Net structure for an adjustable flexible mould for hot bending glass

J.T.J. Gielen

K.P.H.M. Kitslaar

R.N.R Zimny

Issued on: 21-06-2011

Tutor: A.D.C. Pronk Technische universiteit Eindhoven

Production of double curved glass panes:

Auxiliary structures are a necessity in almost every construction process. To build a building or a product, the use of moulds, scaffolding and other structures is a known method. To support a product during production process a reliable mould is necessary to ensure an industrial production method.

Simple straight supporting structure is not a big challenge. When the architectural design consists of freeform double curved shapes however, the supporting structures will become a lot more complicated.

In modern architecture the limits of all kinds of materials are exploited to be able to make extreme designs. A trend within this movement is the increasing use of glass. The transparency and high tech appearance of glass results in a favorable material for modern architects.

The use of glass increases, and with that also the function. Image 1 shows a glass beam structure in which the glass meets constructive requirements. Developments in glass techniques have improved the structural qualities of glass, which widens the use of glass.

The next step in glass technology will be stand alone glass structures made out of constructive glass. To ensure an efficient force transfer within the structural glass, the answer will be in double curvature. Looking at lightweight structures in nature and in modern architecture, dome structures are one of the most efficient structures to span a (large) area.

Beside the structural advantages of double curved glass, the modern blob architecture focuses on freeform designs like in image 2 with complicated double curved surfaces.

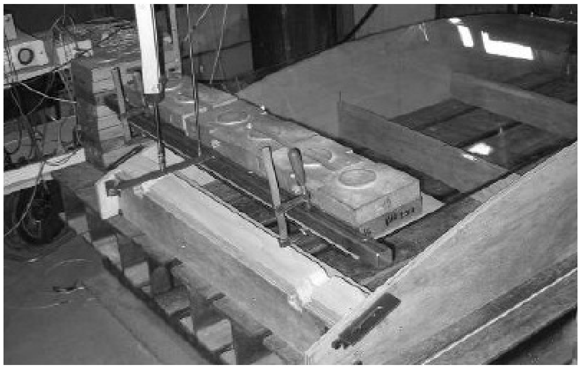
Production process:

The production process of obtaining curved glass has been in development for decades. At first the car industry had the need for double curved glass panes for the use of windshields.

The two most common methods are cold glass bending and hot bending. The two methods are based on the deformation of flat glass panes.

Img. 2: Unique double curved glass panes; architetturaeviaggi.it (2011)

The paper *Freeform glass structures* by ing. W.B. Schuurmans and Ir. A.D.C. Pronk [1] gives a good comparison of different bending methods. Mr. J. Belis et al. [2] emphasizes in his paper *Cold bending of laminated glass panels* the benefits of cold bend glass. Cold bending of glass is less time consuming en therefore a cheaper method to attain curved glass (image 3). Figure 1 shows the process of creating cold bend glass. First the pane will be heated to 70 degrees(1). Next weight is added to force the pane into the mould (2). When the glass pane has the right form it will be mounted to the frame and cooled down to room temperature (image 3 and figure 4).



Img. 3: Cold bending of glass; [2] (2011)

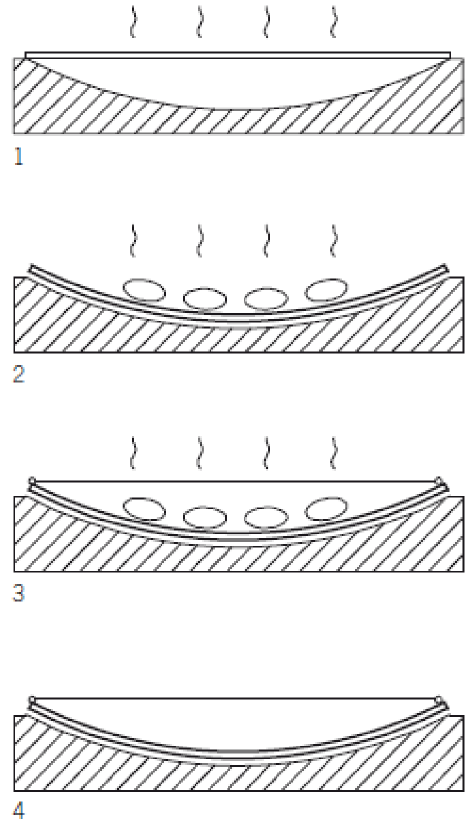


Fig. 1: Process of cold glass bending; [4] (2011)
1: heating of the glass pane up to 70 degrees
2: bending by adding weight at locations
3: fixating the glass pane to the mould
4: removing the weight and cool down the glass to outside temperature

There are several problems with this method. For one, the fact that the glass panes are forced over a frame before fixed to it. Therefore a complete transparent building entirely made out of glass is not possible with this production method.

Secondly this cold bending method has limited radii for different glass thicknesses as shown in table 1. The smallest radius is 2,4 meter, thus meaning a small deformation of half a degree per meter glass pane [4]. Extreme angles are simply impossible without breaking the glass.

Also (extreme) double curved panes are impossible to create with the cold bending technique. The stresses in the glass will get too uneven with fracturing as a result.

The cold bending technique is therefore only suitable for single curved panes with a limited curvature.

Table 1: Bending radius cold bend glass; [4] (2011)

Glass type	Tempered glass			Laminated safety glass made from tempered glass. Not heat treated			Laminated safety glass made from tempered glass. Heat treated		
Thickness [mm]	4	5	6	8	10	12	8	10	12
Radius [m]	2.4	4	6	5.2	8.4	12.3	2.7	4.8	7.2

Hot bending of glass involves a mould which presses the glass in the desired shape. To prevent shattering of the glass panes, the glass is heated until it's viscosity is low enough for free deformation (image 4). Flat sheets of glass are heated up to a temperature of about 600 degrees depending on the glass type.
Nowadays there are two methods for hot bend glass panes:
1: forming by gravitational forces
The glass pane is heated on top of a mould and takes shape only by its own dead weight. This method, described by D. Rietbergen in his paper *Adjustable mould for Architectural Curved Glass* [3], is the most common method to create double curved glass panes.
The flat glass panes are positioned on top of the mould in a kiln. When the temperature increases the pane will sag onto the mould and copies the form of the mould (image 5).
One of the main drawbacks is the limited control of the form finding. The only influential factors you can adjust are the temperature and the soaking time (the time you keep the glass on a certain temperature).
When glass panes are formed with this method, these two parameters need to be exactly right to ensure precise form finding.
Because of the self weight of the glass, the chance of failure is high. The glass test pieces, made in a kiln in Maarheze, showed insufficient sagging at the low points of the mould. Therefore the glass pane did not follow the shape of the mould. These tests are a good example of wrong heating process.
2: The second method uses a press to form the double curved glass panes.
The process is very much the same as with the gravitational method. Only difference is the form finding. With the gravitational method the glass sags without any help. With this pressed method the glass is gently forced into the final shape. This process is far more controllable than just relying on gravity. Alternatives to pressed mould are moulds using vacuum (figure 2), but the principle remains. A mould with a prefabricated shape that forces the glass into a certain shape will result in more accurate glass panes.
These moulds are made out of steel or ceramic and all have an unique shape. These moulds are computer generated and digitally cut with state of the art CnC robots. This makes hot press bending an expensive production method for double curved glass panes.

Img. 4: Heated glass with low viscosity; saddoboxing.com (2011)

Img. 5: Heated glass taking shape by its own weight; [4] (2011).

