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An Edge-integrated Connection for Segmented Glass Beams

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There are different options to obtain a structural glass beam with a span of more than 6 meters. One option is segmentation, which has many advantages compared with the other options. However, the choice for segmentation is often avoided, because of aesthetic reasons. Existing connections, even the most slender ones, result in a reduction of the transparency of the beam. While transparency is the key reason to use glass beams. In this paper a connection is presented that should improve the transparency of segmented glass beam. The connection is integrated in the least transparent part of a glass segment, the edge. It has a twofold effect; the transparency of the beam will decrease less, and by following the contours of the segment the connection is less noticeable. Since such a connection seems to be highly compatible with edge-integrated steel reinforcement, which can be applied to reach safe failure behavior, it is investigated how reinforced beam segments can be connected in an edge-integrated way. A connection is designed and its performance is determined by finite element analysis and physical testing of prototypes.

Keywords: Structural glass, Segmented beam, Connection, Transparency, Reinforcement, Safe failure behavior

1. Introduction

Transparency plays a significant role in contemporary architecture. Architects and engineers are pushing the limits to achieve highly transparent building skins. The ongoing desire to reach higher levels of transparency has led to the use of glass as a structural material. And the pursuit of transparency still continuous.

The level of transparency depends on the amount and size of non (or less) transparent areas. These areas are the edges of the glass panes and the connections between the glass panes. The larger the panes are, the fewer edges and connections are necessary. So the level of transparency is actually limited by the size of the glass pane.

Normally, float glass is produced in sheets not larger than about 3 by 6 meters. If a glass beam has to span more than 6 meters, there are three different beam types available:

- Segmented beam — The beam is divided in multiple segments, which are smaller than 6 meters.
- Splice laminated beam — Standard sized sheets are laminated in an overlapping pattern.
- Continuous beam — Non-standard sheets are used, which are longer than 6 meters.

The advantage of a segmented beam is that segments can be made of standard sized glass sheets, which can be processed with standard equipment and moved by standard transport. Because the whole manufacturing process is standard, segmented beams are relatively cheap and fast to produce. Another important advantage of segmentation is that a structural glass element is not bound to a linear geometry. Smarter geometries can be used, like arches, which can decrease the usage of glass or increase the span compared to horizontal beams.

Despite these advantages, the choice for segmented beams is often avoided, because of aesthetic reasons. Existing connections, even the most slender ones, result in a reduction of the transparency of the beam. While transparency is the key reason to use glass beams. Therefore, splice laminated and continuous beams are more popular. But these alternatives have serious disadvantages.

The disadvantage of a splice laminated beam is the need for a large autoclave. The longer the autoclave has to be, the more rare they become. And the more rare the autoclave is, the more time it takes before it is available and the more expensive it is to use it. In the case of a continuous beam, not only the length of the autoclave, but also the use of non-standard sized sheets will result in increased production time and costs. The larger the sheet, the thicker the sheet needs to be. For thicknesses larger than about 12 to 15 mm, the float glass manufacturer has to adjust its standard process. Such an adjustment is costly and will not happen that often. Another disadvantage of thick sheets is that it is difficult or even impossible to obtain a half hard temper, which is assumed to be the preferred temper.

2. A more transparent connection

Based on this evaluation of glass beam types, it can be concluded that segmentation is the most efficient way to achieve a glass beam spanning more than 6 meters, but it is the connection that makes this option undesirable. Therefore this research investigated how to improve the connection, in order to achieve a highly transparent segmented beam.

From the start it was very likely that the connection will be, partly or even completely, made of a metal and would therefore be opaque. The only variable left to improve the transparency is the location of the connection. It was decided to move the connection to the edges of the segment, since the edges are already the least transparent part of the segment. This adjustment has a twofold effect; the transparency of the beam will decrease less, and by following the contours of the segment, the connection is less noticeable.

Such an edge-integrated connection seems to be highly compatible with edge-integrated steel reinforcement, which can be applied to reach safe failure behavior. The transfer of tensile force, which was considered to be the most difficult force to transfer, can be achieved by coupling of the reinforcement. The combination of an edge-integrated connection and edge-integrated reinforcement seems to be promising, and therefore it was decided to investigate how to connect reinforced beam segments in an edge-integrated way.

3. The connection proposal

The connection is designed for a fictional beam of 18 meters. The beam consists of 3 segments of 6 meters each. The segments are composed of multiple heat strengthened glass panes, stainless steel hollow sections and ionomer interlayers. More detailed information about the segmented beam and the connection can be found in Teeuwen (2015).

