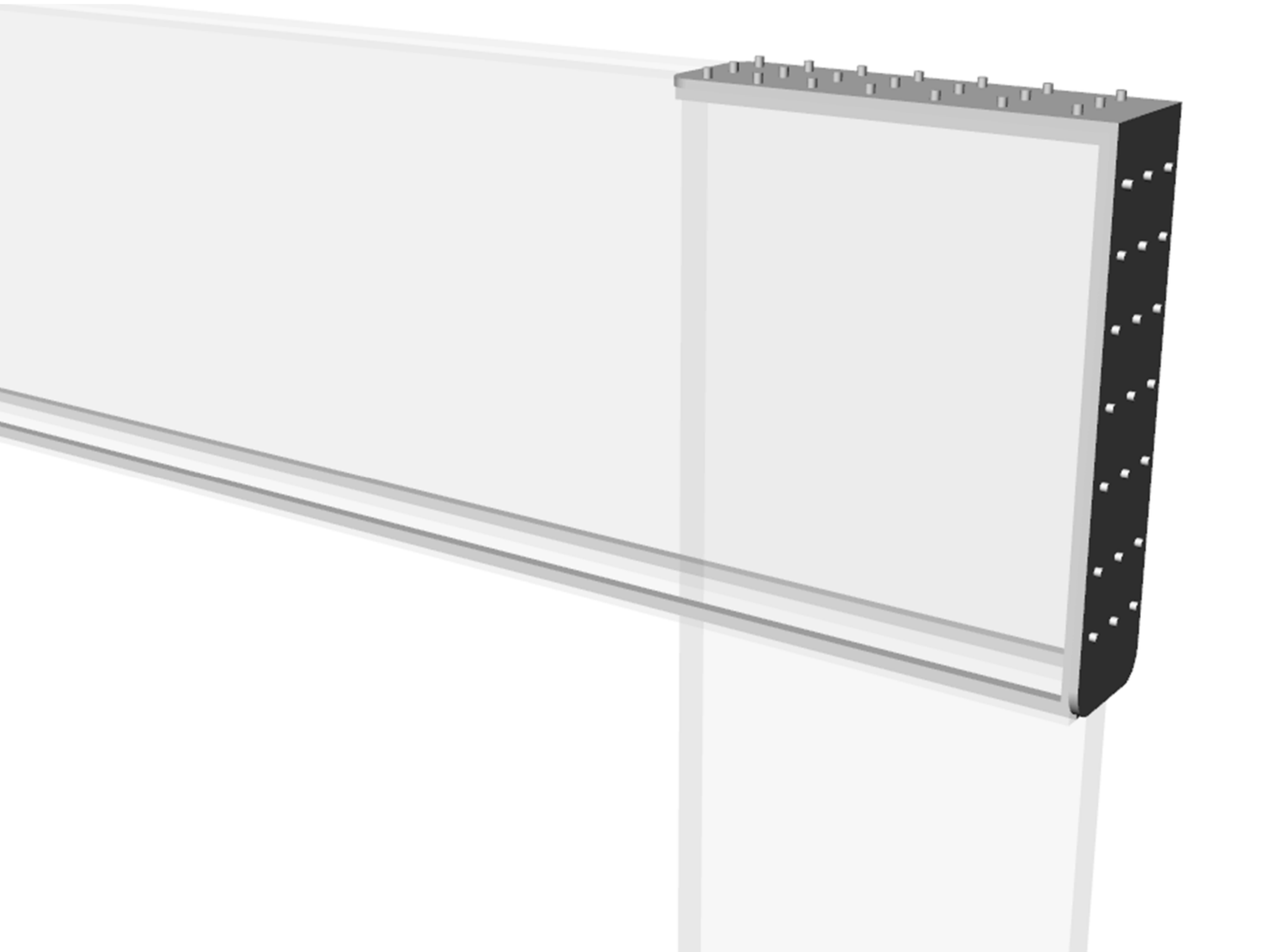
Master thesis

L-shaped Connection for Glass Portal Frame

Structural analysis and its application

Wan-Yun Huang



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January 2017

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Wan-Yun Alice Huang

January 2017

Executive summary

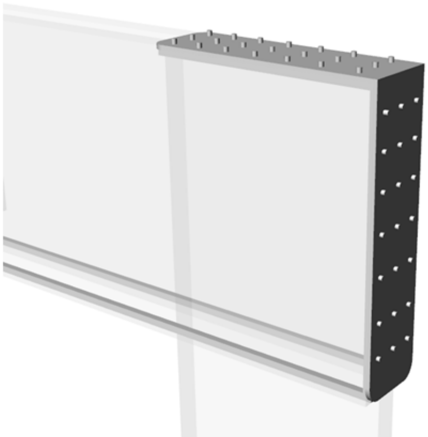
Introduction

Transparency is an attractive feature that designers are looking for in the architectural designs, and glass has played an important role in offering transparency, light and lightness. However, glass has its weakness as structural material; its brittleness and the no-warning fracture failure make it a challenging material to apply in building structure. But with the rapid development of technology, using glass as a load bearing structure is no longer a dream. To achieve higher level of safety in glass structure, the reinforced glass beam, which is an analogy of reinforced concrete, is developed*(Louter et al.2005)*. With its better post-breakage behavior and promising potential for the future glass structure, therefore, a new connection system for reinforced glass beam and column is desired.

In the research (Ate Snijder, Fred Veer, Rob Nijsse, Kees Baardolf, & Ton Romein, 2014)done by the Delft University of Technology, a beam-column connection system designed for the reinforced glass beam-column is developed to test in a 8 by 4 meter glass portal frame. The connection consists of a L-shaped plate and a saddle, however, the saddle shows very little structural function in the test. Therefore the connection with L-shaped plate alone has the potential in reinforced glass portal frame with the feature of remaining the transparency of glass structure offered, but at the same time serve as a structurally better-performed connection. The connection tested shows it is more like a hinge connection rather than a rigid connection expected. However, the structural parameters of the connection has not been fully analyzed and tested. In this thesis, the aim is to further analyze the rotation stiffness k of this L-shaped connection, the parameters influencing the connection's rotation stiffness k and develop a new design procedure of a glass portal frame when using this L-shaped connection to offer a new option for the beam-column connection for future glass structure.

L-shaped connection

The L-shaped connection is designed for reinforced glass beam as beam-column connection. Both glass beam and column are laminated with steel reinforcement bar and the stainless steel connection plate is fixed on the steel reinforcement by the bolts. See figure 1&2. This connection is a semi-rigid connection and its rigidness is defined by the rotational stiffness k, and the value of k is varied from, such as the difference of plate thickness, material, number of bolts .



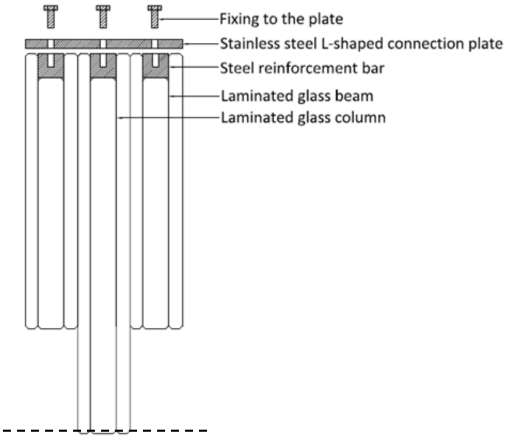


Figure1&2   L-shaped connection connecting principle

Performance of the L-shaped connection

From the lab test performed to find out the rotational stiffness that the current L-shaped connection design provides and the location of rotation point. It can be concluded that as the thickness of the connection plates goes higher the initial rotation stiffness is bigger and the reduction of the rotational stiffness is more gradual. And from the confirmation of the location of rotation point, it is also described the deformation patterns of the plate. Finally, from the comparison of the L-shaped connection and adhesive, it can be concluded that L-shaped connection has much higher initial rotational stiffness k, whereas the adhesive has more constant rotational stiffness but a smaller one.

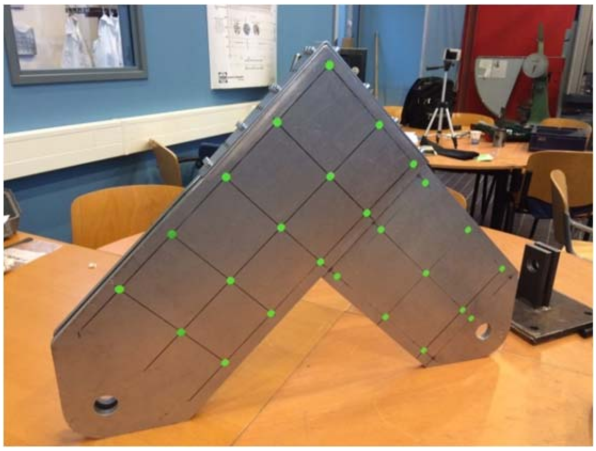


Figure3&4   Test set up

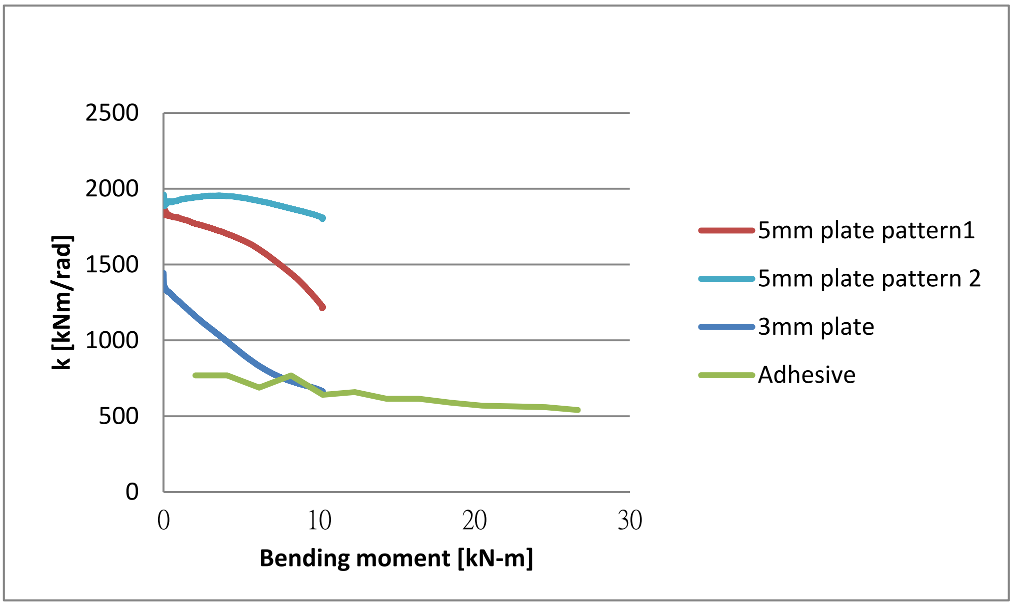


Figure5 L-shaped connection and adhesive comparison in k and bending moment

New design procedure

From the new design procedure for a glass portal frame developed to integrate L-shaped connection in the process, it shows rather efficient steps to get to the optimal joint design for a glass portal frame. From the new design procedure applied on the Dresden pavilion, it is clear to see that the new design procedure integrating rotational stiffness k has the advantage of reducing the height of the beam and not to over design the connection. And as the L-shaped connection can be adjusted to its desired rotational stiffness by adjusting the parameters, it then can be found its initial rotational stiffness and its estimated reduction in k as force applied increases. However, the numerical studies of rotational stiffness in L-shaped connection and other parameters needs further research.

