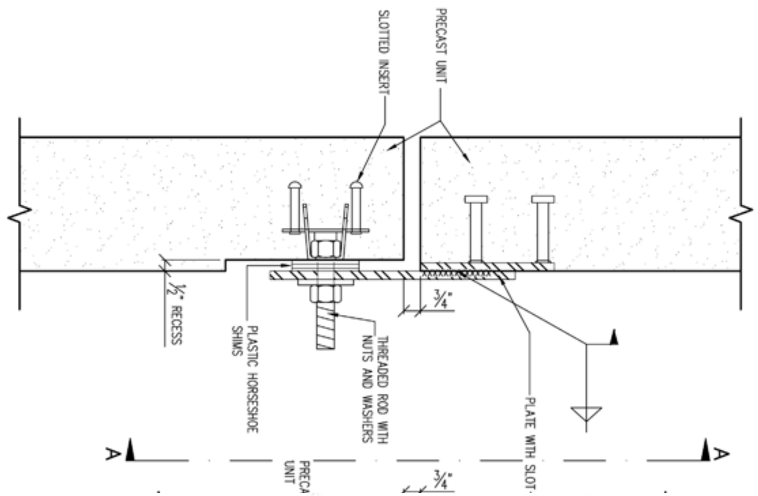
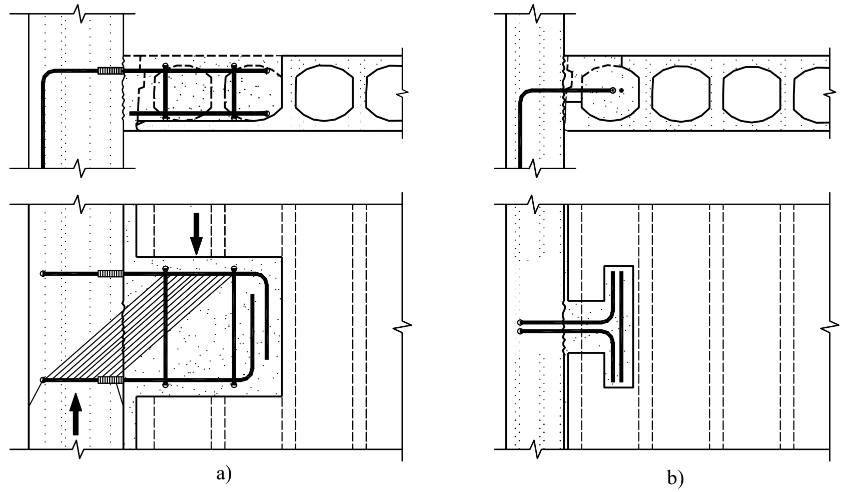
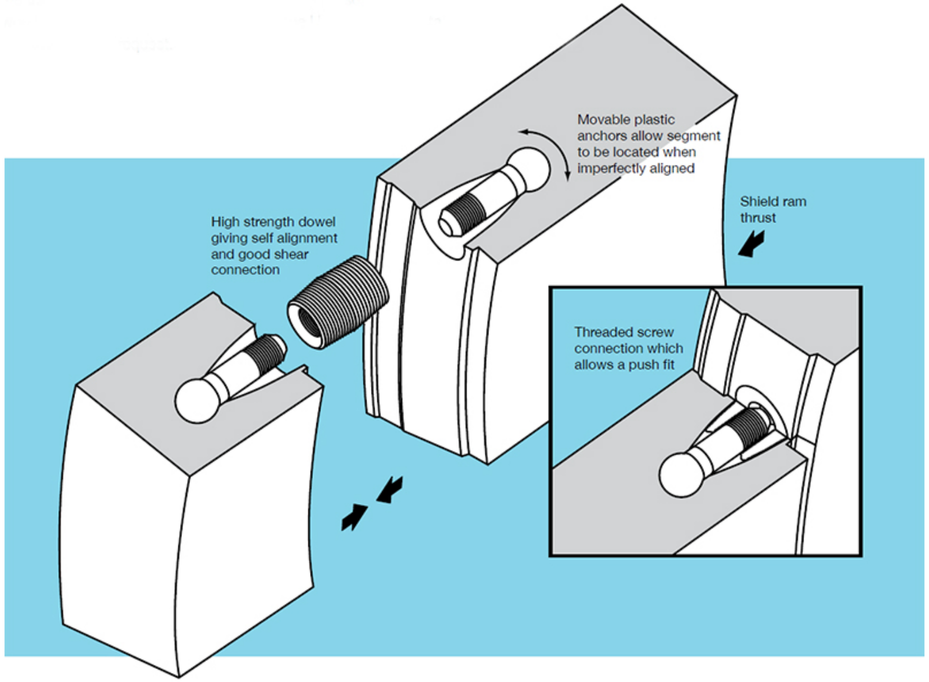
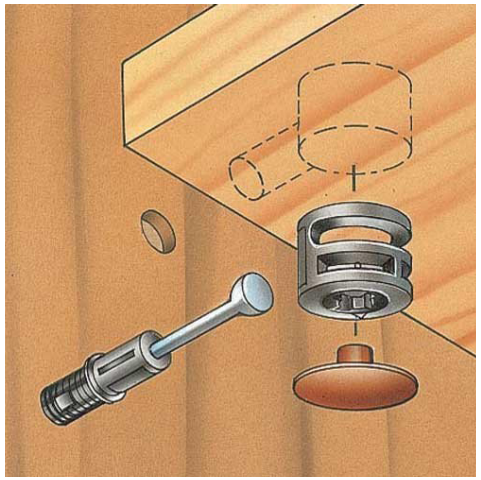
APPENDIX A