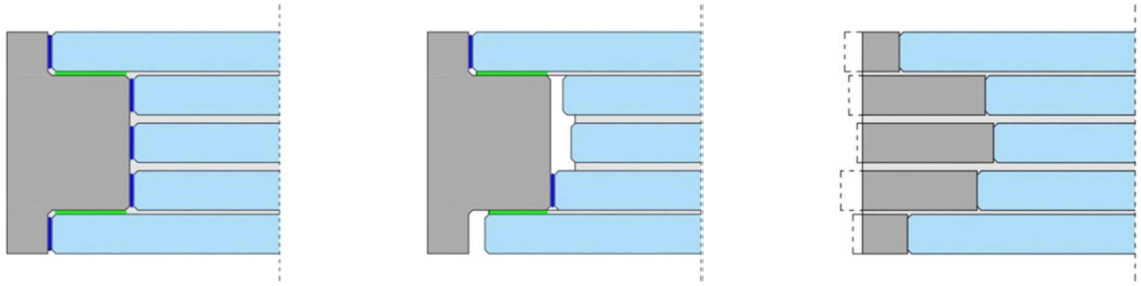
The final connection can be divided in two parts; a part which transfers the compressive and shear force, and a part which transfers the tensile force. These two parts will be discussed separately.

3.1. Transfer of compressive and shear force

For the transfer of compressive and shear force, an edge-integrated profile is chosen. The ideal profile is displayed in Figure 1a. The compressive force is transferred by compressive contact (blue lines). The shear force is transferred by shear contact (green and blue lines). To obtain a proper bond length between the profile and the glass, in order to transfer the shear force, a top-hat-shaped profile is used. The transfer of shear force between the profiles can be achieved by dowel pins, as displayed in Figure 2.

The biggest challenge of this part of the connection is transferring the compressive force in an efficient way. This challenge is created by dimensional tolerances of the glass panes, causing an unequal distribution of force over the panes, as displayed in Figure 1b. The panes are heat treated to avoid stress corrosion, so it is impossible to level the panes after they are laminated.

Some options to fill the space between the profile and the panes are considered, but none of these options led to a satisfying solution. Eventually it is decided to split the profile into multiple strips, as displayed in Figure 1c. These strips are pressed on the edges of the panes during the lamination process, and have to be leveled afterwards by a milling machine.



a) b) c)

Fig. 1 Examples of edge-integrated profiles.

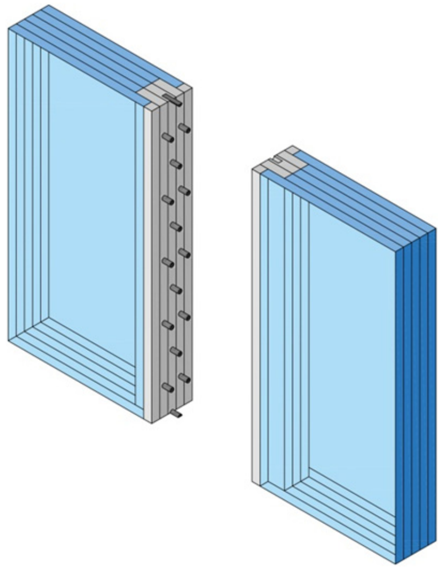


Fig. 2 Transfer of shear force between the profiles, by dowel pins.

Aluminum is chosen as the material for the profile strips. Aluminum itself is quite soft and it is available in many different alloys and tempers. Therefore it seems to be a perfect material. There are multiple alloys which are strong enough to transfer the compressive force, but soft enough to avoid stress concentrations. This is supported by a recent study by Carvalho. Of all the materials he tested, aluminum turned out to be the best intermediate material to transfer compressive force between glass panes (Carvalho, 2014). Aluminum also has the same Young's modulus as glass, which is favorable. An equal elasticity results in an equally distributed force transfer over all the panes, in case of a lap joint as displayed in Figure 1.

Besides these strong points, aluminum also has a weak point. Its coefficient of thermal expansion (CTE) is almost 3 times higher than the CTE of glass. It is expected that small temperature changes will not cause any problems, but larger temperature changes could result in failure of the glass or debonding of the interlayer. The largest temperature difference the segments will probably experience, happens during the production, when the segments cool down after lamination. To determine the effect of unequal CTE's, this temperature change is further investigated.

Lamination takes place at a temperature of about 130 °C. After the liquid interlayer filled all cavities, the segment will be cooled down to room temperature. The CTE of aluminum is higher than that of glass, so the profile will contract faster than the glass. In the length of the profile, the glass will be compressed, which is favorable. The profile itself will experience a tensile load, which is not a problem since the profile is made of a ductile material. It is expected that the stress in the bond is quite small.

Perpendicular to the length of the profile, the contraction has more serious consequences. If the temperature decreases, the thickness of the aluminum strips will decrease more than the thickness of the inner glass panes. The aluminum strips will start to pull at the outer glass panes, causing a bending moment and thereby tensile stress in the outer panes.