The benefits of L-shaped connection

The benefits of L-shaped connection are that it can be integrated in the reinforced glass beam, which can make good use of the embedded steel reinforcement section to have a better post-breakage behavior for the glass beam. In the aesthetic point of view, the connection can be quite compact by connecting glass beam, column, to reduce the visual disturbance and give a transparent view of the glass portal frame. In a structural point of view, since the rotational stiffness can be known by having laboratory test, the structural system and the design of the glass portal frame , for instance, its dimension and the type of glass used. And with the semi-rigid connection as this L-shaped connection provides, the joint design in a glass portal frame would be more efficient and not over designed. For construction aspect, compare to the totally transparent adhesive connection, this L-shaped connection is possible for replacing and dissemble the glass member locally. However, the detailed design of the L-shaped connection needs to be further developed in numerical studies and verify in further laboratory tests.

Conclusion

From this research, it can be concluded as following

- There is a significant increase in rotational stiffness k when increasing the thickness of the plate and the amount of the fixing.
- L-shaped connection has much higher initial rotational stiffness k, whereas the adhesive has more constant rotational stiffness but a smaller one.
- The new design procedure can efficiently find the smallest beam height and desired rotational stiffness k for the portal frame design. and by adjusting the parameters of the L-shaped connection this desired rotational stiffness can be achieved in the connection design.
- The L-shaped connection has many advantages in different aspects compared to the beam-column connection for glass portal frame in the current glass building design.

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Chapter 1

Introduction of the thesis

1.1 Introduction

Transparency is an attractive feature that designers are looking for in building designs, and glass has played an important role in offering transparency, light and lightness. However, glass has its weakness as structural material; its brittleness and the no-warning fracture failure make it a challenging material to apply in building structure. But with the rapid development of technology, using glass as a load bearing structure is no longer a dream. As the glass has limitation in size production, weakness in tensile force and low resistance to concentrated stress, having connection between glass elements is inevitable and it plays an important role in the safety of glass structure. The connection is then desired to achieve a higher level of structural safety but at the same time it is wished to be designed as less visual intrusive as possible to maximize the transparency of glass structure.

To achieve higher level of safety in glass structure, the reinforced glass beam, which is an analogy of reinforced concrete, is developed *(Louter et al.2005)*. With its better post-breakage behavior and promising potential for the future glass structure, a new connection system for reinforced glass beam and column is desired. In the research (Ate Snijder, Fred Veer, Rob Nijsse, Kees Baardolf, & Ton Romein, 2014)done by the Delft University of Technology, a beam-column connection system designed for the reinforced glass beam-column is developed to test in a 8 by 4 meter glass portal frame. The connection consists of a L-shaped plate and a saddle, however, the saddle shows very little structural function in the test. Therefore the connection with L-shaped plate alone has the potential in reinforced glass portal frame with the feature of remaining the transparency of glass structure offered, but at the same time serve as a structurally better-performed connection. The connection tested shows it is more like a hinge connection rather than a rigid connection expected. However, the structural parameters of the connection has not been fully analyzed and tested. In this thesis, the aim is to further analyze the rotation stiffness k of this L-shaped connection, the parameters influencing the connection's rotation stiffness k and develop a new design procedure of a glass portal frame when using this L-shaped connection to offer a new option for the beam-column connection for future glass structure.

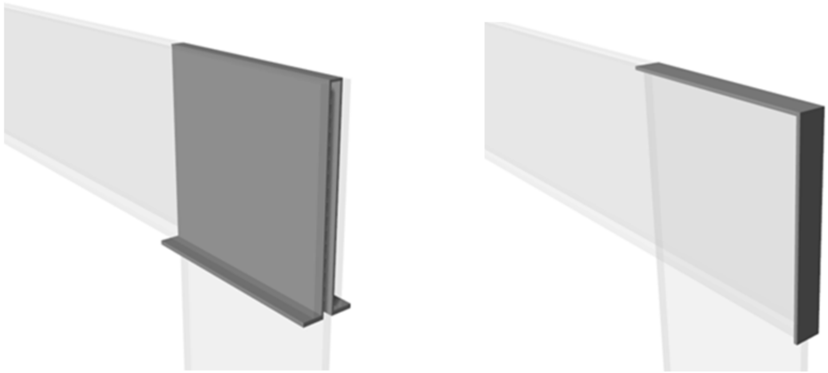


Figure 1-1 Connection , inner plate and outer plate

1.2 Problem statement

In the earlier research of a 8 by 4 meter glass portal frame and a connection designed for reinforced glass beam-column has been developed and tested at the Delft University of Technology. By then the steel connection was consist of two parts: a saddle and a corner plate. From the research, the connection behaves more like a hinge rather than a rigid joint. The reason why it is preferred to be a rigid joint is that it will give a smaller bending moment to the glass beam in the middle, which a smaller beam height can be possibly achieved. And the test indicated that the outer plate plays a much more significant role than the inner plate in the distribution of the force. In a later research done by Eigenraam and Snijder in Figure1-1, it is suggested that the inner saddle plate can be ignored to reach the maximum transparency and still has the good structural performance as a connection.

After some literature studies that I 've done, the L-shaped connection has potential for further development can be concluded in following reasons.

- No hole-drilling in glass element is needed for this L-shaped connection. The glass beam-column mechanical connection applies in the existing glass structures nowadays are bolted connection, which is unfavorable in stress concentration for glass material.
- Comparing to the adhesive connection, this L-shaped connection has the advantages of easy on-site construction and it can be replaced when glass element is broken. Adhesive connection is sensitive to humidity and temperature in the curing process and not easy to apply evenly in a larger planner connection.
- It has the potential of bringing higher level of safety to glass structure, not only better post-breakage behavior based on the reinforced glass beam applied but also the redundancy offer by the this ductile connection.
- The rotational stiffness k of the connection can be determined by adjusting the parameters of the connection properties; therefore, it is possible to achieve the k that is desired in different glass portal frame design cases. This can be beneficial in designing the glass portal frame to give more precise information about structural behavior while this connection is applied.
- With the ability to adjust the rotational stiffness k in a portal frame, it is possible to have a smallest beam achieved.

However, with all these potentials of this connection, as the relationship of rotational stiffness k with glass portal frame and the L-shaped connection are not clear yet, and the rotational stiffness k of the L-shaped connection is not yet confirmed, these potentials cannot yet be proved.

In this thesis, the focus will be on the finding of rotational stiffness k of L-shaped connection and its relationship with a glass portal frame design and L-shaped connection design. In the later part, a design procedure of a glass portal frame using this L-shaped connection will be developed.

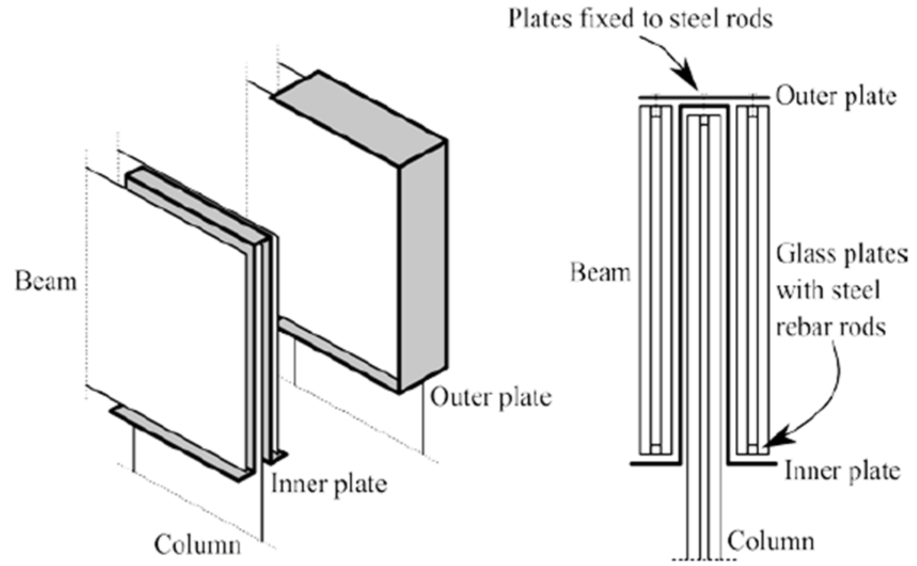


Figure 1-2 Connection principle (Eigenraam & Snijder)

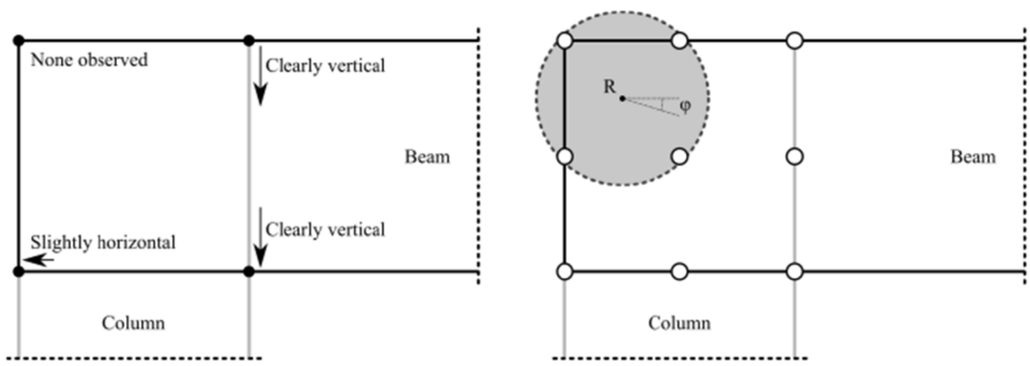


Figure 1-3 Rotation point (Eigenraam & Snijder)

1.3 Research question

Main question

"How can we use the parameters of a L-shaped connection to determine the construction of a long-span glass portal frame?"