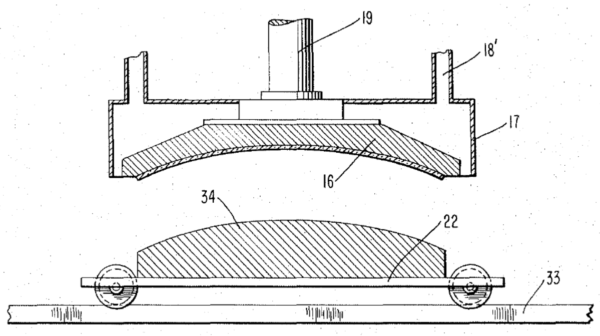


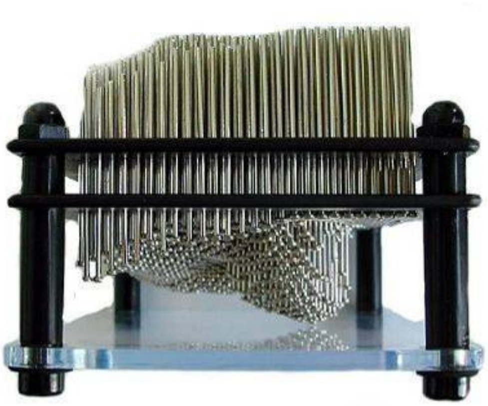
Fig. 2: Press mould automotive industry; [5] (2011).

When mass production is possible, for example in the car industry, this costly method eventually will be economical.
For the purpose of free form double curved glass panes this type of mould is far too expensive. A fixed mould is not an option to use. There is a need for an adjustable mould which can produce multiple double curved glass panes.

Trends in adjustable moulds:

There are several concepts in development of adjustable flexible glass moulds. A summary of these concepts are discussed in the paper *Free form glass structures* [1].
There are three main methods to create an adjustable double curved mould.

- The pin-bed type mould follows the principle of the pin-bed toy, where a large amount of pins can be positioned according to the form it is pressed by. This form will be copied (image 6). When these pins are connected to a computer they can be controlled individually.
This system can make endless extreme forms with one mould. The problem with this type of mould is the imprint the pins can leave in the glass pane. Therefore further research has to be done to successfully use this principle to hot bend glass panes.

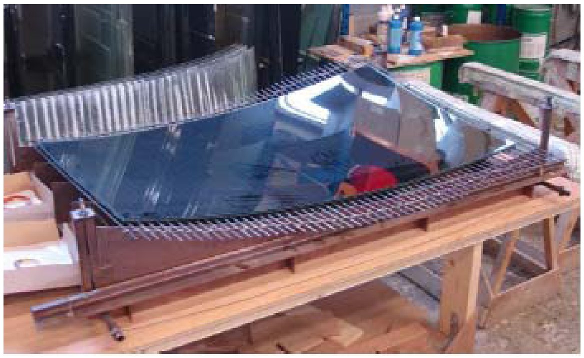


- Another known method to create an adjustable mould is the use of air pressure. Especially in the concrete architecture, pneumatic moulds are used to support the concrete forms. These moulds are inflated and will support the concrete structure until it hardens. Image 7 shows a inflatable mould consisting of balloons covered by netting.

Img. 7: Inflatable mould; Butink-technology.com (2011)

At this moment however there are no materials known that can be inflated and resist the high temperatures.
For the use of concrete or plastic this seems to be an efficient method to create complicated double curved forms, but in the glass technology this method is not the answer.

- Third method consists of an adjustable mould with a steel rod system. The university of Delft experimented with their so called Flex-rod System (image 8). Here the glass is lowered on a frame and is supported by a series of rods.



Img. 8: Flex-rod system; [6] (2011)

The glass pane is heated when lying horizontally. When the right conditions are met, the mould lowers over a series of steel plates which are cut to a certain form. The steel rods under the glass rest on these steel plates thus shaping the glass pane.

This method has positive results in form finding as well as quality of the glass panes. There is virtually no imprint.

Downside is the use of steel plates precut in a certain form. This means the mould is not fully adjustable. For free form glass production the material costs of all these steel plates is not economical.

Furthermore, the created glass pane has no extreme double curvatures. It is not clear if the result will be as good when more demanding forms are created.

Design of an adjustable mould:

By looking at the existing trends in adjustable moulds an underexposed direction has been found: a mould which uses flexible steel netting to create double curved forms.

This method ensures full adjustability thus eliminating excessive use of material. The mould should consist of a netting which can be tensioned in a frame. This frame needs to be able to vary in height to create a variety of double curved forms.

The literature shows a big advantage in precision if a glass pane is produced in a double mould. The form of the mould will be copied more accurate when the glass will be forced into the shape. This means some kind of double steel netting which encloses the glass pane could be a solution.

During the bending process the glass will be heated in a flat horizontal position. After heating, the mould with the glass will be adjusted to the right form during soaking.

When cooled, the upper netting has to be able to be removed, and the glass pane is ready for use.

Study of meshes and net structures:

To function as an adjustable mould, one of the most important properties of a mesh is the structure. The structure of the mesh has a big influence on the flexibility and adjustability of the mesh. Existing literature contains little information about the use of meshes for moulds for bending glass panes.

Pneumatic moulds are a known method to realize double curved surfaces in today's modern architecture. They can be used for creating concrete or plastic surfaces. Another known method to create double curved surfaces are membrane structures. These light structures consist of meshes which are tensioned between their supporting structures. The form of the flexible membrane takes shape by tensioning the membrane using several edge cables.

The tensioned membrane will take a form which transfers the structural forces as efficiently as possible.

This type of construction defines a lightweight efficient structure. Image 9 shows an example of a membrane structure in which the mesh takes an efficient form.

One of the most important qualities of a good membrane is flexibility. The mesh needs to be able to adjust its structure to form smooth curvatures. To attain this high level of flexibility, the most common mesh structure is a woven structure.

Image 10 shows a woven structure of a polyester cloth. The mesh consists of flexible wires which are bundled to strings. These strings are woven into a mesh. This kind of connection results in a mesh where the strings are able to move independently.

This freedom is a necessity when creating a double curved form which can change shape.

Img. 9: Membrane structure; Buitink-technology.nl (2011)

Img. 10: Structure of a mesh; Dreamstime.com (2011)

By looking at existing double curved structures and their material specifications, the qualities for the mesh in the concept mould can be determined to create a double curved surface:

-material should not have a permanent deformation

-the nodes have to have enough movement possibilities to reorganize in space.