To check the magnitude of this stress, a thermo-mechanical FE model is made. This model consists of a transient thermal analysis system, which simulates a laminate that is convection cooled from 130 °C to 20 °C. The results of the transient thermal analysis system are used as a thermal load in a transient structural analysis system. The mechanical properties of the ionomer interlayer change during the cooling process, so these properties are applied as temperature depending properties. After 3 hours of cooling, the laminate is almost completely cooled down to room temperature.

The result is displayed in Figure 3b. Tensile stress, caused by bending, is clearly visible in the outer panes of the laminate. After 3 hours of cooling, the maximum principle stress in the glass is about 4 MPa. This tensile stress is small enough to deal with, but highly unfavorable. The relatively large CTE of the interlayer provides an opportunity to solve this problem. By increasing the thickness of the aluminum strips, and thereby decreasing the thickness of the interlayer between them (Figure 3c), it is possible to achieve equal contraction of the profile and the glass (Figure 3d).

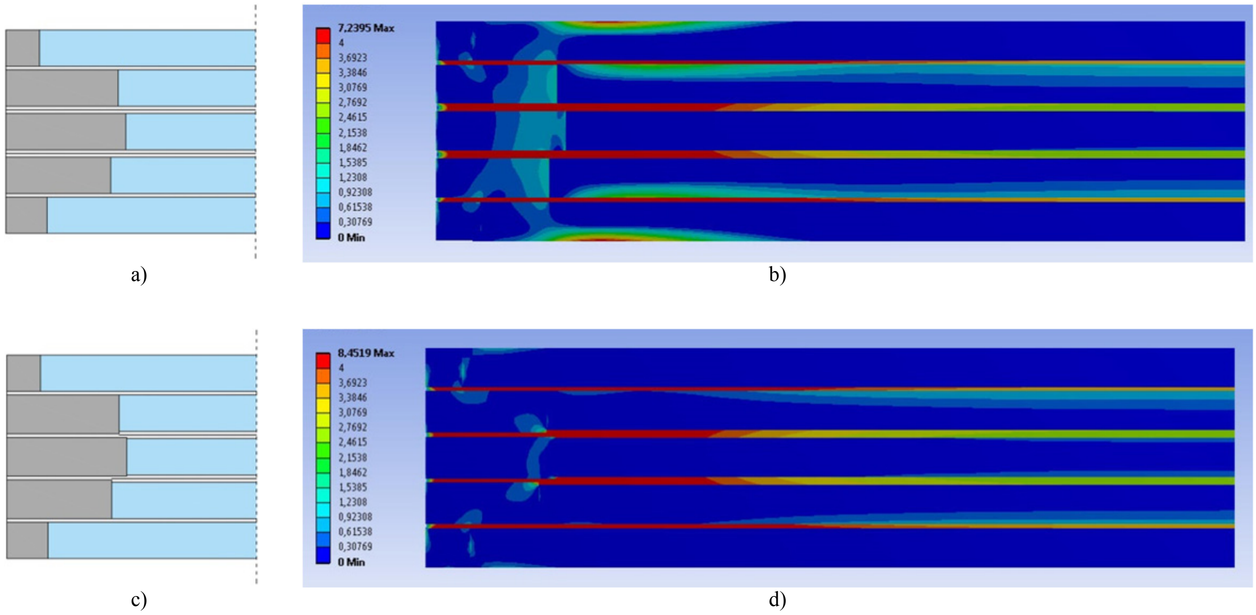


Fig. 3 Maximum principle stress [MPa] caused by thermal contraction after lamination, for two different profiles.

3.2. Transfer of tensile force

The transfer of tensile force is critical. The tensile strength of glass is much smaller than the compressive strength, so the strength of the total beam will be determined by the highest tensile stress. The challenge is to transfer the tensile force very gradually, to keep the tensile stress around the connection as low as possible. Ideally, the tensile stress around the connection should be smaller than the highest bending stress in the beam.

The tensile force is transferred by an internal coupling pin, connected to the bottom of the reinforcement by bolts, as can be seen in Figure 4. The use of bolts seems to be contradictory, because an adhesive is able to transfer a force more gradually. But the use of an adhesive also has disadvantages. The process of applying, removing, and checking the condition of an adhesive joint is complicated and it is also difficult to control the distribution of force through an adhesive joint. Therefore a row of many small bolts is chosen.

Some parameters, like the length of the bolt row and the distance between the end of the segment and the first bolt, have been studied to check their influence on the transfer of tensile force. Based on the FEA results, a bolt row length equal to half the height of the beam and a distance between the end of the segment and first bolt equal to a sixth of the height of the beam were chosen.