Sub questions

"What is the potential of this L-shaped connection?"

"What are the current structural principles of the existing beam-column connection for glass structures?"

"What parameters should be considered in the design of glass portal frame?"

"What are the relationships between different parameters regarding the glass portal frame and rotation stiffness k?"

"What are the parameters that influence the rotation stiffness k in this L-shaped connection?"

"What is the range of the rotation stiffness of this L-shaped connection?"

"Where is the location of the rotation point? And does the location change as the initial rotation stiffness goes higher?"

"What is the design procedure for designing a glass portal frame when applying this L-shaped connection?"

1.4 Research objective

-To understand the glass portal frame structural behavior and to identify the parameters of glass portal frame and L-shaped connection that affects the change of rotational stiffness k.

-To find out the relationships between rotational stiffness k and the bending moment and deformation of glass portal frame.

-To find out the rotational stiffness k of the current L –shaped connection design from the laboratory test.

-To develop a new design procedure of a glass portal frame when applying this L-shaped connection.

-To compare the existing glass column-beam connection in existing glass building, in terms of structural performance, construction, maintenance, aesthetic and safety.

1.5 Research and design methodology

Based on the previous research done in Delft University of Technology, the L-shaped connection for the glass portal frame is developed; however, a crucial research in the development of this connection is not yet finished, which is the finding of its rotational stiffness and how other parameters change it. Therefore, I continue the research and the development of it and to develop the design process of the glass portal frame by using this L-shaped connection.

In my thesis, the approach is basically design by research. The finding and conclusion from the research stage is the element of my design, in this case, it is the design process of a glass portal frame and how to apply it in an all-glass building. The research and design methodology is shown in Figure 1.5. The methodology used in this thesis starts from literature studies with case studies to have an overview and knowledge to understand the current development in both academic area and in practice. Throughout the process, I established my thesis objective that I want to focus on. Also from the literature studies, parameters for the design of the glass portal frame and L-shaped connection is then having a more clear definition. Because the starting point of this thesis is from the structural perspective, so the structural theoretical calculation, FEM analysis and laboratory test is performed to find and confirmed the rotation stiffness as well as to learn more about its structural behavior. Theoretical calculation and FEM analysis are to verify each other to see if either is not correct, and the laboratory test is the verification of both. For the design part, the design process of a glass portal frame when using L-shaped connection is designed from the conclusion and the input of the research stage. And this new design process is compare with the original design process in current practice. At the end of this thesis, the design process will be applied to the Dresden pavilion, to verify the result of the research and design process and to compare with the adhesive connection applied in this pavilion. Moreover, a table of comparison of different all-glass buildings using glass portal frame will be presented regarding different aspects, such as structural system, construction, aesthetic, transportation and safety, to show the advantages and disadvantages of using each different kind of connection, and that is to help the architects or engineer in the future to have an over view of what are the options and possibilities in that certain condition for that certain all-glass building project.

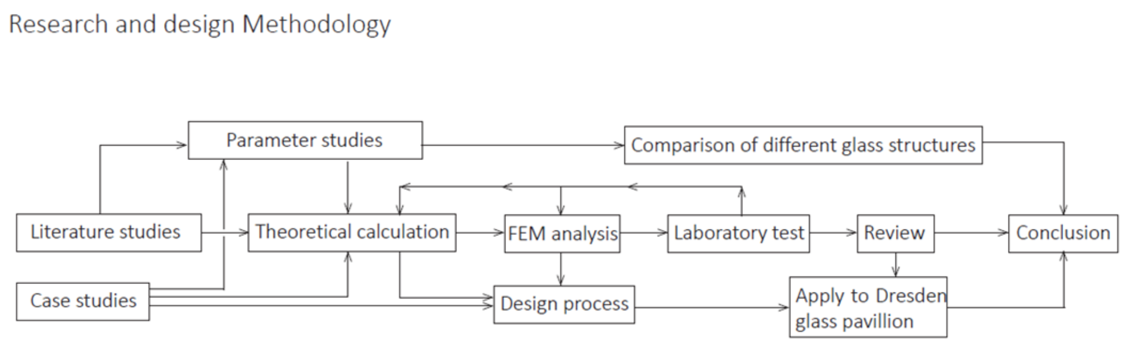


Figure 1-4 Research and design methodology

1.6 Hypothesis

- It is assumed that by cooperating rotation stiffness k in the design procedure of a glass portal frame, the procedure will be simpler and more efficient to get a smallest height of beam.

- It is assumed that once the rotation stiffness k when the ratio of moment at both end and the moment in the middle of the beam equals to 1 is found; the smallest height of the beam can be achieved in a glass portal frame design.

- It is assumed that the L-shaped connection designed for the reinforced glass beam and column is safer since both material of the L-shaped plate connected with the reinforcement laminated in the glass are ductile.

- It is assumed that the L-shaped connection can be adjusted according to the parameters identified to reach the desired rotation stiffness k in the glass portal frame design case.

Chapter 2

Literature studies on glass and semi-rigid connection

In order to understand the behavior of glass structure, the literature studies will be focusing on glass, including glass as material, types of glass, connection of glass and safety measures of glass construction. For the L-shaped connection, the studies will be on the design of semi-rigid connection.

Because the connection is designed based on applying to the reinforced laminated glass beam, the following paragraph will also be focused on the behavior of reinforced laminated beam and the influences of its durability.

2.1 Glass as building material

Glass is a material known as its brittle nature; it behaves elastically until the moment it fractures into pieces. Although theoretical tensile strength of glass is high, based on the chemical component bonding of glass, which is about 8 GPa in the literature; however, in practice, the tensile strength achievable is only about one one-hundreds of the value. The reason is that the strength in practice depends on the degree of damage of the glass surface, such as microscopic damage, scratches and notches caused by production or abrasion.

The tensile stress in bending at these notches will cause stress concentration which leads to the propagation of the crack and eventually exceed the stress peak to failure. In addition, humidity and temperature also influence the tensile strength in bending. The influence of temperature and humidity to glass will be discussed in the later paragraph. Although glass is low in tensile strength, it is high in compressive strength, about 10 times to its tensile strength, which is around 50 Gpa.

Glass is a material that is brittle and fracture without warning, therefore the safety measure is crucial in glass building design.

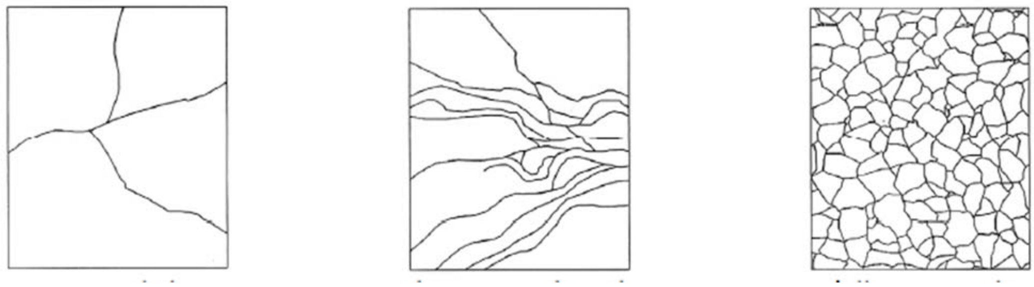
Material	**Glass**	**Concrete**	**Steel**	**Aluminum**
Density (kg/m3)	2520	2500	7600	2700
Modulus of elasticity (GPa)	70	29	210	70
Tensile strength (GPa)	0.045	0.0022	0.24	0.276

Table 2-1 Characteristic material properties with other material (CES)

2.2 Types of structural glass

Based on heat treatment, glass can be divided into three types:

Annealed glass, heat-strengthened glass and fully tempered glass. this order is by the ascending of its characteristic strength.



Annealed Heat-strengthened Fully-tempered

Figure 2-2 Fracture pattern of annealed glass, heat-strengthened glass and fully tempered glass.

Annealed glass

Annealed glass is produced without internal stresses imparted by heat treatment, and it is also known as a standard sheet of float glass. It has the strength of 45MPa and large fragment is its fracture pattern.

Heat-strengthened glass

Heat strengthened glass is a type of tempered glass but cooling is done at a slower pace. The thermally strengthened procedure has the effect of cooling and solidifies the surface first and as the core cools it tries to shrink. As the tension stress inside increases, the surface of the glass compressed. See figure 2-3. Heat strengthening adds strength to the glass while limiting the change in its breakage characteristics; it has the strength of 70 MPa, which is about twice as strong as annealed glass. The cooling process places the surfaces of the glass in a state of high compression and the central core in a state of compensating tension. During the failure stage, the glass will be break into medium size fragments. See figure 2-2

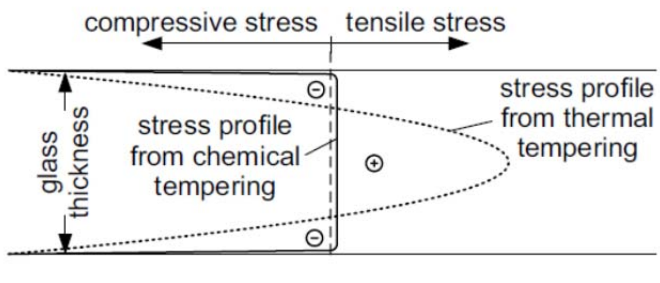


Figure 2-3 Tempering effect on glass (Structural use of glass in building)

Fully tempered glass

Fully tempered glass is under the similar process as heat strengthened glass, whereas the biggest difference is that fully-tempered glass is cooled down more rapidly. Therefore resulting a high residual stress. Therefore, it has higher strength than heat-strengthened glass, which is 120 MPa. At the failure stage, fully tempered glass will break into small pieces, which is also known as safety glass.