BOLTED









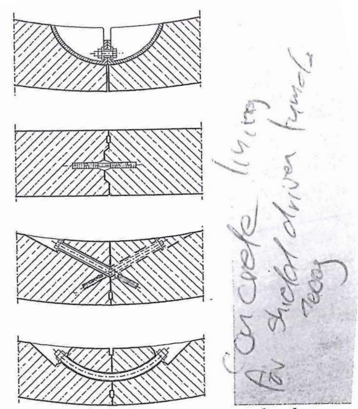
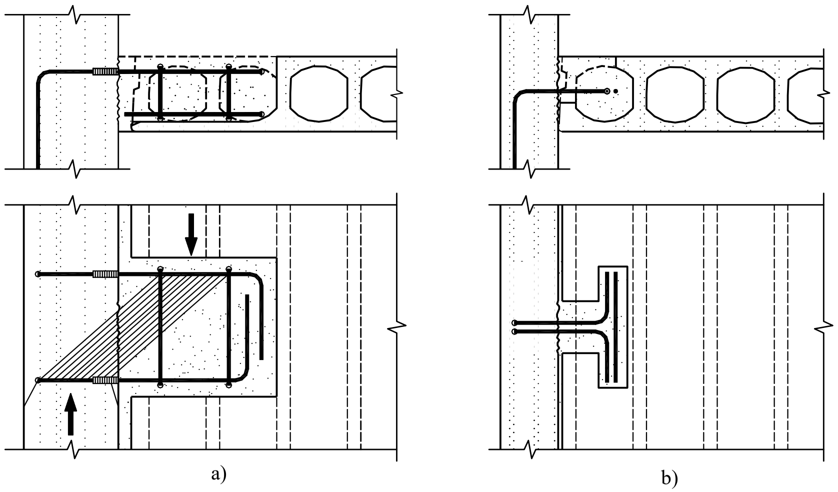