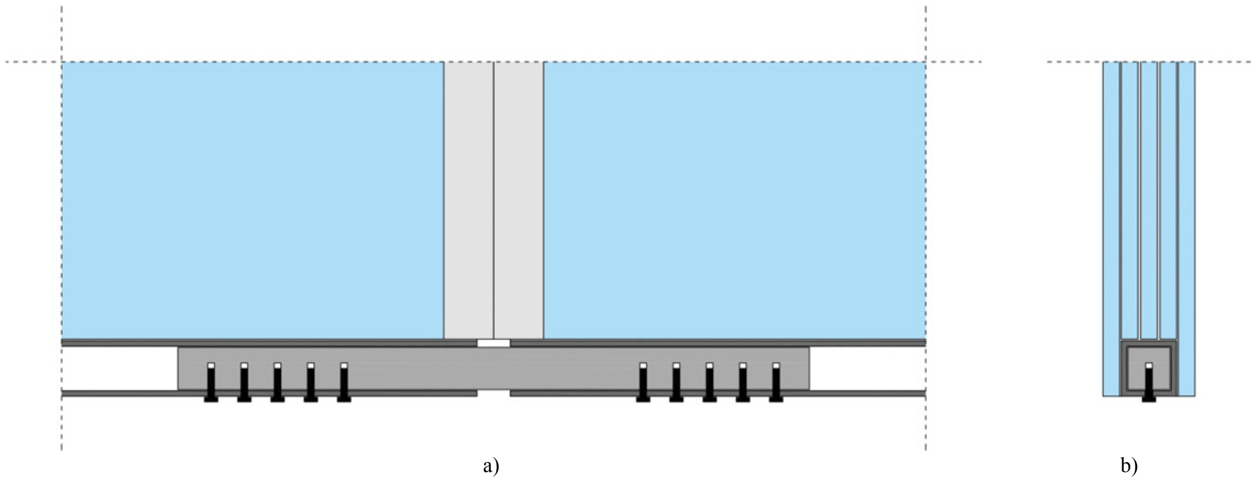


Fig. 4 Concept of the transfer of tensile force.

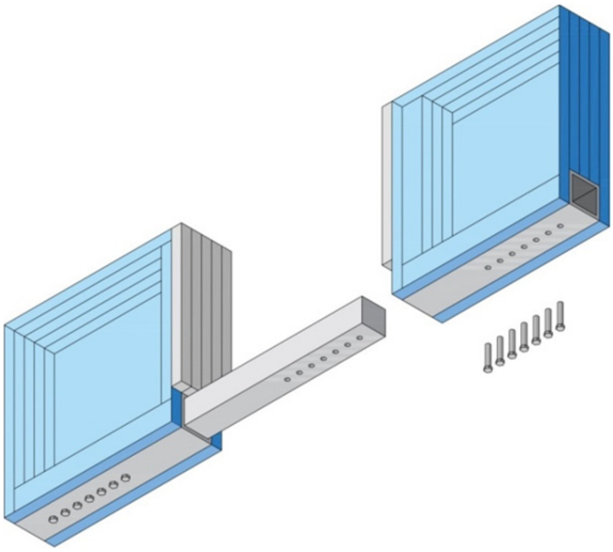


Fig 5 Transfer of tensile force by an internal coupling pin, bolted to the bottom of the reinforcement.

Due to unequal strain of components in a lap joint, the outer bolts of the bolt row will normally transfer more force than the inner bolts. Especially the outer bolts near the end of the segment in this case. Increasing the stiffness of the pin e.g. by using a tungsten alloy will decrease the problem, but will not solve it. To distribute the force more equally over all the bolts, it is decided to use ductile bolts which will be loaded around their yield strength in the ultimate limit state (ULS). This approach sort of limits the amount of force a single bolt can transfer. From the viewpoint of force distribution, it is the right choice, but there are some potential threats.

Loading bolts near their yield strength to transfer a variable load could result in fatigue related failure. Although it is a real threat, it is not further investigated as part of this research. Another threat is that the ultimate strength of the connection is limited. The connection makes use of the steel reinforcement, which is used to reach safe failure behavior. That means that the beam, and thereby also the connection, should be able to handle higher loads than assumed for the ULS. The bolts are designed to be loaded at their yield strength in the ULS, so the ultimate strength of the connection is limited. The ratio between the yield and ultimate strength has to be large enough to ensure safe failure behavior.

Multiple specimens are tested to investigate the influence of three parameters on the ratio between the yield shear strength and the ultimate shear strength of a single row of bolts. These three parameters are:

- Material of the bolts
- Amount of bolts (including the diameter of the bolts, and the length of the bolt row)
- Material of the pin

All three variables do influence the ratio, but the material of the bolts has the most influence. The largest ratio is achieved with annealed Monel alloy 400. The results of the Monel specimen are displayed in Figure 6. The kink in the curve of the derivative reveals the point where all bolts are yielding. The yield strength of the connection refers to this point. The ratio between the yield strength and the ultimate strength is 3.6.