Type of glass	Characteristic strength (N/mm2)
Annealed glass	45
Heat-strengthened	70
Fully-tempered	120

Table 2-4 The characteristic strength of different glass types(NEN)

2.3 Connection for glass element

The connection of glass element can be divided mainly in two groups: mechanical connection and adhesive connection. In the development of the connection, avoiding stress concentration and redistributing the force applied have played a very important role in the design. To redistribute the force applied and to avoid stress concentration, it is common to apply soft material, like rubber, plastic or wood, between glass and the hard connection, like steel or aluminum.

The mechanical connection has been developed for a long time, whereas using adhesive to connect between supporting element is relatively a new approach. Using adhesive as a method of connecting between glass supporting elements has the benefit of reducing the visual disruption and maximize the transparency of the glass structure. However, the major concern of using adhesive connection at the moment is its uncertainty about durability and not able to replace the glass element.

The current connection developed is largely an adaptation of existing connection in steel and timber connection. As structural glass has become more and more popular in building industry , it is essential to develop new connection and design method that allows the architect or the engineer to apply it and use simple but at the same time accurate calculation.

The following objectives of new connection type should mainly focus on are suggested in the text by Dr. Mick Eekhout, Dr. Jurgen Neugebauer, Dr. Geralt Siebert and Ronald Visser in the book “structural use of glass” (2008)

- The improvement of the load carrying behavior.
- The improvement of the load bearing capacity after partial or total failure of a glass member.
- The development of new connection systems that is more suitable for the brittle material behavior of glass.
- The development of connections that provide some structural redundancy, thereby increasing the safety of glass structures.
- The combination of various connection types in order to compensate unfavorable properties of one connection type by favorable properties of another.

In the following paragraph, the existing four types of connections in will be discussed:

- Clamped connection (mechanical connection)
- Bolted connection (mechanical connection)
- Adhesive connection
  Silicone
  Laminated
- Glass welding

2.3.1 Clamped connection

The clamped connection usually consists of metal plates that are clamped together with a bolt that passes through the glass pane, which is used friction as the principle of connection. The bolt hole is made oversized to prevent the direct contact with the glass, therefore around the hole, there will be placed a layer of neoprene, EPDM rubber or similar less rigid material to evenly distributed the load, that is to prevent stress concentration. The hardness, durability of this intermediate layer has a large influence on the behavior of the connection. (Structural use in glass. 2014)

The clamped connections are point support at the edge of the panel or the corner. Out-of-plane loads are transferred by mechanical interlock, in-plane loads are transferred by setting blocks and brackets. Clamping joint results in wider plates, but can accommodate more construction tolerances. (Jan Wurm, 2012)

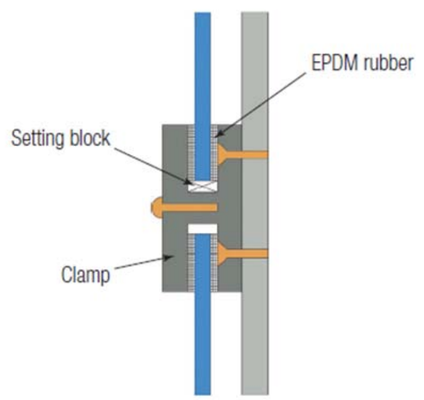


Figure 2-5 Section and facade using clamped connection (Structural use of glass in building)

2.3.2 Bolted connection

For bolted connection, the internal force in the glass is transferred to the bolt through contact stress. When there is direct contact between the bolt and the glass high peak stresses can occur. A solution is to make the hole bigger and apply a material that transfers the loads to a larger area. The materials that can be used are nylon, POM or aluminum. During assembly a fitting hole is drilled through the material. The disadvantage of this connection is that drilling affects the local strength of the glass. The connection plate transfers the forces to the adjacent glass beam. In order to transfer these loads, the connection plate has to have certain stiffness. This leads to a relatively large plate , which disturb the transparency we aim for.

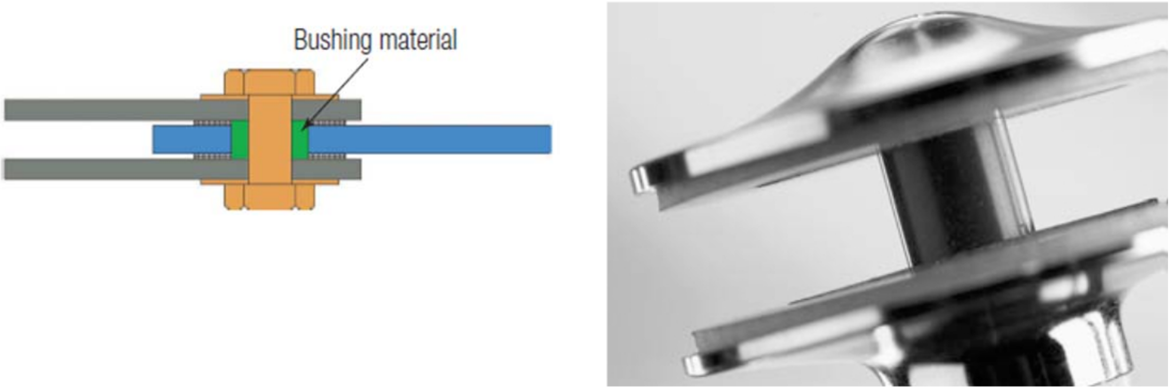


Figure 2-6 Section and model of bolted connection (Structural use of glass in building)

2.3.3 Adhesive connection

Adhesive is currently that offer most transparency among all the connection type for glass elements, which is favorable in glass structure for its visually undisruptive feature. Apart from the feature of transparency, adhesive connection can also transferred large shear force without worrying the stress concentration problem. However, the quality of the adhesive is very important since it influences the strength of the joint. Furthermore, moisture, temperature and durability need to be taken into serious account, because it has a large influence on its structural performance. Some adhesive is required to be processed in certain environment, therefore, making adhesive on-site require through preparation. Thus, adhesive planner joint is challenging when applying adhesive in thin gap between glass panes without bubbles. And the special attention should be paid to the shrinkage behavior of the adhesive.

Broadfield house glass museum extension in England and Leibniz Institute for Solid State and Materials Research in Dresden are the examples of using adhesive bond to connect glass beams and columns. See figure 2-7

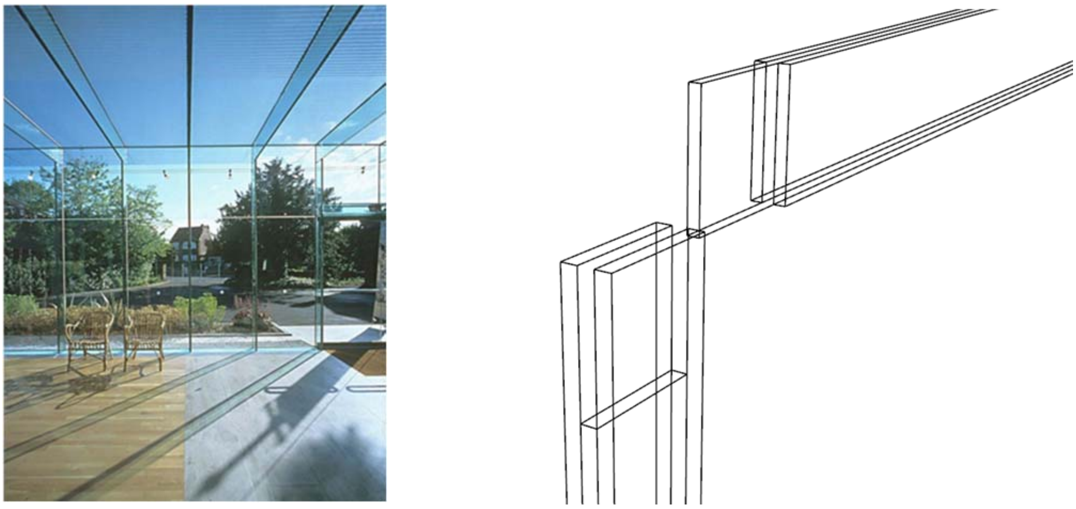


Figure 2-7 Broadfield house glass museum adhesive bonding beam and column

However, there is another type of adhesive connection that is more commonly used : Structural silicon. It was used as soft connection between glass and metals or glass to glass. When structural silicone is used in combination with laminated safety glass, it shows good performance as protective glazing, which can be the façade subjected to impact load or blast load. The good performance is due to the low Young's modulus of the material that has the capacity to absorb high amount of energy.

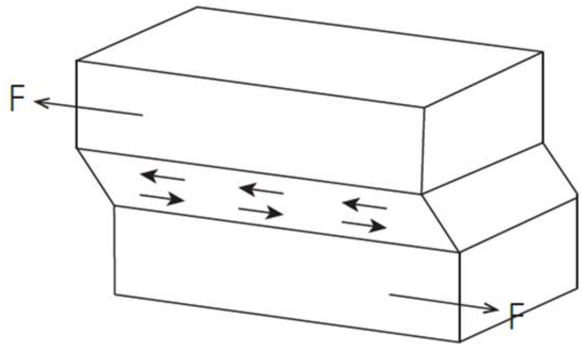


Figure 2-8 adhesive deformation under shear force

2.3.4 Glass welding

It is still in research phase for using glass welding in glass structure. An experimental research on glass welding in structural use has been done at Delft University of Technology. The experiment was focused on the tube-shaped glass. Welding glass have shown a potential in high-end application, however, further research is required to validate this concept.