Figure 15. Bolt configurations and a photogra

WELDED



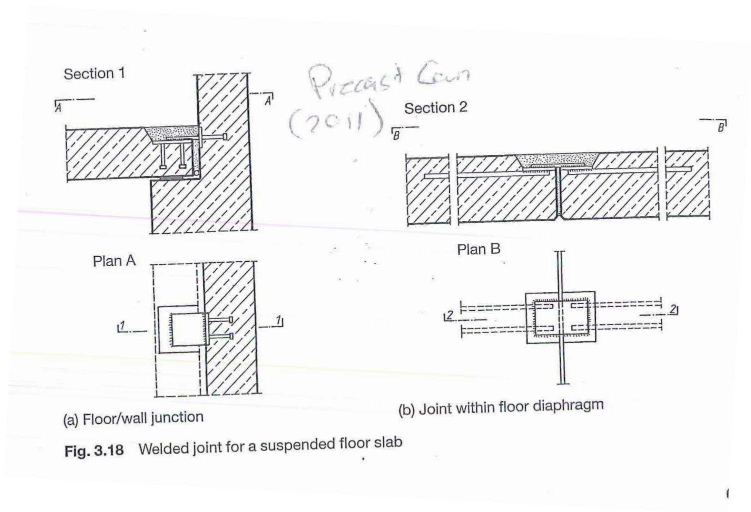
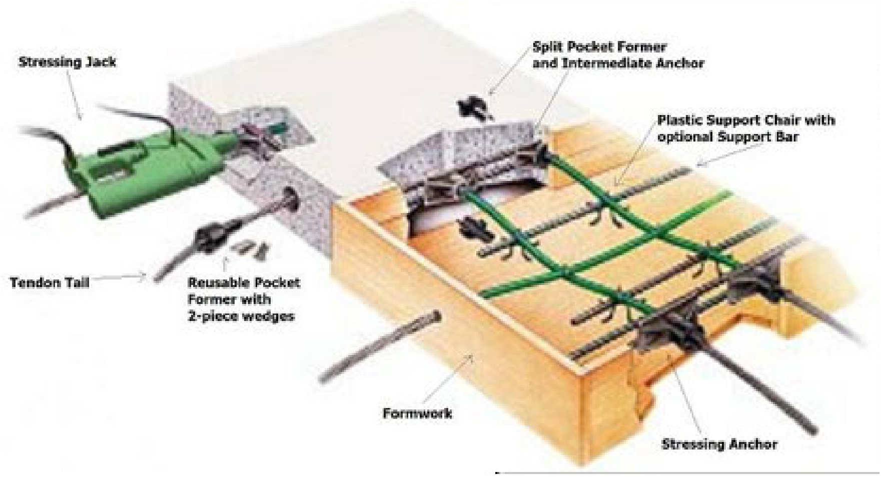
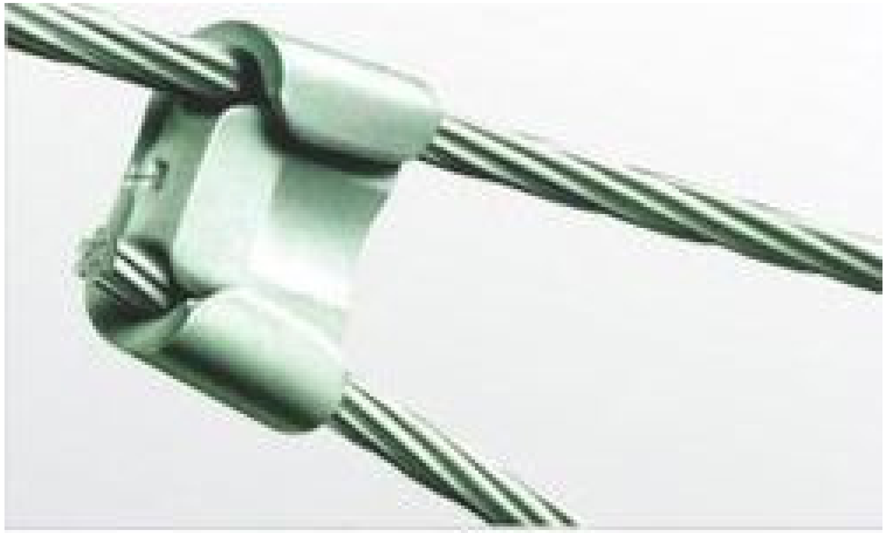