- the material should not stretch to much when tensioned

- if the nodes are fixed, the material itself has to deform to create flexibility

Additional conditions for the mesh of the concept mould:

-resistant to high temperatures (min 700 degrees)

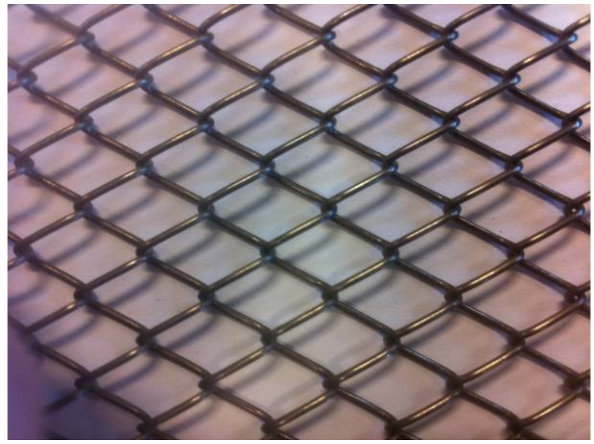
- the design has to be durable to be economical

-the material should not leave any residue or imprint in the glass

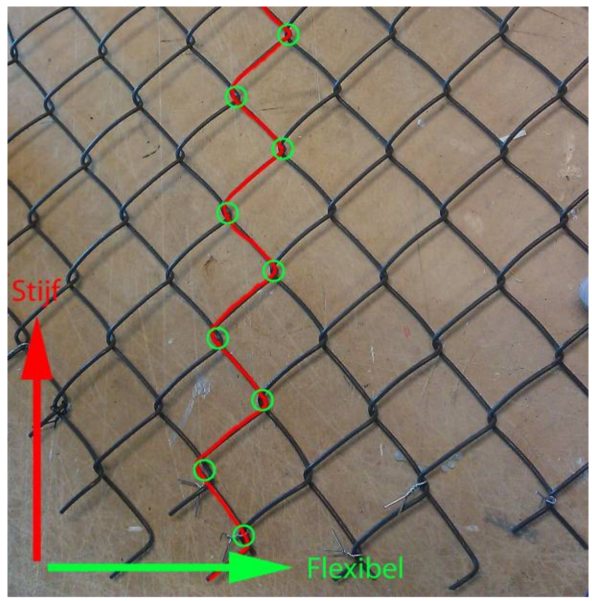
The flexibility and high temperature resistance seems to be a difficult combination.
To determine if and which existing products can be suitable for the function of an adjustable mould, a variety of products are compared with the conditions mentioned above in mind. The full comparison of these products can be found in appendix 1.
A variety of steel meshes has been looked at together with steel curtains and heat resistant fabrics.
The conclusion of the test has given insight in the way a mesh obtains its flexibility.

A short summary:
Steel curtains:
The steel curtains have a structure which is made out of long steel wires chained together.
Image 11 shows a sample of a steel curtain. The wires have a hinging connection which allows total freedom of movement. The structure of the mesh is anisotropic which results in different qualities in de mesh. Image 12 shows the anisotropic feature in the steel curtain. The windings have total freedom, but the layout is made out of stiff wires parallel to each other.
Therefore deformation in the stiff direction is only possible when the material deforms plastically.
Plastic deformation is not acceptable with stiff wires looking at the durability aspect of the mould.

Heat resistant blankets:
The steel curtains showed the downside of an anisotropic material. It is not suitable for extreme double curved surfaces because the material has to deform plastically.
Looking at the existing lightweight structures a membrane cloth which can resist high temperatures is a good option. Therefore a test has been done with a fire blanket.
The blanket is made out of glass fibers woven into a sheet. A coating has been added to make



Img. 11: Steel curtain manufacturer Omnimesh (2011)



Img. 12: Anisotropic structure (2011)

Img. 13: fire blanket; brandblussershop.nl (2011)

the blanket airtight. The blanket is quite stiff which results in folding when trying to make a double curved shape. Furthermore at a temperature of 800 degrees the coating will catch fire and the glass fibers will become brittle.

Steel wire netting with a woven structure:

The two products mentioned above gave an inside in de best structure an material. Steel is the way to go.

The fire blanket showed a fairly good deformation due to the woven structure.

To create a durable mould a wire netting has to be found made out of thin steel woven into a net, which has the heat resistance of the steel curtain and the structure of the fire blanket.

The manufacturer Omnimesh situated in Lokeren delivers steel meshes in kinds of woven structures. The main market is the use of filter in machines.

A variety of sample meshes from Omnimesh were obtained and tested.

The main difference between de the meshes was the thickness of the wires and the size of the meshes.

Six woven wire nets have been tested, all with different wire thickness and mesh size, and they show a coherence between the two variables.

A net with thick wires and small meshes is not flexible because the wires have little freedom of movement.

Wire nets with very small meshes and thin wires have such a microscopic structure (mesh of 0,1 mm en wire thickness of 0,065 mm) that it reacts the same as a sheet of paper. (Image 14)

The woven structure is so small resulting in to little freedom of movement around the knots.

Deformation in every direction is possible, but trying to create a double curvature results in folds.

The coherency of the thickness of the wires and the size of the meshes results in a certain ratio:

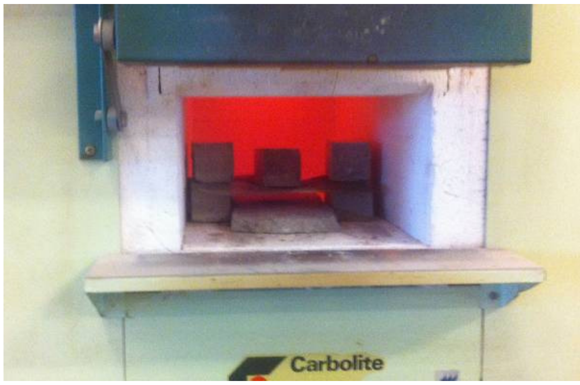
Size of the mesh / thickness of the wire =

The higher the number the more flexible the net is.

The tested wire nettings vary from score 6 to score 1,5. The net in figure 6 has the score 1,5 and the net in image 15 has the highest score of 6.

Img. 14: Onimesh WF I07 steel wire netting (2011)

Img. 15: Onimesh WB I05 steel wire netting (2011)



Img. 16: Onimesh WB I05 steel wire netting heat resistance test (2011)

The nanomesh cannot deform at all, only bend in one direction at a time. The wire netting with score 6 has a high degree of freedom and can deform freely in all directions. This freedom of movement is critical for the durability of the mould, because it prevents plastic deformation.

The steel netting with a wire thickness of 0,25mm and a mesh size of 1,5mm has been further tested to determine the heat resistance of the thin wires.

Up to a temperature of 800 degrees in a loaded situation there was no sign of failure in the net (image 16). The slim wires result in a relative flat surface in comparison to the steel curtains. This will have a positive effect on the elimination of imprint in the glass sheets.

The wire netting WB I05 meets all the set criteria for a net needed in the flexible glass mould.

This material study has shown which kind of requirements a wire netting has to have to span a good double curvature.

Most important feature is the freedom of movement. This can be obtained by flexible wires and fixed nodes, or stiff wires woven to a net with loose connections.

The second option proves to be a better option because the net can have a flatter surface. Secondly the stiff wires prevent buckling of the mould and the flexible nodes create a high freedom of movement. The result is a wire netting which can be tensioned in the length of the wires. These wires can slide in an efficient position to handle the tensional forces thanks to the flexible nodes.

Steel netting seems the best product for a double curved mould. Critical point with this material is the ratio between the thickness of the wire and the size of the meshes. The chosen mesh has a ratio of six. This mesh had the highest ratio and will be used in the concept mould (image 17).

Img. 17: Test mould with Omnimesh steel wire netting (2011)

Forces in the wire netting:

In a traditional wire netting fixation, the wire netting is cut into the correct shape for the form it has to resemble. So the shape of the wire netting is known and the optimal netting can be calculated. Before the shape is made, the wire netting is cut in this optimal way. After the fitting of the netting in the right shape, it fits perfectly and has the correct force density to keep its shape.