2.3.5 Laminated glass

Laminated glass is a process in which two or more pieces of glass are bonded by means of a viscoelastic interlayer. Laminates can incorporate many thickness and combination of glass types to give a range of product with required ranges of mechanical and optical properties. Basic annealed, heat strengthened and fully tempered glass can all be laminated. The structural behavior of laminated glass depends on the types of glass used and properties of the interlayer. The effective thickness of a laminate is the thickness of an equivalent monolithic sheet, which needs to be applied in the structural analysis for laminated glass. It offers many performance benefits than monolithic glass pane, most commonly use in safety, security and solar control aspects.

Safety: if layer of glass break, the shattered pieces will still bonded to the interlayer. This largely reduces the possibility of serious injury caused by the falling glass.

Security: using thicker interlayer will help increase the resistance of penetration of unwanted object, for example, polycarbonate interlayer is used in bullet-proof glass.

Solar control: The tinted, translucent, opaque and patterned interlayers are used to reduce the intermission of the solar radiation to achieve the function of solar control.

Here are five material that are used for the interlayer:

- PVB Poly vinyl butyral : It is the most common sheet of interlayer material.
- TPU Thermoplastic polyurethane : It is often used to protect glass pane.
- EVA Ethylene vinyl acetate: It is heat resistant, therefore, it is mainly used in photovoltaic.
- Sentryglas (SG) Ionoplast :It is much stiffer than other conventional interlayers and less vulnerable to the exposure of moisture or yellowing over time to lose its clarity. Sentryglas is now used in high budget glass structure due to its expensive cost.
- Resin (acrylic, Polyurethane, polyester): Resin is not commonly used in laminated glass. The process of the production starts with pouring the resin between two pane of glass, when all the air has been taken out, the open edge will be sealed, and wait for the resin to cure and solidified. It is cured by chemical reaction or UV light. The production size is limited.

Laminated procedure:
The sheets of glass are assembled with an extruded sheet of interlayer between them. The 'sandwich' is then passed through an oven that heats it to approximately 700C, from which it passes between rollers that squeeze out any excess air and form the initial bond. The laminate then moves to an autoclave where it is heated to approximately 1400C under a pressure of about 800kN/m2 (120psi) in a vacuum bag. (Structural use of glass in building, 2014)

2.4 Reinforced laminated glass beam

The brittle nature of glass and its no-warning failure upon overloading requires a specific safety measures apply in structure members in a building structure. To improve the structural performance of glass beam, the Zappi glass& transparency group in Delft University of Technology has developed a concept of reinforced glass beam, which has the analogy with reinforced concrete. (Louter et al. 2005) As the glass is strong in compression strength and weak in tensile strength, the idea is to adhesively bond a small stainless steel reinforcement section at the tensile zones of glass beam. The reinforcement in mainly activated upon failure of glass and is intended to bridge the cracks and to carry the tensile forces over cracks in the glass to remain its integrity. The idea is similar to the concept of reinforced concrete and provides a certain residual strength and stiffness to glass beam, which allows them to still carry the loads despite the occurrence of glass breakage. (Louter et al.2012)

However, there are still some major differences to take into account to prevent directly transfer the knowledge of reinforced concrete to reinforced glass beam.

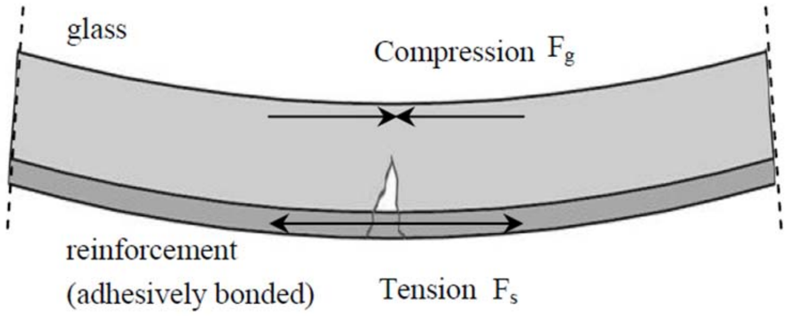


Figure 2-9 Schematic overview of reinforced glass beam (Louter et al. 2005)

As Louter. et al.(2012) states that “From a design point of view, both structural materials should be approached differently: in concrete cracks will often be perfectly acceptable in a serviceability limit state, whereas in glass cracks will automatically be related to an ultimate limit design. Consequently, in contrast to concrete, reinforcement of glass components will be of significant importance only in post-breakage conditions, more specifically to ensure structural integrity and transfer of tensile stresses in a broken glass element.”
And secondly, because of it production process, reinforced glass beam needs a totally different reinforcement technology to achieve its expected performance. The technique similar to reinforced concrete, which is to embedded a thin metal mesh sheet in glass, so called wired glass, is far from sufficient to be the component acting as structural glass (Louter, Belis, Veer, & Lebet, 2012a)

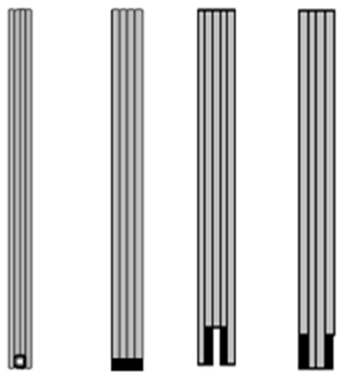


Figure 2-10 Different cross section of reinforcement beam

2.4.1 Stress redistribution in reinforced glass beam

In the research done at Delft University of Technology on stress redistribution in cracked reinforcement glass beams, it is concluded that the vertical cracked propagation which originates at tensile zone is stopped by the compressive stresses in the upper compression zone. And then the horizontal propagation is further initiated and enhanced by the progressive detachment of the reinforcement. Because at this stage the reinforcement is mostly detached at the mid-span, the load carrying system is relying on the compression zone at the upper beam and the reinforcement at the bottom of the beam to carry tensile force. (Louter. C, H. G. J., Guse. E.A., Veer, F.A.)

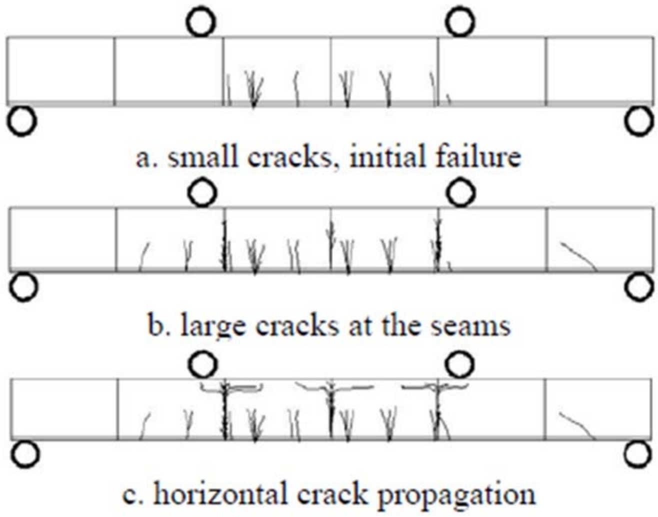


Figure2-11 Schematic crack branching behavior at different stages during the bending tests (Louter et al.2005)

2.4.2 Glass type for reinforced laminated glass beam

In the research of Louter et al. 2012, the structural response of SG-laminated glass beams regarding the effects on different type of glass, annealed glass, heat strengthened glass and fully tempered glass were tested. It is concluded that the type of glass influenced not only the initial failure strength, but also the post breakage strength and ductility. In terms of post-breakage strength the fully tempered beams reached lower residual strength levels than annealed glass and heat strengthened glass beams, due to full fragmentation of the glass.(Louter et al. 2012)

It is suggested that stronger glass types may provide some advantages in design due to their higher initial strength, but the reduction in global post-breakage resistance and post-breakge deformation capacity as a results of the application of a stronger glass type in a reinforced glass beam has to take into account. (Louter et al.2012)

2.4.3 Adhesive layer

Since the standard maximum size of glass pane is 6 X 3.21m, to achieve glass beam which exceed 6m, glass beam which is adhesively bonded by overlapping glass segment is created. This concept also enables the realization of continuous and fully transparent glass beams without using metal joint or drilled holes.

The SG-laminated reinforced glass beams have been tested and shows that it provides a highly redundant post-breakage response. The beams display ductile post-breakage strength levels ranging from 96% up to 166% of the initial failure load. It is also concluded that SG-laminated reinforced glass beams are highly durable.(Louter et al., 2012a)

2.4.4 Reinforcement percentage

In the research, it shows that the percentage of reinforcement has a significant effect on the structural performance of the beams. Increasing the reinforcement percentage causes an increased initial height of the compression zone, and higher post-breakage strength and stiffness of the reinforced glass beams.

2.4.5 Beam size

From the test in the research done by Louter in 2012, it is concluded that the bean size has only a minor effect on the structural response of the reinforced glass beams. The crack shapes in both beams are similar.

2.4.6 Temperature

In a research done by Louter (Louter et al., 2012a), the temperature effect on the laminated reinforcement is conducted in pull-out test in -20℃, +23℃, +60℃, +80 ℃ respectively. From the results, it is concluded that at increased temperature the shear transfer capacity of SG interlayer is decreased. Whereas it is increased at decreased temperature. And from the -20,+23 and +60℃ bending test , it is observed that temperature also has a significant effect on the structural response of the SG-laminated reinforced glass-beam. Compared to room temperature +23, the post breakage strength level of the beams is reduced both at -20 and +60℃.

2.4.7 Humidity

The results seems to confirmed recent stress transferring capacity of small-scale SG-laminates exposed to moisture. Although the exact failure mechanism could not be determined from the tests, it is assumed that these effects results from

(1) Water penetrating between the SG interlayer and the glass, thereby breaking the interconnecting physical bonds

(2) water absorption by the SG interlayer itself.

The research is done but not yet sufficiently understood the effect of humidity apply the beam in highly humid environment.