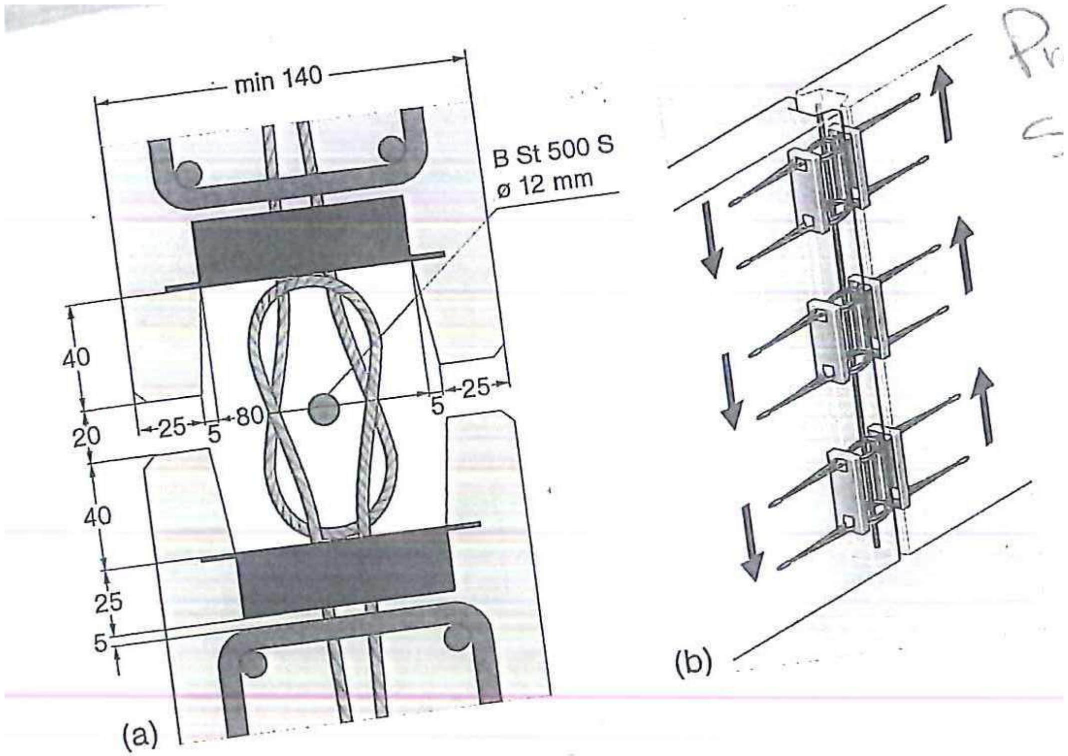
Fig. 3.18 Welded joint for a suspended floor slab

TENSION



Stressing Jack
Split Pocket Former
and Intermediate Anchor
Plastic Support Chair with
optional Support Bar
Tendon Tail
Reusable Pocket
Former with
2-piece wedges
Formwork
Stressing Anchor