In an adjustable mould it isn't possible to prefabricate the wire netting in the optimal shape since the shape will never be the same. This leads to flexible fixation methods that can adjust to the variable shapes that will be imposed. For this purpose an alternative fixation method has to be developed. To assure the wire netting structure can deform in an optimal way for every shape, it is necessary to fixate the net without clamping the nodes. As is showed in the previous paragraph, flexible node intersections are a very important quality. The wire netting has to be able to deform to different shapes. If the nodes are clamped, the wire netting can't deform properly because the wires can't slide over each other. This gives an extra difficulty to the fixation since there is no way to get any grip on the wire netting.

Clamping the individual wires could be a solution to prevent any clamping of the nodes. But this isn't a practical solution since the wires are very thin and there are a lot of wires. There won't be enough space in the oven to fixate all the wires individually and still keep it flexible. During the adjustment of the mould, the distance between the corners will increase.

The fixation needs to depend on the internal friction generated between the individual wires of the wire netting and not by the force generated by the clamp. The internal friction in the wire netting is generated by the weaving of the wires. Because of little displacements in the wires, the wires interlock with each other when stressed. This leads to small friction forces between the wires. These friction forces can be used to fixate the wire netting to the adjustable structure using pins (figure 3). These pins will put force on one wire or a node without prohibiting its ability to shift. The nodes are still free to move and wires can shift within the wire netting. Force is transferred from the adjustable structure to the wire netting using the friction forces of the wire.

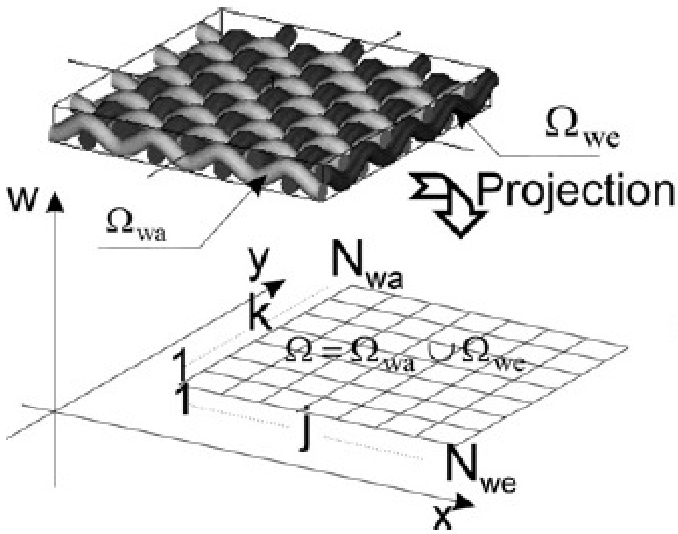


Fig. 3: Friction in two directions in a woven structure (B. Ben Boubaker et al., 2007) [7]

Net fixation:

The pin fixation will be tested on maximum allowable force and displacement with different setups of the pins. The net is positioned between the adjustable rods in a way that the wires are orientated in the direction of the adjustable rods. This means that the further you move from the corner to the middle, the longer the perpendicular wires will be. This also means there are more nodes and more friction between the wires. Theoretically the forces within the wire netting can be much higher.

Mould corner pin fixation testing

To test the allowable force there will be two different pin setups with three different depths from the corner. The first pin setup will consist of three horizontal pins placed four mesh sizes from each other. The forces of the pins on the wire will be distributed. The second setup will be diagonal. The middle pin will be placed two rows higher than the other pins. This means that the forces in the wire netting will be distributed on to two wires, increasing the total friction forces and thus the maximum allowable stress the net can take.

The set up of the tests is shown in the figures below. The colored dots represent the placement of the pins. Each of the colors shows a different depth in the wire netting that has been tested. The depth of the placements is calculated from the bottom corner of the wire netting sample. The blue dots are placed ten meshes from the bottom, the green dots are placed fifteen meshes from the bottom and the red dots are placed 20 meshes from the bottom. For the diagonal test, the middle pin is placed two meshes higher. So for the blue dots the amount of meshes from the bottom are ten and twelve. During the test, the top of the wire netting sample is clamped to fix the parallel wires like they will in the mould. The perpendicular lines can move freely and have to depend on the friction forces between the wires to keep from failing. The wires that have to withstand the stress of the pins are colored red to make them more visible.

For a sense of scale, a background of squares is placed behind the wire sample.

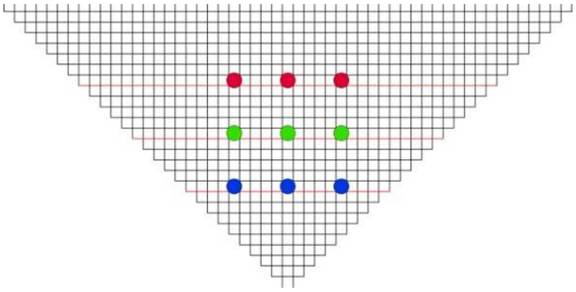


Fig. 4: Test setup for three horizontal points with different depths

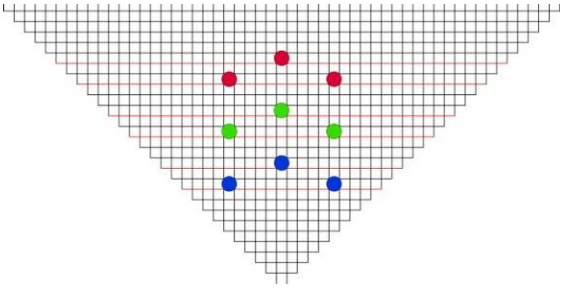
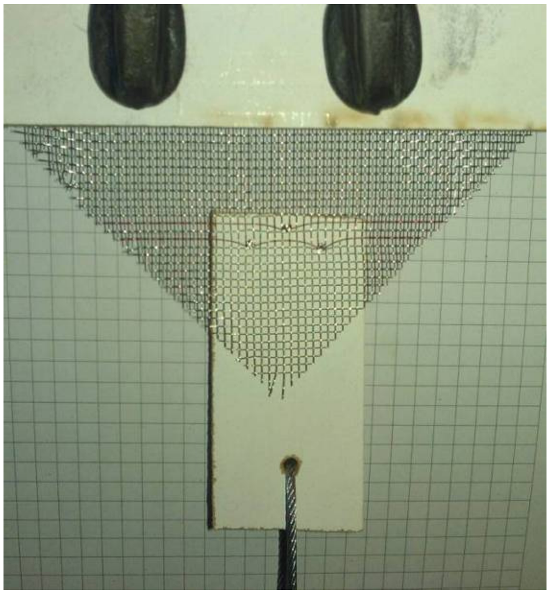


Fig. 5: Test setup for three diagonal points with different depths



Img. 17: Wire netting sample with three diagonal points without force

These squares have an edge length of 5 millimeters. The background can be used to show the scale of the displacements. The meshes of the wire netting deform during the stress test and thus can't be used as a reference point.
The pins, as shown in the figures, are attached to a small MDF piece. This MDF piece has a hole in it where weights can be added. After each added weight the displacement will be measured from the bottom of the clamp to the highest pin.
After testing of the first two setups a third test is performed with a different pin placement. With the observations from the first two tests the setup of the pins has changed. The amount of pins has been increased and the pins are diagonally placed to make sure the forces are divided on to different wires. These pins are placed at twenty, twenty-two and twenty-four meshes from the bottom. This pin placement is shown in the figure below.