In order to reach safe failure behavior, this ‘bolt ratio’ has to be larger than the ‘glass ratio’, which is the ratio between the design tensile strength and the actual tensile strength of the glass. The magnitude of the glass ratio depends on the material safety factor and the difference between the characteristic strength and the actual strength, which is usually quite large. If a bolt ratio of 3.6 is large enough to ensure safe failure behavior is difficult to say.

While the feasibility of this approach may seem questionable, it should be kept in mind that the contemporary glass ratio is quite large because of safety reasons. The consequences of a structural glass element that exceeds its strength are large, so the chance this exceedance happens has to be small. In order to achieve this small chance, the glass ratio has to be large. But if a structural glass element is reinforced, the consequences are much smaller, and it should be possible to reduce the glass ratio. Therefore it is expected that this approach is still a feasible approach.

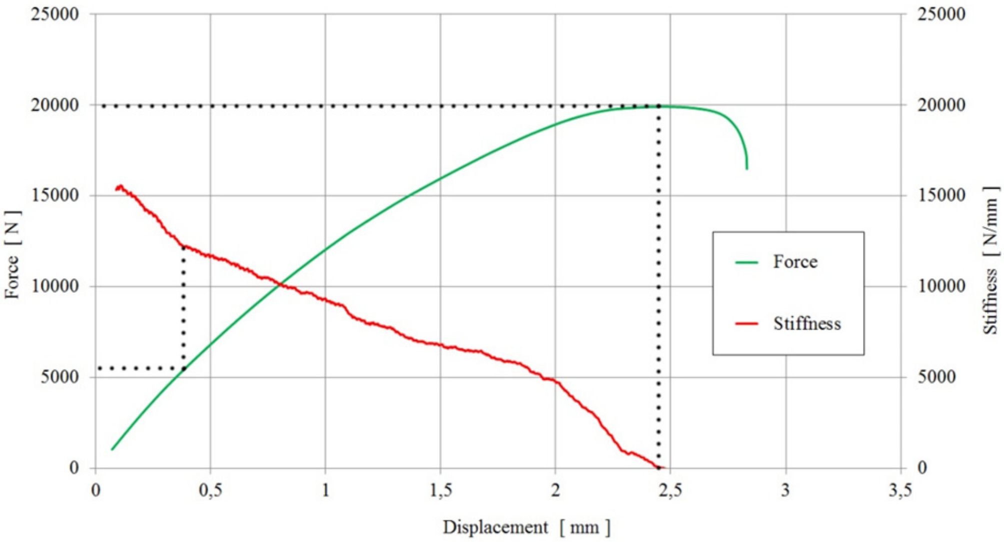


Fig. 6 Force - displacement curve of the Monel alloy 400 specimen, including its derivative.

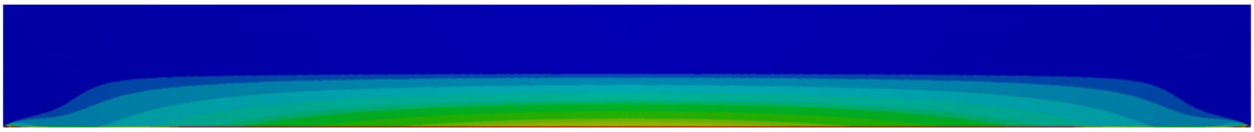
4. Theoretical performance

The performance of the connection, in terms of strength and stiffness, is investigated by finite element analysis.

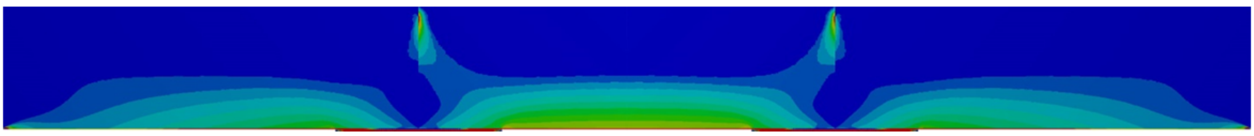
4.1. Strength

Since the compressive strength of glass is much larger than the tensile strength, the strength of the total beam is determined by the highest occurring tensile stress. Compared to the stress distribution in a continuous beam, in a segmented beam, the stress will be higher around the connections. The highest stress can be found around the connection or in the middle of the beam, depending on the efficiency of the connection.