min 140
B St 500 S
ø 12 mm
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20
40
25
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25
5
80
5
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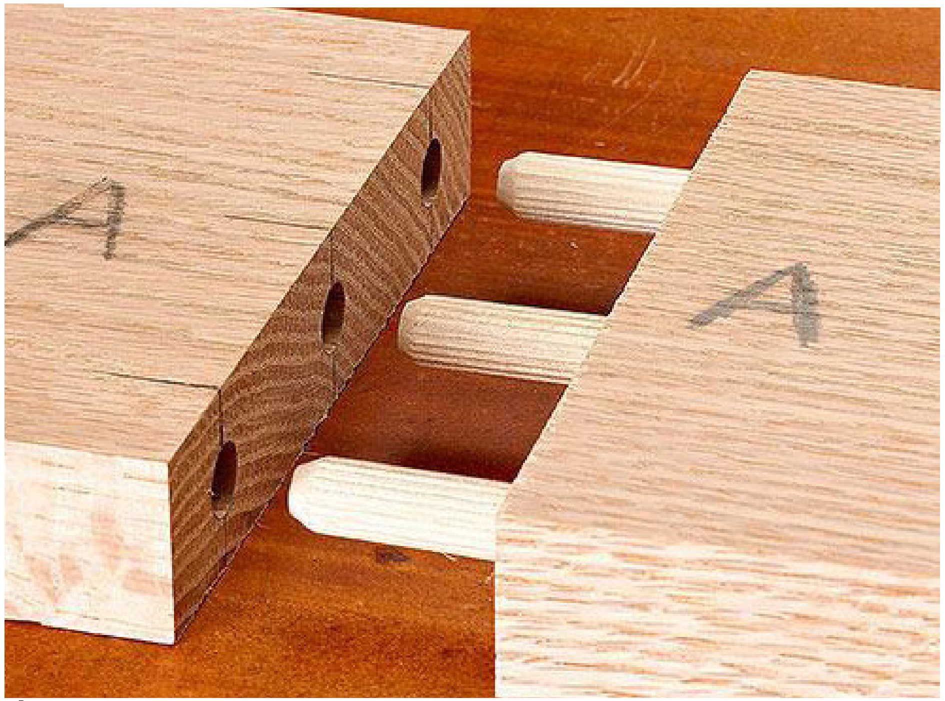
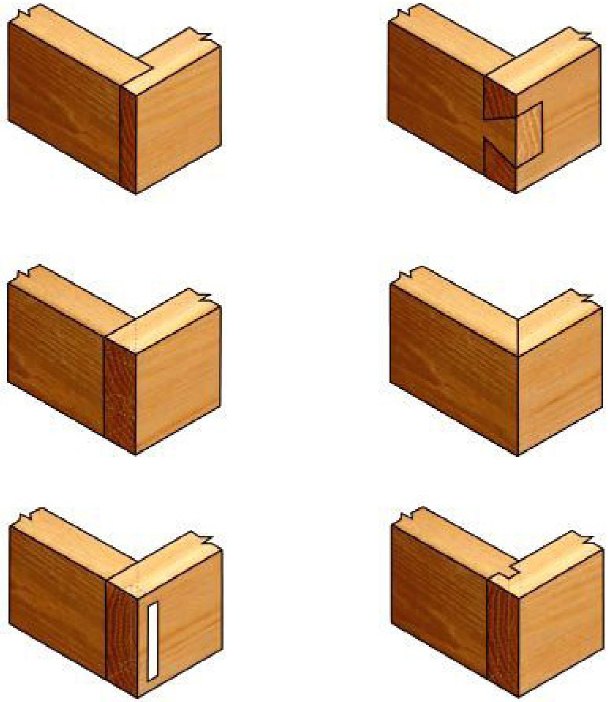
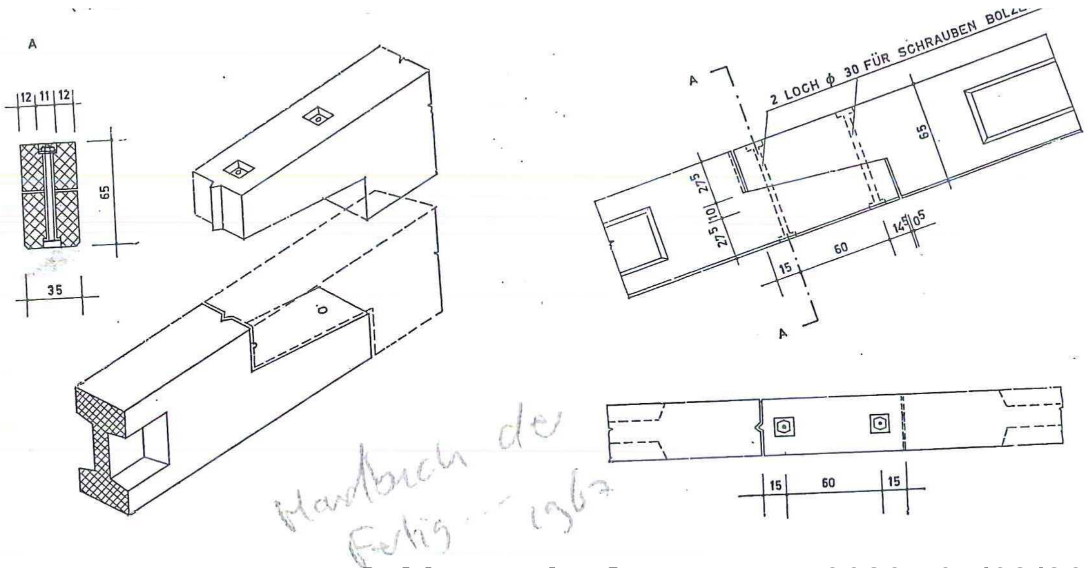
(a)
(b)