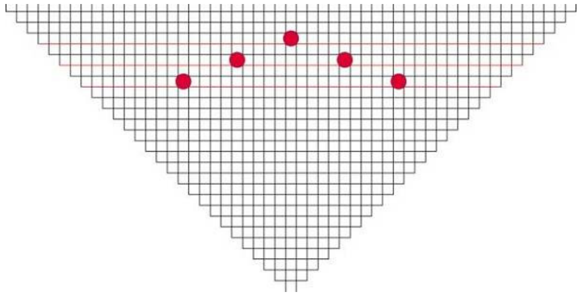
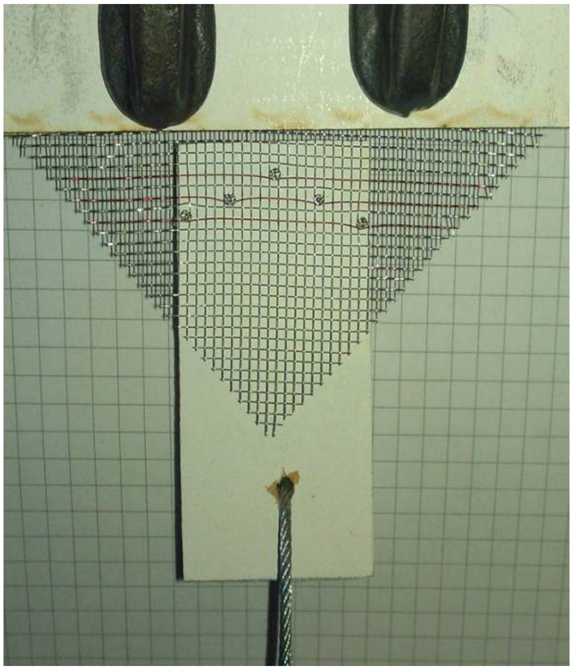


Fig. 6: Test setup for five diagonal points



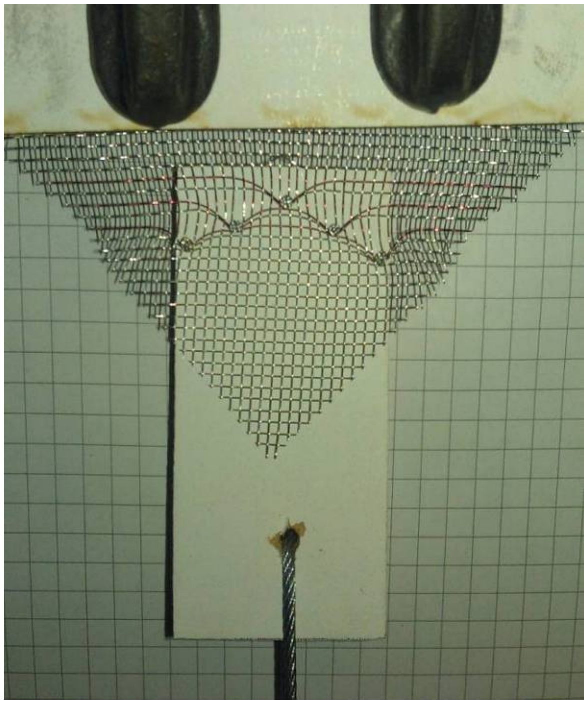
Img. 18: Wire netting sample of five diagonal points without force

Conclusion of the corner pin tests:

The test results from the three test show that the setup of the pins has a big influence on the maximum collapse stress. The three tests show that the total displacement doesn't have a linear relationship with the increment of force. The three horizontal points fail with only little force compared to the other test. This shows a linear placement of pins isn't favorable. Five diagonal points can take more force than the three diagonal points, but have less displacement than the three diagonal points before collapsing. This is a positive attribution, because the displacements in the wire netting has to be as little as possible. The five diagonal points can withstand sixteen kilograms of force with four millimeters displacement while the three diagonal points have a displacement of eight millimeters with the same amount of force.

When the wires are placed diagonally and thus transfer their force on to more different wires, the collapse stress is increased. The more wires are involved in the transfer of force, the more friction is generated. The friction leads not only to a higher allowable stress, but also to a lower displacement. In the graph of the five pin test some horizontal points can be detected. This means the displacement is very small. Additional force is divided by the wires to the nodes. The shear resistance is greater than the force developed by the pins. The bumps in the graph are a result of the exceeding of this shear resistance which leads to a sudden displacement. This is sudden because nodes at the edge of the wire netting detaches. This leads to lower friction forces in total and a displacement of the pins. The displacement is intercepted by the pileup of wires. This can be seen in image three. The wire net has deformed drastically. The wires between the pins are arched. The pin top pin transfers force to this arch which keeps it from displacing and divides the force even more to the other wires. The edge of the corner is deformed so much that wires are interlocked even more. This will also lead to higher allowable forces on the corner sample.

The wire netting can take a lot of stress before it breaks, but there is too much deformation at this breaking point to make it reusable. To be able to reuse the wire netting several times, the displacement should be kept to a minimum. The graph of the five point setup shows a maximum displacement of four millimeters at a force of sixteen kilograms. In the wire netting the meshes have a width and length of one and a half millimeters. The displacement of four millimeters equals less than three meshes. This is a reasonable displacement because the edge is still intact, as is shown in image 19.



Img. 19: Wire netting sample of five diagonal points with a force of sixteen kilograms and a displacement of four mm

Tensioning of the mesh:

The mesh structure that will be used in the adjustable mold has to be tested to see what the maximum force is that can be put on the mesh. This force will be transferred by using the pins. There will be four main points in the corners of the wire netting to adjust the net into the right shape. But this will lead to a centralized tension in the wire net between the corners. The sides of the net won't be tensioned with only four points. It is necessary to tension the sides of the wire netting separately.

The optimal way to do this would be to tension every individual wire of the net. The wires should be tensioned during the whole process of adjusting the mould. Since the distance between the edge of the wire netting varies during the adjusting, tensioning it beforehand isn't possible. A system of weights or springs could be developed to make the tensioning possible. A disadvantage is that the wire netting can't be replaced easily since all the wires are connected individually and need to be reconnected individually to the mould in the kiln. Another disadvantage is that the wires reach the edge of the wire netting at an angle of approximately 45 degrees depending on the shape of the net. This will lead to a very complicated mould with a lot of different parts. This is very unpractical and expensive.

The question is if this complicated edge tensioning is even necessary to make a tensioned net structure in the mould. To evaluate this necessity the net can be compared with membranes that are used for lightweight structures [8]. In these membranes the force imposed on corners leads to a force arch of tensioned membranes. Without an edge cable the edges of the membrane won't be tensioned and therefore not in the right shape. This part of the membrane will be a loose and unnecessary part of the membrane. If this happens in the mould, the glass will deform in an unwanted and uncontrolled way.

To be able to tension the wire netting properly there has to be some sort of edge control.

The stress implemented on the edge doesn't have to be big to get it in the right shape.

Figure 7 shows the tension in the net with different numbers of edge connections. The grey parts are the parts of the net that are not tensioned. It becomes obvious that the more connections are available, the smaller the grey area is going to be. However the difference in the amount of net that isn't tensioned between 3 or 4 connections isn't that great anymore compared with the difference between 1 or 2 connections. Therefore it isn't necessary to make a great amount of connections. 4 connections on each edge of the net will be enough to tension almost the whole net. If a greater net has to be used.

The mold will be over dimensioned to cope with the area of the net that isn't tensioned (area A in figure 7). This leads to an unused strip on the sides of the mesh of two centimeters. The part of the net where the glass will be put on, is therefore fully tensioned and can be put into the best form possible.