In Figure 7 the tensile stress in a continuous beam (7a) and in the segmented beam (7b) is displayed. The tensile stress at the bottom of both beams is compared in Figure 7c. As can be seen, the peak stress of 12.8 MPa, at the end of the pin of the middle segment, determines the strength of the beam. The tensile stress of the continuous beam, at the same location, is 10.4 MPa.



a)



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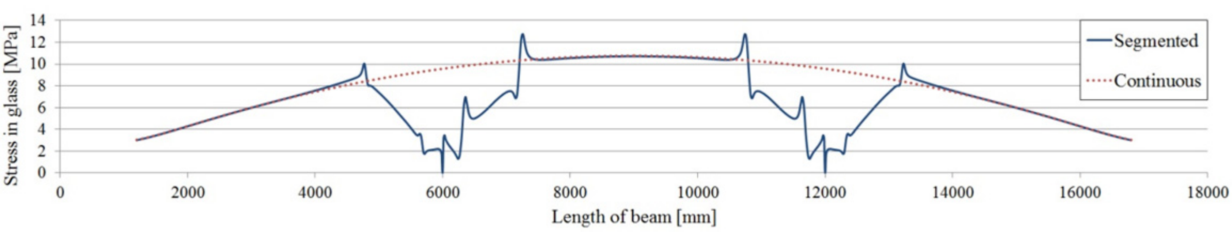


c)

Fig: 7 Maximum principle stress in the glass, collected along a path at the bottom of both beams.

It should be possible to improve the efficiency by optimizing the force distribution over the bolts. The highest tensile stress is located at the end of the pin. By decreasing the amount of force that the last bolts transfer, this stress peak will probably decrease. This can possibly be achieved by tapering the pin at the end, or by using bolts with a lower yield strength at the end of the bolt row. Also, preloading the connection will have a favorable effect, but only for loads which are smaller than the pre-load.

4.2. Stiffness

In the case of a continuous beam, the deflection of the beam is directly related to the stiffness of the beam itself. In the case of a segmented beam, the total deflection is the sum of the deflection as a result of the stiffness of the beam and the deflection as a result of the stiffness of the connection. The vertical displacement of a continuous and the segmented beam, is compared in Figure 8.

The maximum displacement of the continuous beam is 6.4 mm, and of the segmented beam is 14.3 mm. That means that the displacement caused by the stiffness of the connection is 7.9 mm. The stiffness of the connection mainly depends on the stiffness of the bolted lap joint. Because the bolts are loaded at their yield strength, the stiffness is of the bolted joint is relatively low. A relatively low stiffness does not have to be a problem. Most of the time there is a surplus of stiffness, since strength often governs the design of a glass beam.

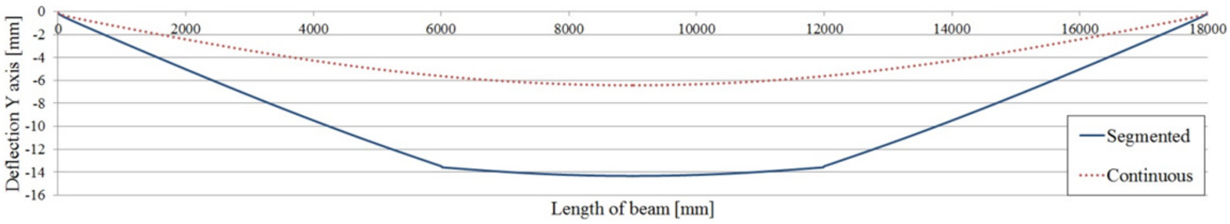
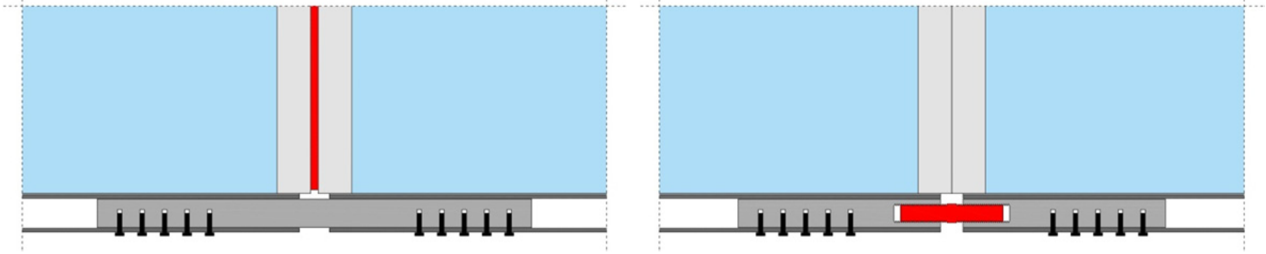


Fig. 8 Vertical displacement of a continuous and the segmented beam.

It should be possible to improve the stiffness of the joint. By preloading the bolted joint, the bolts (and adjacent areas) will plastically deform until the load is equally distributed over all the bolts. If the bolts are deformed by a certain preload, the bolts will not plastically deform anymore by a load smaller than the preload, so the stiffness will be higher. Beside settlement of the bolts, there is also clearance between the bolts and the pin or hollow section. This is not taken into account in the FE model, but in reality it is not possible to obtain a perfect fit joint. The clearance causes extra displacement between the segments and thereby extra vertical displacement of the beam.