The following are the summery of the research done by Louter about parameters of laminated glass beam.(Louter)

2.4.8 Segmentation of glass beams

The segmentation of adhesively bonded glass beam is crucial to the structural performance of the beam, different segmentation scheme is dependent on the beam length and load distribution.

2.4.9 Beam height to span ratio

Previous research shows that the ratio of beam height – span should not exceed 1:10. The deeper the beam will result in high elastic energy release upon glass failure.

2.4.10 Number of glass layers

As the bonded glass layers increase the interlayer increase accordingly, it takes longer production time and also the cost is much higher.

2.4.11 Number of glass segments

The number of glass segment needs to be large to reduce the number of seams between two glass segments, which has a thin vertical line due to the appearance of the glass edge, to maximize the transparency of glass.

2.4.12 Overlap length

To avoid high shear stresses in the glass-glass adhesive bond, a certain minimum overlap of glass segments is required. The exact minimum overlap ratio has not yet been determined, but has been temporarily set at 1/3.

2.4.13 Position of the seams

At the seams between the glass segments, the local bending stresses increase due to a reduced cross-section. A seam is therefore preferably not placed at the zone of maximum bending moments.

2.4.14 The segmentation scheme of the beam

Comparing the symmetric and asymmetric segmentation scheme, the asymmetric segmentation scheme is more favorable, due to the minimal reduction of the cross section at the seams.

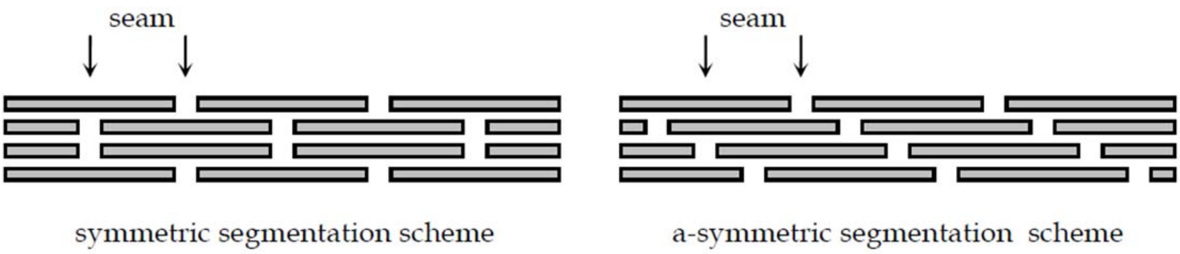


Figure 2-12 Example of symmetric and asymmetric segmentation(Louter)

2.4.15 Reinforcement and transparency

At first, it may be questioned that the reinforcement steel section at the edge of the glass beam will largely affect the transparency of glass beam and become a visually disturbing element in the glass. But since the edge is opaque, the influence may be reduced from the side angle. In order to understand the visual impact on reinforcement section, the analysis is conducted as follow.

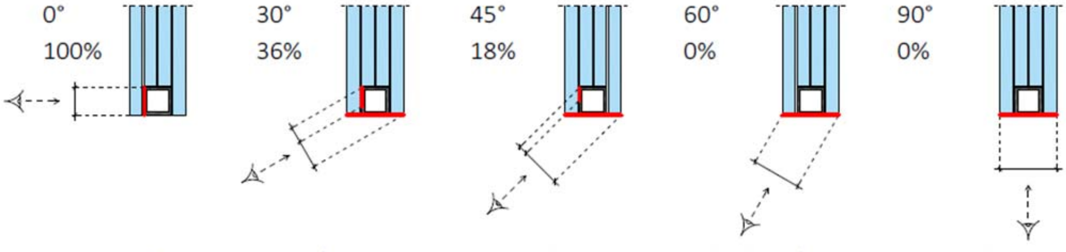


Figure 2-13 The percentage of opaqueness caused by the section, looking from multiple angles (Teeuwen, 2015)

As the beams are located at the height of 8 meters in the air, it is interesting to see what the level of visual impact is at that height from the ground view. To analyze its visual impact, the rhino model is made and the picture is captured from the 1.7 m persons perspective to look upward. From the figure 2-14, it is shown that the difference of visual impact with or without reinforcement can hardly tell the difference where glass beam at the height of 8m in the all-glass pavilion case. Therefore, it is further ensure the transparency of glass would not be disrupted with the reinforcement.

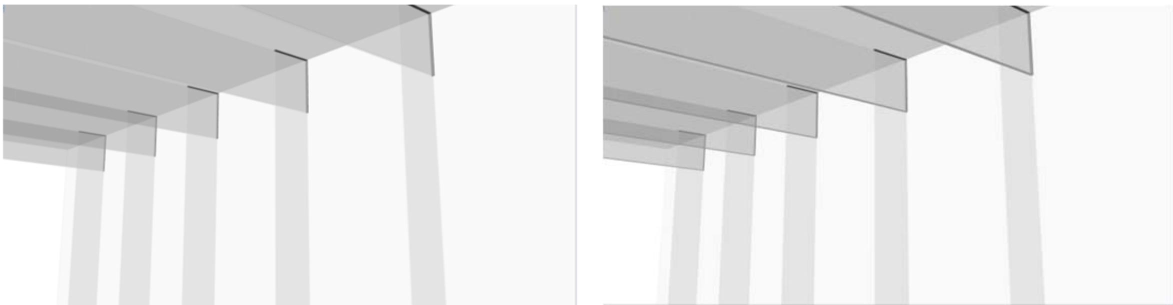


Figure 2-14 the perspective of reinforced glass beam structure (a)without reinforcement (b)with reinforcement

2.5 Safety and redundancy

Safety measure and redundancy is crucial in glass structure design, due to glass can only deform elastically or fracture. The goal is to avoid complete collapse of the whole structure when a glass element failure occurs, for example at the scenario of overloading or bomb blast. The safety concepts can be achieved in two levels: component level and structural level.

For component level the common techniques are:

- Using heat-treated glass, namely heat strengthen glass and fully tempered glass.
- Laminated with PVB foil or SentryGlas foil.
- Designing with higher safety factor.
- Designing sacrificial outer glass pane

For structural level

- Remain integrity of the structure not complete collapse
- Designing warning signal when failure occurs.

2.6 Development of structural glass in all glass building

The case studies 1-4 are mainly focus on all- glass structure building, which contains beam-column connection. And case study 5 is focus on the example of steel-reinforced glass beam connection.

Case study 1: Broadfield house glass museum, UK

The museum has a great collection of glass object, from 17th centry till present days. The extension of the museum is designed to use glass as the only material; it was one of the very first few projects using glass as the building skin and the structure at that time. The extension is 11x3.5x5.3 m, the roof is triple –glazed and the façade is double glazed. The glass beam and column is consist of 3 sheets of float glass laminated together and joined to each other in simple tenon method bonded by silicone. it is seamless and totally transparent. The principle of the joining method is shown in the previous paragraph 2.3.3.adhesice connection.

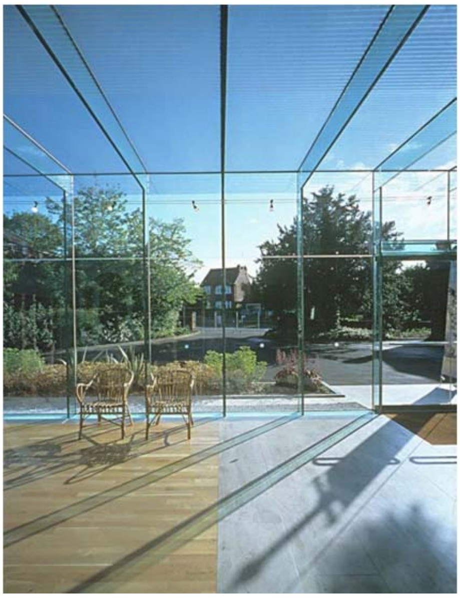



Figure 2-15 Broadfield house glass museum gallery extension 1995 (Sprits architects)

Case study 2: Dresden pavilion

- Design

The all-glass pavilion is built as part of the helium liquefaction unit for Leibniz Institute for solid state and material research in Dresden. This fully-glazed enclosure is using the adhesive connection for the glass portal frame and using structural silicone for façade fixing. The pavilion is a 7.7x4.4x2.5m all-glass structure with 4 glass portal frame. The frames are made of 4 layers of 12mm laminated glass, while the beam-column is bonded with transparent acrylic adhesive. To ensure the safety when adhesive joint fails, the beam-column is also constructed in "corner bridle joint" as figure shows below, enables the structure to remain its integrity.

Figure 2-16 *All-glass enclosure with glued frames, Dresden, Germany (Weller 2010.)*

- Connection method

The acrylic based connection applied in this project has a great advantage for its transparency feature, not to have any visual disturbance fits the goal of having a total transparent glass structure. Compared with the silicone based adhesive, the acrylate adhesive has higher initial strength and easier to apply in thinner joint. However, this UV light -curing adhesive faced some challenge when applying in a less than 2mm thin planner joint without bubbles. Thus , its temperature and humidity sensitive material nature should be paid attention during construction. (*Weller 2010.)*

Figure 2-17 Manufacturing of the glued connection: application of adhesive (left), curing with UV- and visible light (right).(Weller 2010.)

Case study 3: Apple store 5th avenue, New York City, U.S.

- The background

In the cases of Apple glass cube version 1 and 2, it is a perfect example of the process of "renovation through innovation with structural glass", which clearly demonstrates the significant improvement in the development of glass technology and the detail design over the recent decade.

The project is located on 5th avenue New York City, and it is a glass entrance for the underground retail space for iconic Apple store. The first apple glass cube on 5th avenue was completed in 2005, by then due to the limited size of the furnace for the glass panels, the maximum size of a glass panel was 3.21x6m. For a size 10x10x10 m glass cube, it requires 106 glass panels to complete. But as the glass technology becomes more advanced and the larger glass tempering oven is built, the largest size of glass panel can be produced is 15x3.6m panel. For this reason a revised version of Apple cube on 5th avenue using bigger panels and more sophisticated connection to reach its maximum transparency was suggested and completed in 2011 November.