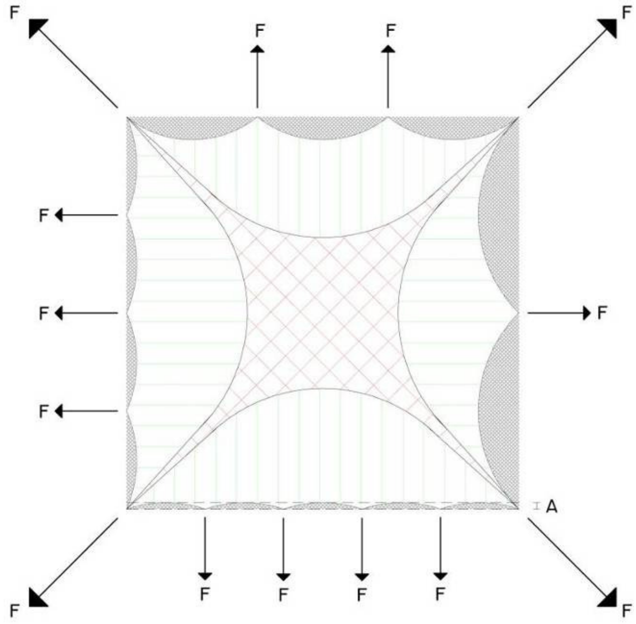
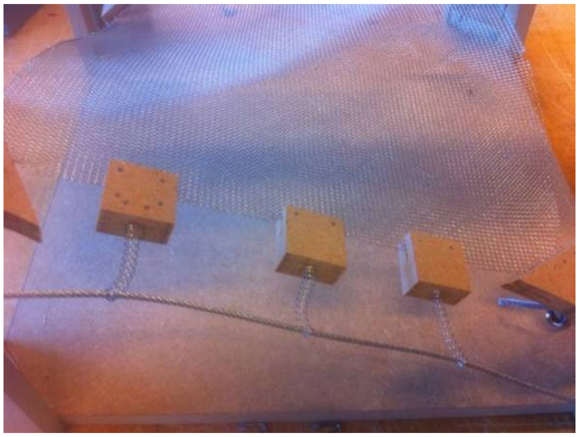


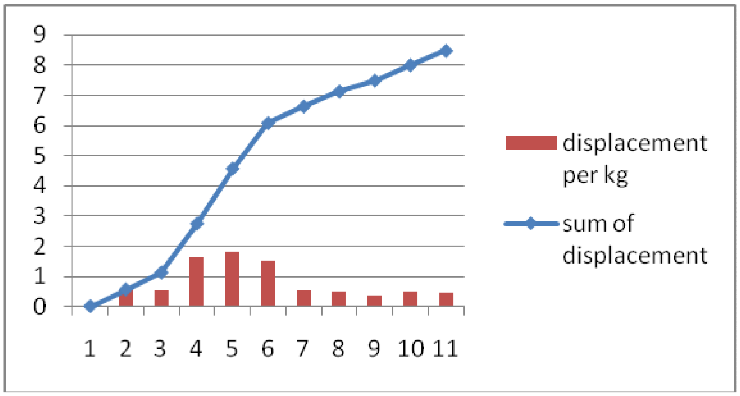
Fig. 7: Different tension zones with more edge tensioning

In image 20 and 21 two designs have been made according to the edges of the net. The top figure shows three clamps which are connected to net on one side and to an edge cable on the other side. The bottom figure shows the same clamps, but they are connected to the edge cable with springs. The idea is that the springs regulate the tension that is needed, and therefore take care of a better deformation of the net. However the net without the springs showed the best deformation, and therefore will be used in the final design.
The edge has the same demands for grip as the corner does. So there needs to be a system which can tension the edge without clamping it. The same pin system as is used for the corners can be used for the edges. The pins will also take advantage of the friction forces between the different wires. The stress implemented on the edge doesn't have to be big to get it in the right shape. To test the allowable force on the edge using the pins, another test has been performed. In this test the depth is measured in the amount of nodes from the edge. This is shown in figure 8. The graph for the displacement shows an increasing displacement for the first half, but it settles into an almost linear displacement at the last half of the graph. The bar chart also shows that the displacement is constant at the second half of the test. This could be subscribed to the clutter of wires that inhibit the movements to the maximum force until it collapses.

Img. 20: Edge tensioning with clamps connected to an edge cable



Img. 21: Edge tensioning with clamps connected to an edge cable with springs



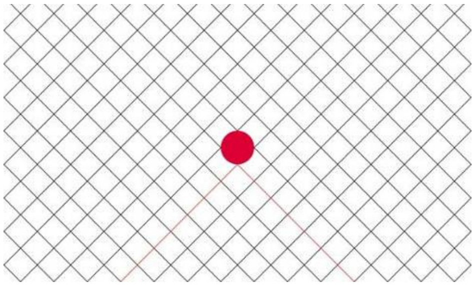
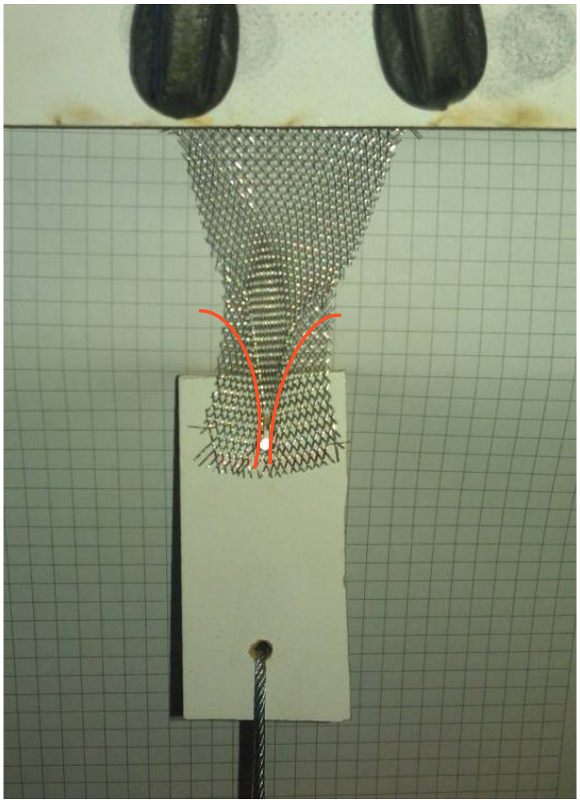


Fig. 8: Force displacement diagram of edge clamps

Image 22 shows the displacement of the edge sample piece before it collapses. The piece is stretched far out since this is the most flexible direction of the wire netting. This sample also shows the tensioned arches that arise when the edge is stressed.

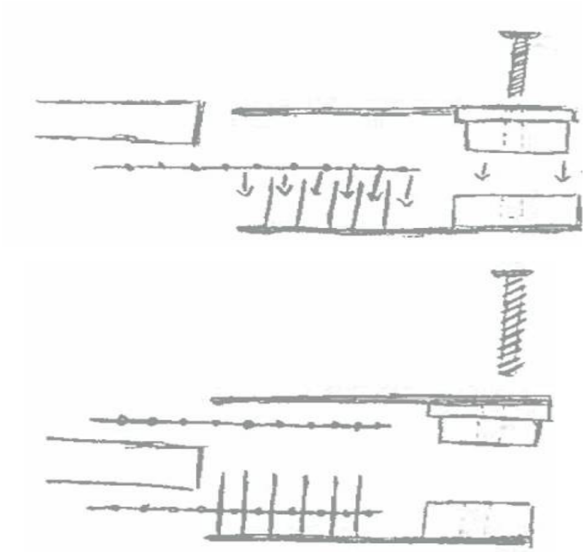


Img. 22: Edge tensioning with clamps connected to an edge cable with springs

Unobstructed deformation and flexibility:

The deformation of the net is realized by the flexibility in the connections of the wires. This leads to a deformation of each individual mesh into a checkered form. To allow this deformation at the fixation points to the frame of the mould, the connection is not allowed to grip the net. So there needs to be a system which can tension the edge without clamping it. The edge has the same demands for grip as the corner does.