FORM







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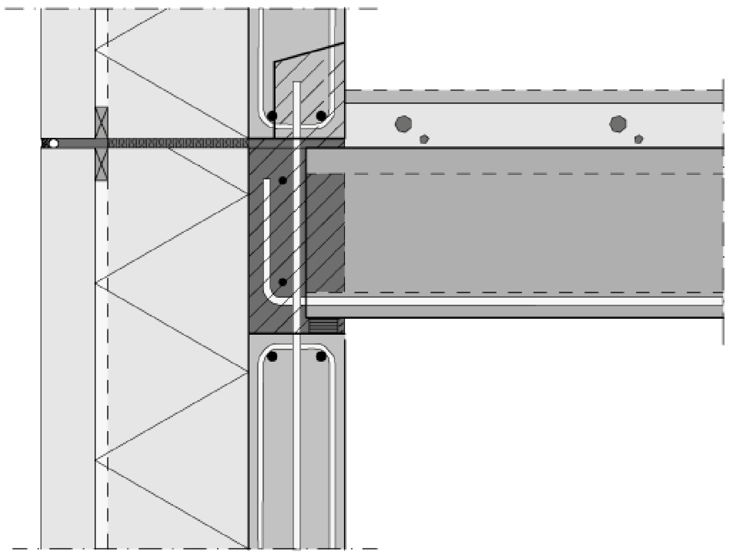


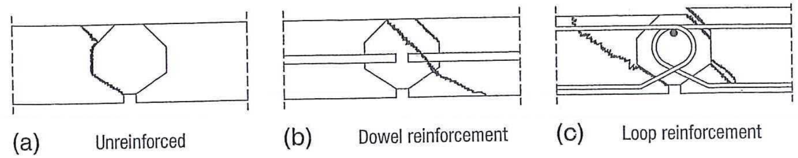


Fig. 3.39 Failure mechanisms for unreinforced, dowel-reinforced and loop-reinforced joints (according to [244] and [245])

Precast Concrete Structures (2011)

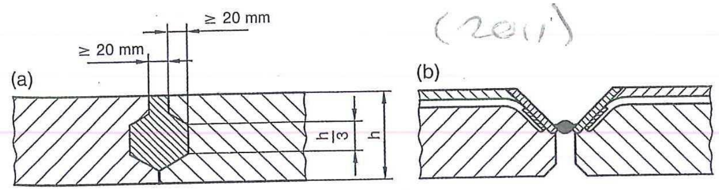
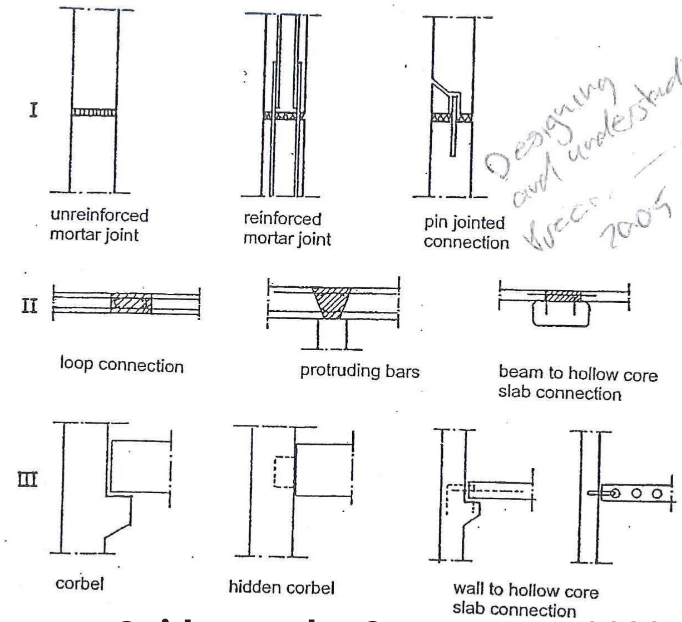


Fig. 3.40 Examples of joints between precast concrete elements to DIN 1045-1 (dims. in mm)



Designing and understanding precast ... 2005