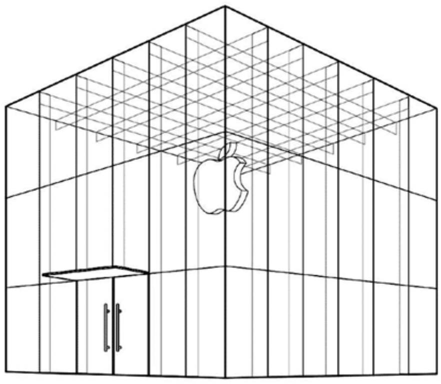



Figure 2-18 Apple cube 5th avenue, New York, 2006 (Eckersley O'Callaghan)

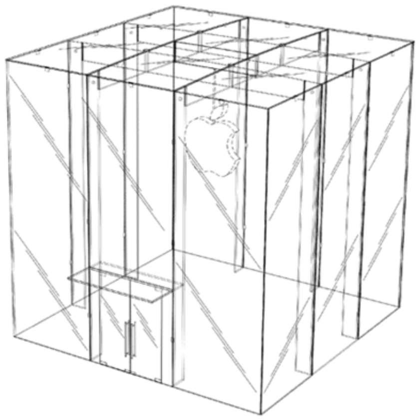



Figure2-19 Apple cube 5th avenue, New York, 2011 (Eckersley O'Callaghan)

- Structure system

The new structure is heavier than the original one, because of the thicker glass envelope given by the bigger span between the vertical fin supports. With bigger span, the number of point load accommodated by the fin is therefore reduced from 5 to 2 fins on each side. Consequently, there is slight over stress in the existing steel and the bigger deflection is expected in the unbalanced loading condition. As a result, the existing structure had to be reinforced in the new design and a more complex method to support the fins and glass panels need to be redesign in order to even out the deflection of the glass panel.

- Connection method

The beam-column connection of a glass portal frame in this project is using the bolted connection a hinge joint. This mechanical connection is located in the middle of the area where the glass column and beam overlapped.

Figure 2-20 Apple cube 5th avenue, New York, 2006 (Eckersley O'Callaghan)

The bigger size glass panels lead to the reduction of the number of glass panels and the number of the connection. The challenge was to develop the laminated inserts which the bolts and screws cannot be seen from any visual aspect. As it is states by O'Callaghan in his paper," This detail has worked perfectly and has resulted in there being no fittings on any side of the cube protruding from the face of the glass itself. This adds real magic to the structure and results in perfectly reflective and flat surfaces on each face of the structure." The connection in the first Apple cube is using bolted and clamped fixing. Comparing Apple cube version 1 and 2; version 1, structurally, the glass panel is much preferred not to be drilled hole in it to reduce the local stress happens. And aesthetically, the metal plate of the connection is on the outer surface of the façade and thicker, whereas the embedded connection in version 2 is visually more elegant and more blended-in and integrated in the building design.

Figure 2-21 Connection of Apple 5th avenue 2006 and 2011(Eckersley O'Callaghan)

Case study 4: Pavilion Patek Philippe Basel world

- Design

The pavilion is designed for the one-week-use Basel world exhibition in 2014. The dimension of the pavilion is 20x20x9 m and the design by Ottavio de Blasi is to be full glass structure. The structure system and detail of connection is then developed and designed by Glas Trosch. Basically, this case is showing the application of TSSA (transparent structural silicone adhesive) bonded elements with laminated inserts as connection for the glass elements. In this structure, due to the maximum standard size of a glass panel, the façade is divided in three panels in height.

Due to the choice of using annealed glass, it is very important to analyze the stress level in glass and the interlayer. It is also shown that the shape, geometry and the size of the laminated inserts are the parameters affects the stress level of each element.

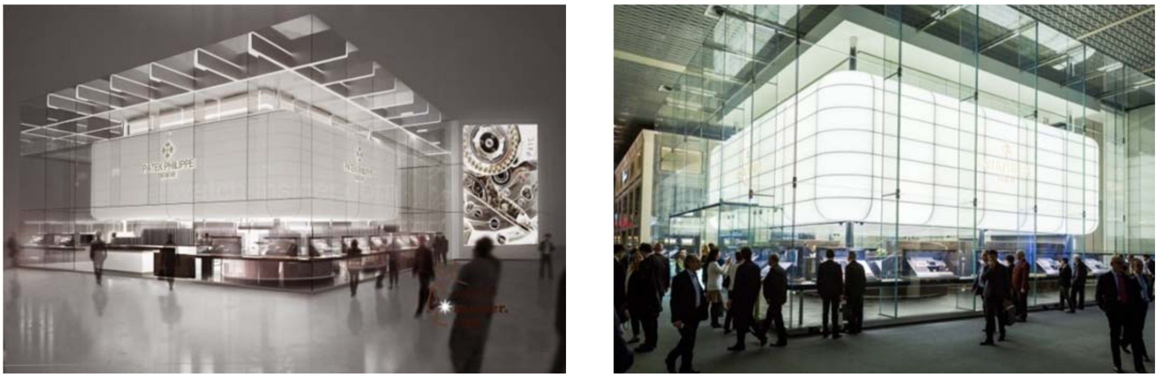


Figure 2-22 Pavilion Patek Philippe Basel world (Kessnel-Henneberg 2016)

- Connection method

In this all-glass pavilion, the glass fin at the front entrance is designed as z-shaped element, therefore, the detail of the connection needs to use laminated insert with a pin in the additional borehole fixing to increase the safety due to the residual strength criteria when overloading situation happens.

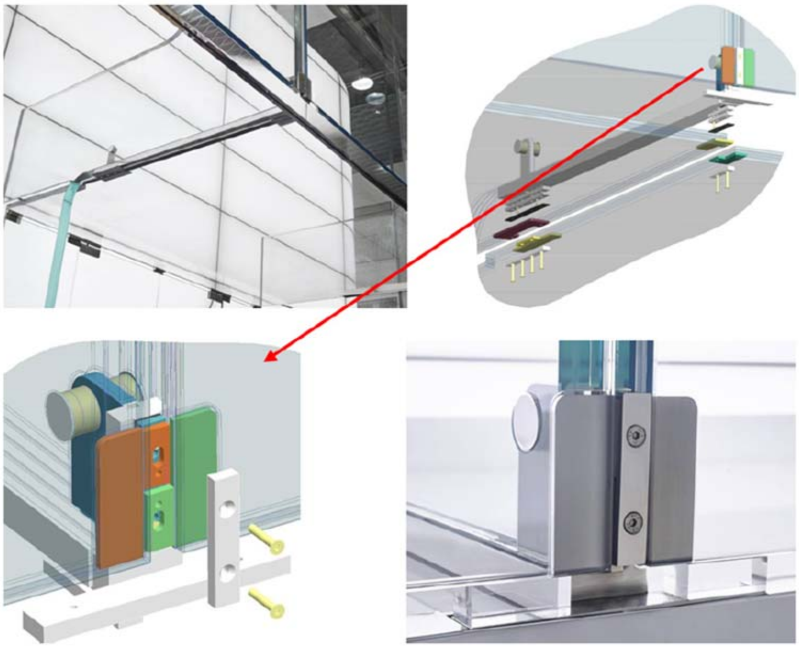


Figure 2-23 Connection detail of (Kessnel-Henneberg 2016)

The connection method for this glass pavilion is mainly using TSSA(transparent structural silicone adhesive) bonded elements with laminated inserts to connect between glass elements. From the graphs below, it clearly demonstrates the sequence of the connection construction.

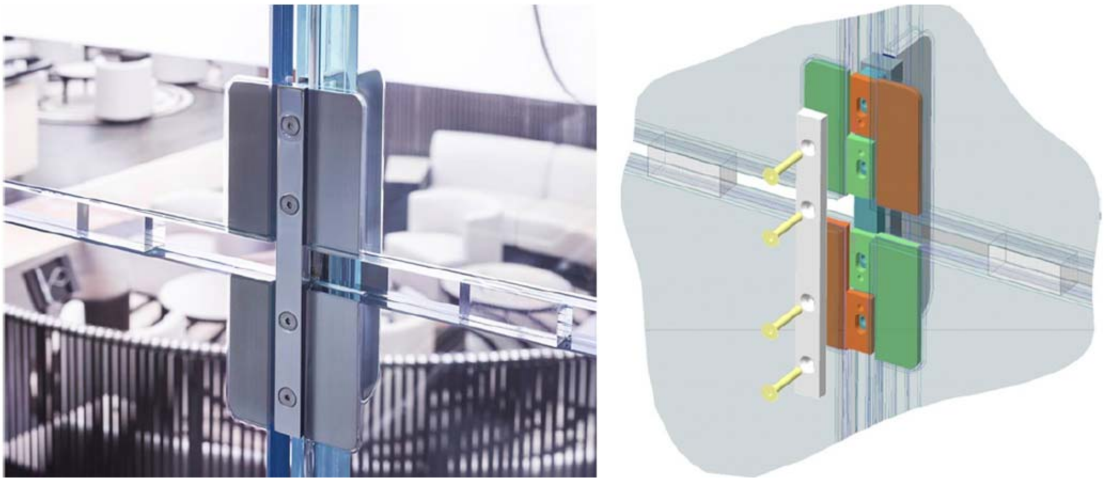


Figure 2-24 Connection detail of glass fin and façade (Kessnel-Henneberg 2016)

Case study 5: 6 meter long glass footbridge at ancient public slaughterhouse of Pisa

- Design

This case is one of the very few projects that applies reinforced laminated glass beam in the current glass structure design. A glass footbridge was designed and built to bridge the gap between two sides of the floors. The glass footbridge has a length of 6000mm, a width of 1760mm and it consists of a laminated glass deck, glass railing and reinforced laminated glass beam. The glass deck is one side supported by one continuous 5790mm steel-reinforced laminated beam, and the beam is simply supported at the end of the beam by the existing wall. The paragraph here will mainly focus on the reinforced laminated glass beam and its way of connection to the other glass members.