The design concept for the clamps is shown in image 23. The top design is for a single net and the bottom design for a double.



Img. 23: Concept drawings of the corner clamp

The starting point is a series of pins which go through the meshes of the net. On the top and bottom of the clamp, two plates are mounted with a screw or a bolt. The pins should have been welded on the bottom plate for better handling.

After putting the net(s) into place, the top plate can be put on the pins. The pins can pierce trough the bottom plate to close the total package.

On the right side of the clamp (where a nut with bolt keeps everything in place), there is an opportunity to put plates between the top and bottom part. The amount of plates depends on the thickness or amount of glass plates that are going to be bend. The difference in the amount of plates creates flexibility in height, so the same clamp can be used for a wide variety of glass plates.

Flexibility is also needed in the connection between the net and the supporting structure. To prevent the net from deforming in a way that is not desirable, the clamp has to be able to turn with the corners of the net. For example if the clamp can only stay in a horizontal position, the net is not able to deform as desired (figure 9). Therefore a hinged joint has to be made on the backside of the clamp, so it will be in an optimal position at any time.

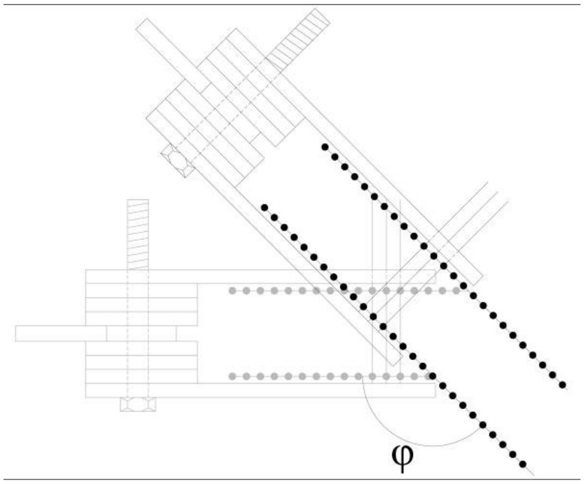
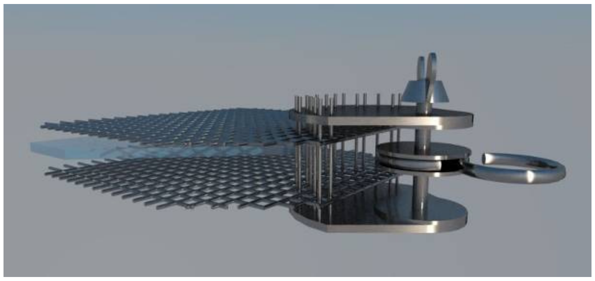


Fig. 9: flexibility in positioning of corner clamps



Img. 24: Exploded view of clamp design

Design of the clamp:

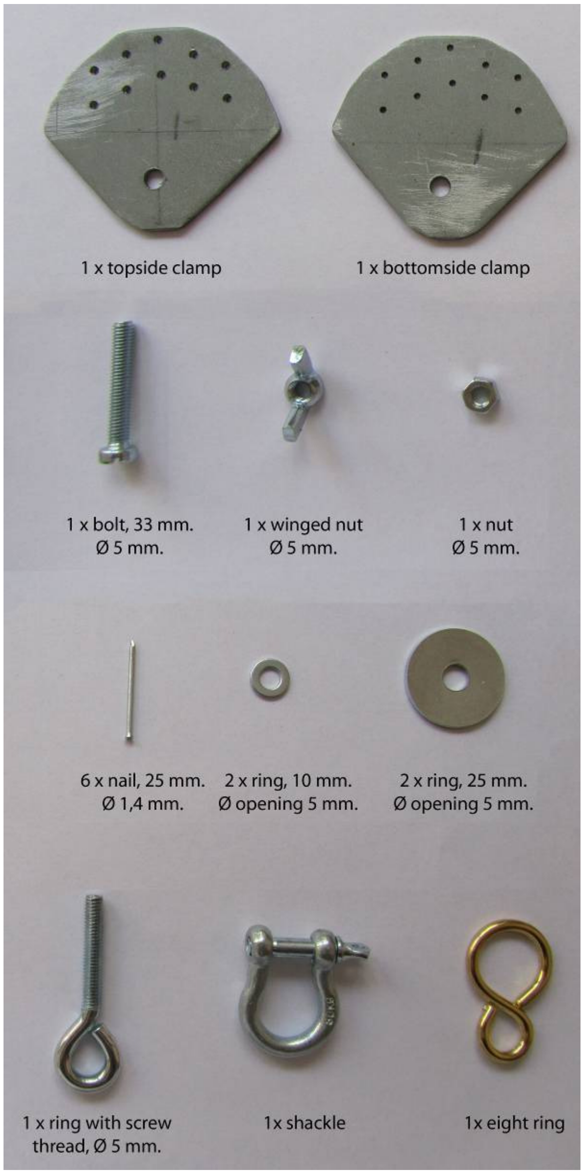
A said earlier, the basic parts of the clamp are a set of pins, a top and bottom plate, a couple of spacer plates to adjust the height of the clamp and a bolt with a winged nut to connect al pieces together.

The form of the clamps for the four corners of the net is a result of the test described earlier in this paper. Figure 6 shows the optimal position of the pins as tested. This position forms the base of the form of the top and bottom plates of the clamps (image 24). This also allows the net to deform freely in all directions and is not obstructed by the clamp.

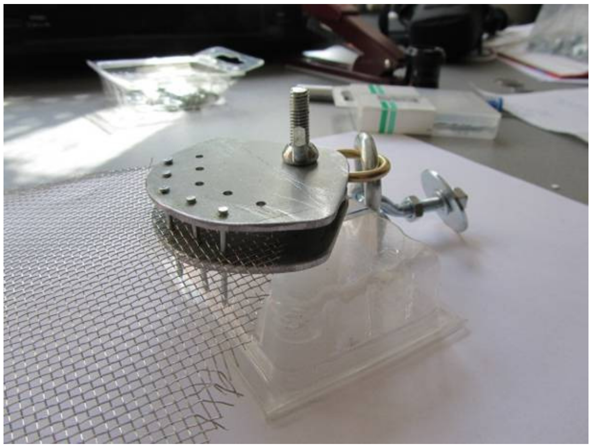
In figure 24 and 26, the design is shown of the clamps to connect to corners of the net to the supporting structure.

The clamp is designed so it can be build out of regular materials, which can be found in common shops. In the future, special parts can be made to enhance durability and loading capacity. Image 25 shows all the parts which are used for one corner clamp. The rings are there for the adjustment of the height of the clamp acting as spacers. Each of these rings has a thickness of 1 mm.

The produced clamps vary a bit from the designed ones. The pins should have been welded on the bottom plate, however it was very difficult to get this done by hand.