Figure 9 shows two solutions to get rid of the gap between the segments, caused by dimensional tolerances and settlement of the bolts. The first solution (9a) is to fill the gap between the segments with, for example, aluminum strips. The strength and stiffness of the coupling pin can be maintained. The downside of this option is that the connection has to be preloaded on the building site, during the assembly. Another downside is that the total width of profile will increase, so the transparency will decrease.

The second option (9b) is implementing an adjustment rod in the middle of the pin. This rod is provided with a right and left hand thread. The middle of the rod is hexagonal, so the rod can be rotated with a wrench to eliminate the displacement. Because the coupling pin is split up in two parts, the pins can be preloaded separately. This also means that the preloading does not have to be done at the building site. The downside of such a rod is that it reduces the strength and stiffness of the coupling pin. In the case of a square pin, the problem of strength can be solved by using materials with a high strength. If the sectional shape of the hollow section and of the pin is any shape other than square, the ratio between the sectional areas of the components gets out of proportion.



a) b)

Fig. 9 Solutions to get rid of the clearance between the segments.

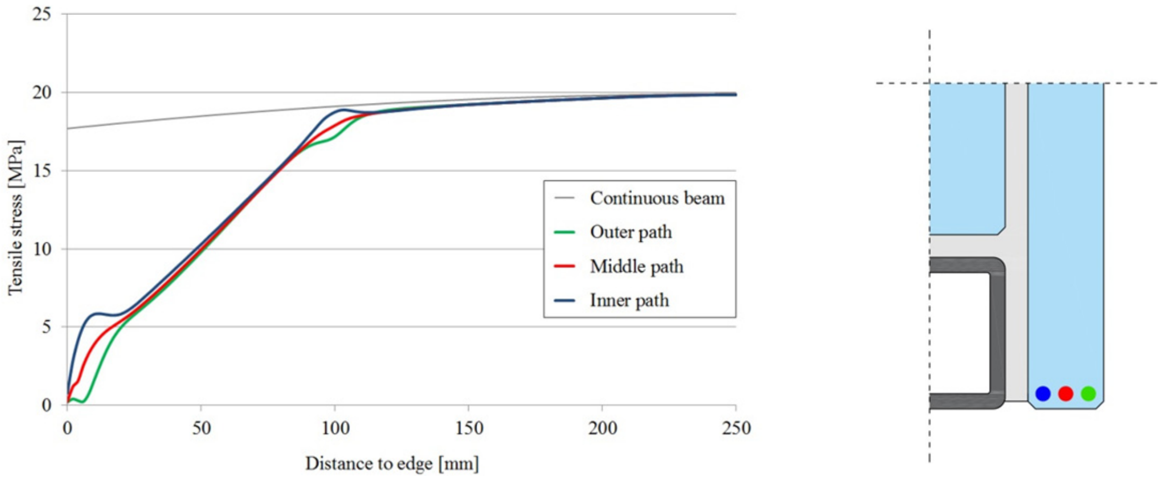
5. Physical performance

To validate the theoretical performance, prototypes are constructed and tested. Beams with a total length of 1.5 meters, consisting of 3 segments, each 0.5 meters in length were tested. The design for the 18 meter beam cannot simply be scaled down with a factor 12, due to several scaling effects. Therefore a new beam is designed, and its theoretical performance is determined by FEA.

5.1. New beam design

Because of the small size and the less complex section, a 3D FE model is used. The highest tensile stress is located in the bottom of the outer panes. At the bottom, the values for the tensile stress are collected from three different paths. The location of these paths is shown in Figure 10b. The tensile stress along these paths is displayed in Figure 10a.

Along the inner path, just a small peak in the tensile stress is visible at the end of the pin. This little peak stress is still smaller than the maximum bending stress in the middle of the beam. Assuming these results are valid, it can be concluded that the connection is highly efficient.



a) b)

Fig. 10 Tensile stress collected along three different paths.

5.2. Reproduction

The ideal material to bond the glass panes and the steel section is a thick ionomer interlayer. However, due to practical reasons, the glass and steel section are connected using adhesive bonding. Using an adhesive instead of an interlayer has consequences for the way the tensile force is transferred between the reinforcement and the glass. The transfer is much more direct, because of the higher Young's modulus and a smaller thickness of the adhesive layer. This will have a negative impact on the efficiency of the connection.

This effect can be compensated by increasing the stiffness of the reinforcement. Increasing the stiffness has the opposite effect, it causes a less direct force transfer. Increasing the stiffness is done by using a stainless steel section with a larger sectional area. Several beam sections are tested with FEA to determine which section reproduces the performance of the original beam the best.

Table 1: Properties of the original design and the two final prototypes.