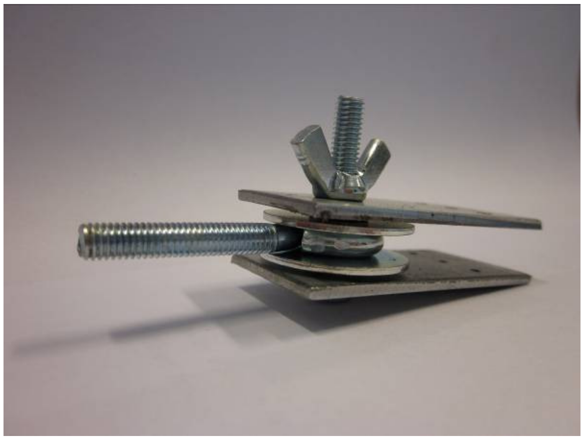


Img. 25: Parts for one corner clamp



Img. 26: Prototype of corner clamp

The pins have to be in a perfect vertical position in order to go through the net fluently. If the pins are not perfectly vertical, the net will be deformed, which will influence the accuracy of the glass pane negatively. Therefore the pins are put in place on the top part. This ensures that the pins will not fall out of the clamp, when they are put into place in the mold.
To increase the ease of use the clamps are connected to the frame with shackles. This connection is easy to demount, so the mould can be removed and the glass pane can be replaced.
The design of the clamps for the edges of the nets varies not much of those for the corners. The same principle with the pins is used and the position of the pins also follows from the test mentioned earlier. Image 27 shows one of the clamps for the edges of the net.



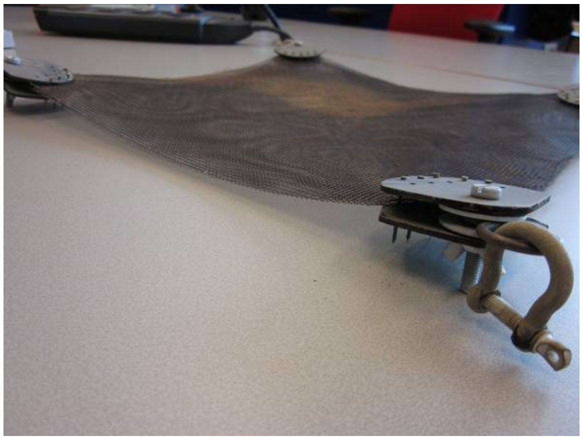
Img. 27: Prototype of edge clamp

Conclusion double membrane mould:

Extensive testing showed an inaccurate bending process when the moulds were used with only one steel netting.
Some degree of regulation was possible by adjusting the temperature and the soaking time but the results did not meet the set requirements to obtain double curved glass panes for architectural purposes. The glass panes could not be forced into a shape with only one steel netting as a mould. The sagging of the panes only by gravitational force is not a good production process.
Therefore the goal of this research was to create a mould which can provide a precise controlled deformation of the glass panes. The answer has been sought in a double steel netting. The benefits of a membrane structure and a pressed mould are combined in one product with this concept.
The flexibility and adjustability of a membrane structure combined with the high degree of influence in form finding and accuracy of a pressed mould give this new concept a good set of qualities.
The first test piece, made on July 21st 2011, had a positive result (image 28). The kiln was heated to 640 degrees. The 3mm thick glass pane was put in between the steel nettings.
The adjustable mould itself was set horizontal during the heating stage. When the temperature reached 640 degrees, the mould was set in a double curved shape. After the forming the kiln was turned off.
The glass test pane shows good deformation with this improved mould and heating process (image 30). The pane has a nice smooth radius without any folds (image 31). The upper mould pushed the glass into the right shape.
There was a little hesitation about the imprint with this new method because the glass will be pushed into the right shape.
However the glass pane shows very little imprint despite the forced form finding. This can be subscribed to the equally divided force on the glass. The imprint in the glass panes, which were curved on the mould with single

steel nettings, was local. Because of the high temperature needed for the forming of the glass, these local areas have deep imprints in the glass, which decreases the architectural quality and usability greatly. This major drawback has far less been seen in the first glass pane tested in the new mould. The glass pane made in the new mould did not had to be very hot for long, therefore decreases the risk of imprint.
The first test has been done without any edge tensioning. The double steel netting was tensioned with the four corner clamps described in the previous paragraph (image 29).
The clamps are fully adjustable and demountable. This makes it easy to remove the whole net and replace the glass panes. The adjustability in height makes it possible to bend more than one glass pane at once.

Img. 28: Concept mould with double steel netting (2011)



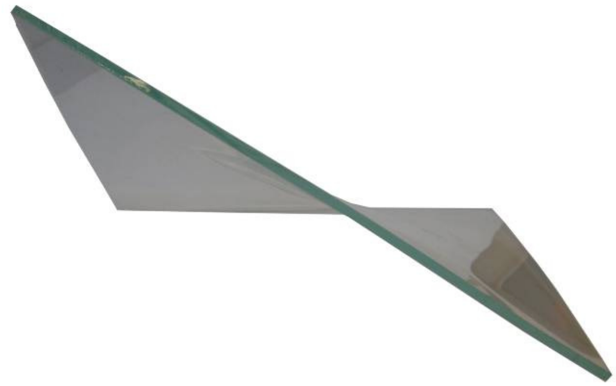
Img. 29: Concept mould with designed corner clamp (2011)

Discussion:

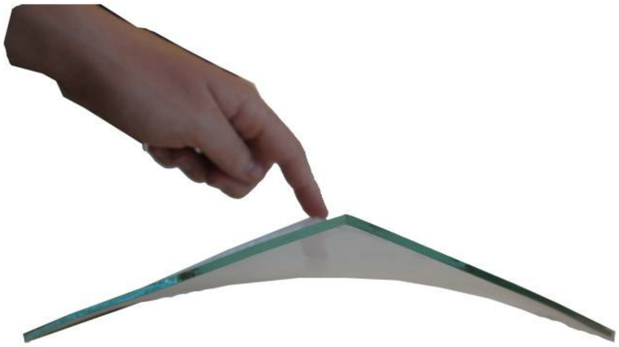
The successful result with the new double steel netting prove that this way of bending glass is a good alternative. The imprint is far less than expected and the form finding has greatly increased in comparison to the single steel netted moulds. Therefore further research and testing with double steel netted membranes should solve the current drawbacks.

For one, there still is some imprint in the glass. Further testing at different temperatures are recommended, especially because the new forming method does not need a high temperature to sag. A lower temperature can reduce the risk of imprint but the pane needs to be heated enough to be able to bend easily. Further research at this optimum temperature could eliminate the imprint completely.

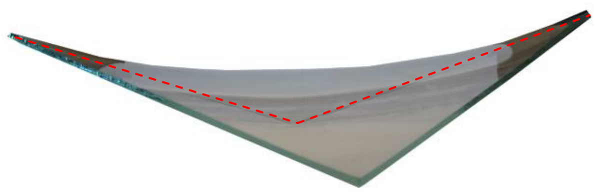
The second problem that might occur is the different radii of the steel nettings when more extreme double curvatures are planned. The steel nettings are separated from each other by steel rings acting as spacers. When the mould was tensioned the two nets squeezed together at the saddle point. If this tension gets to high there is a fair chance that the nettings pushes the glass out of the centre, thereby ruining the glass pane. Further testing with the new mould should determine if this problem will occur in certain double curved forms.



Img. 30: test pane showing good deformation (2011)



Img. 31: test pane showing smooth curvatures (2011)



Img. 32,: test pane showing smooth curvatures (2011)

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