Property	Unit	Original design	Prototype 1	Prototype 2
Float glass temper	[-]	Heat strengthened	Annealed	Annealed
Dimensions inner pane	[mm]	10 x 127	-	-
Dimensions outer panes	[mm]	5 x 150	10 x 140	8 x 140
Bonding layer	[-]	Ionomer interlayer	Epoxy adhesive	Epoxy adhesive
Thickness bonding layer	[mm]	1.5	0.1 – 0.2	0.1 – 0.2
Material reinforcement	[-]	AISI 316	AISI 304	AISI 304
Dimensions reinforcement	[mm]	10x10x1.0	15x15x1.5	20x20x2.0
Material bolts	[-]	Monel 400	AISI 304	AISI 304

The two sections with the most comparable performance are chosen for validation. The section properties of the original beam and the two chosen sections are displayed in Table 1. Four prototypes are constructed and tested: two beams for each beam section, one without an adjustment rod (Figure 9a) and one with an adjustment rod (Figure 9b).

The prototypes are tested in a 4 point bending test setup. The distances between the load points and the supports are chosen in such a way that the ratio between the maximum tensile stress in the glass and the bending moment at the connection of the original beam is reproduced.

5.3. Testing

All four prototypes are tested in a four point bending test setup, at a constant displacement rate of 5mm per minute. At a load of about 5.8 kN the ULS is reached, and the connections should have reached their yield strength. All prototypes passed this load without any problems. At a load of about 13.0 kN, the maximum tensile stress in the glass should be 45 MPa, which was assumed to be the tensile strength. Only prototype 1 (without adjustment rod) showed some initial failure at a load of 13.5 kN. The other three prototypes collapsed due to sudden failure of the bolted joint.

There is no clear difference in stiffness found between the prototypes with an adjustment rod and the prototypes without. However, there is a difference in strength. The prototypes with an adjustment rod have a lower strength because the rod reduces the internal arm a bit.

Safe failure behavior was not achieved, because the glass did not fail at the expected load. Three out of four prototypes collapsed without any warning, due to failure of the bolted joint. It is expected that these disappointing results are a consequence of the way in which the beam is reproduced. Due to the use of a thin and brittle adhesive, severe debonding took place between the glass and the reinforcement. Due to debonding, in combination with the small scale of the segments and the relatively stiff reinforcement, it is expected that the tensile force is transferred mainly by the reinforcement. Also the use of stainless steel bolts reduced the strength of the bolted connection.

Aside from safe failure behavior, the results are more positive. Large forces, two to almost three times the force the connection was designed for, are transferred without failure of the glass. And the uniform debonding along the bolt row, as can be seen in Figure 11b, indicates a gradual transfer of tensile force.

Table 2: Results of the load tests, displayed values just before ultimate failure.

Aspect	Unit	Prototype 1	Prototype 1 + rod	Prototype 2	Prototype 2 + rod
Force	[kN]	15.4	14.6	15.8	14.0
Displacement	[mm]	20.7	18.9	20.3	19.1
Moment at load point	[kNm]	4.81	4.56	5.14	4.55
Tensile stress glass	[MPa]	53.0	50.3	54.6	48.3
Moment at connection	[kNm]	3.46	3.28	3.56	3.15
Tensile force on pin (estimated)	[kN]	26.9	26.2	27.9	25.7

a) Test setup

b) Failed connection

Fig. 11: Physical testing of prototypes.

6. Conclusion

Segmentation has many advantages, but existing connections between segments reduce the transparency of the whole beam, while transparency is the key reason to use glass beams. A more transparent connection could solve, or at least decrease, this problem. A connection is designed which is located in the edges of the segment. It has a twofold effect; the transparency of the beam will decrease less, and by following the contours of the segment the connection is less noticeable.

The connection can be divided in two parts, a profile that transfers the compressive and shear force and a coupling pin that transfers the tensile force. A highly efficient transfer of compressive force can be obtained by splitting the profile into multiple strips. Soft aluminum seems to be the best material for the strips. According to the FEA results, the difference in thermal expansion will not cause problems during the lamination process.

The transfer of tensile force between the segments is critical. The internal coupling pin is connected to the bottom of the reinforcement by bolts. To distribute the force very gradually, the bolts are designed to be loaded at their yield strength. This approach results in an efficient connection, but it also has a downside. By loading a connection at its yield strength, the ultimate strength is limited. However, the ultimate strength has to be large enough to reach safe failure behavior.

Although it is not proven through this research, it is expected that safe failure behavior can be achieved with the approach used in this research. In theory, the difference between the yield and ultimate shear strength of the bolts could be larger than the design strength and the actual strength of the glass. Further research is necessary to prove this.

For now, connecting glass beam segments in an edge-integrated way, still seems to be feasible. The use of such a connection results in a highly transparent segmented beam. It is expected that edge-integrated connections make the choice for segmentation much easier. In Figure 12 two impressions of segmented glass structures are shown, making use of the proposed connection.

a)

b)

Fig. 12 Impressions of a segmented beam and arch, using edge-integrated connections.

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