Figure 2-25 reinforced laminated glass beam of the glass footbridge (Mamone,Masiello, Lani. 2016)

The steel-reinforced glass beam is 5790mm long, 368mm wide and 48.56 mm thick. It consists of four layers of heat- strengthened glass panels, with two external layers of 10mm and two inner layers of 12mm panels. And the four layers of glass are laminated by 1.52mm of SentryGlas interlayer. The steel reinforcement is a 25x30mm cross section laminated at the bottom of the glass beam. *(V.Mamone,G.Masiello, L.Lani. 2016)*

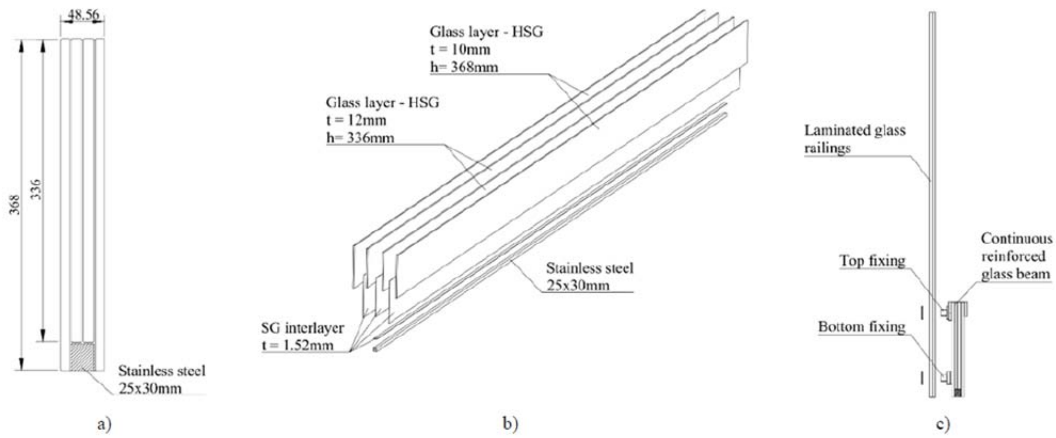


Figure 2-26 reinforced laminated glass beam of the glass footbridge (Mamone,Masiello, Lani. 2016)

- Connection method

The connection of glass beam and glass railing is relying on mechanical fixing and adhesive. A height of 1500mm 3-layered glass railing is attached to the outer surface of the reinforced glass beam. For the bottom fixing, the glass railing is drilled to make holes for metal fixing and the other end of the metal is glued on the surface of the reinforced glass beam. For the upper fixing, the holes are also drilled on the railing side for mechanical fixing, however, the metal fixing is mechanically fixed on the steel strip which is glued on the top edge of the reinforced glass beam.

Case study 6: Van Gogh Museum Glass entrance, Amsterdam

Figure2-27 Van Gogh Museum Glass entrance (Ronald Tilleman, Luuk Kramer)

- The background

The main structure system of the Van Gogh Museum glass entrance is a hybrid system of steel tube, glass panels and glass fins. Designed as a glass envelope, it is architects wishes to have as minimum metal as possible to maximize the transparency of the glass entrance, but without the high budget of Apple store.

- Design procedure

The dimension of glass beam is mainly determined by the span of the beam. In the design of glass beams, dimensions are governed by strength as allowable stress are relatively low. A ratio is determined in which this normative (simplified) load combination would lead to stresses equal to about 50 % of the allowable stresses. As bending stress in an equally distributed loaded beam on two supports quadratic relates to the span, and the stress is also quadratic relate to the height of the beam. And in the case of Van Gogh Museum glass entrance, a linear relation between the height h and the span L was chosen for a fin with a glass composition for 3x15 mm.

$h=L/17>=200mm$

Later on, as the lateral torsional buckling of the longest beam is concerned, a stability analysis is done to make sure the thickness of the glass beam is thick enough. Since the calculation of the glass beam were based on the interlayer of PVB which resulted in almost no shear interaction between the glass sheets, therefore, the torsional stiffness is mainly determined by the thickness of the single glass sheet.
For the safety reason, the three-layered laminated glass beam is designed to satisfy the maximum loading when one panel is broken. Moreover, fully-tempered glass is chosen to increase the allowable stress and SentryGlas interlayer is chosen to improve the post failure characteristic when all three layers of glass is broken. (Bijster, J., Noteboom, C., & Eekhout, M. 2016)

The pursuit of maximum transparency

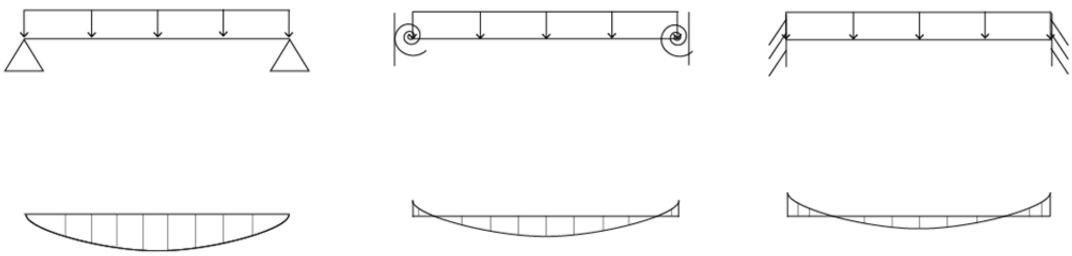
Case study 7 : Apple Zorlu, Istanbul, Turkey

The Apple Zorlu in Istanbul has achieved the ultimate transparency and purest structural approach within the limitation of glass technology today. The building is formed by 4 panels of glass wall and a Carbon Fiber Reinforced Plastic (CRFP) panel as roof. The glass wall is 10m wide x 3m tall and are formed of 3 x 12mm fully tempered glass laminated with Sentry Glass interlayer. The roof is a single Carbon Fiber Reinforced Plastic (CRFP) panel with a complex 'precambered' shape to ensure the soffit is completely level though out when installed. The external form rises to 210mmin the center to facilitate water run-off. It is a constant 60mm at the edges where it meets the wall panels. Apple Zorlu shows the ultimate simplicity and transparency that architects has been dreamed of for years and the advanced glass technology today.

Figure 2-28 Apple store Zorlu, Istanbul. (Eckersley O'Callaghan)

2.7 Semi-rigid connection

In the previous research done by Snijder shows that the laboratory test results indicate that the glass beam to column connection is neither complete articulated nor complete restraint; rather it is in the form of semi rigid. Therefore, for accurate response of structural behavior, needs further research. Here present some studies on semi-rigid connection.



Pin-pin Spring- spring Fixed-fixed

Figure2-29 Moment diagram for beams subjected to uniform distributed load

Connection stiffness has a considerable impact on the load-displacement behavior of structure. The semi-rigid design is the most cost effective solution when it is compared with the traditional pinned and rigid joints. The semi rigid joint between beam and column provides a lower moment at the end of the beam when it is compared with fully rigid joint. This lower design moment can reduce the required section modulus of the beam and subsequently a potential cost savings may achieve. In order to obtain the optimal design, the rotational stiffness and moment resistance is required to analyze. (Ferdous, 2014; Simões, 1996)

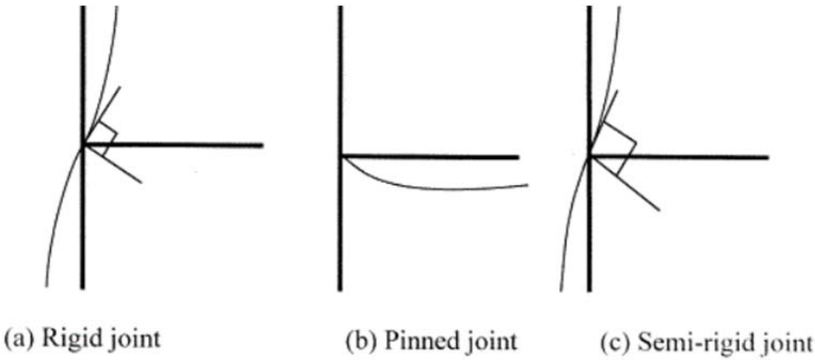


Figure2-30 Different joints according to rotational stiffness (Jaspart, 2000)

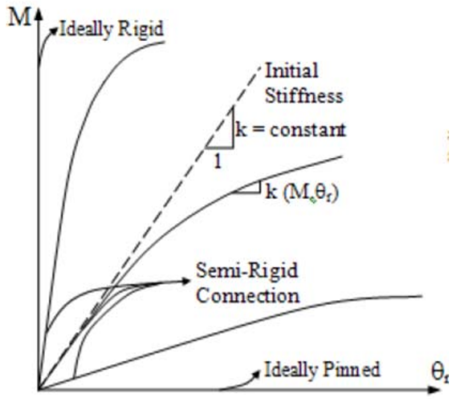


Figure 2-31 Structural behavior of connections (Kartel 2010)

In practice, the joints between beam and column is traditionally considered ideally as rigid connection or the which actually not fully rigid in reality and therefore accounted an extra moment leading to structural over-design (Ferdous, 2014).And in finite element analysis, the semi-rigid joint is usually assuming as rigid or pin joint for simplified calculation, but if the analysis wants to be more accurate, the connection should be designed according to their moment-rotation curve, which is the indication showing how rigid the connection is.

The benefit of semi-rigid connection

- Avoid connection over-design
- enable to predict the structural behavior more accurate
- Reduce the height of the beam

- Reduce building height

The rotation stiffness k is given as

$$\mathrm{k} = \frac{M}{\theta}$$

Where M is applied moment and θ is the rotation

Chapter 3

Introduction of structural design parameters

3.1 Structural design parameters of glass portal frame and L-shaped connection

To understand the structural behavior of the glass portal frameand the L-shaped connection , it is essential to know what are the parameters and the relationships between them. The key parameters that links both componants in this research is the rotational stiffness k. Therefore, in the following paragrahs, the parameters that will mainly influence the rotational stiffness k of the glass portal frame will be discussed. For L-shaped connection, as the connection becomes more rigid, the ability of holding the the glass beam and column together is then higher. Therefore, the parameters that affects the rigidness of the connection itself and consequently influnce the rotational stiffness k will also be discussed.

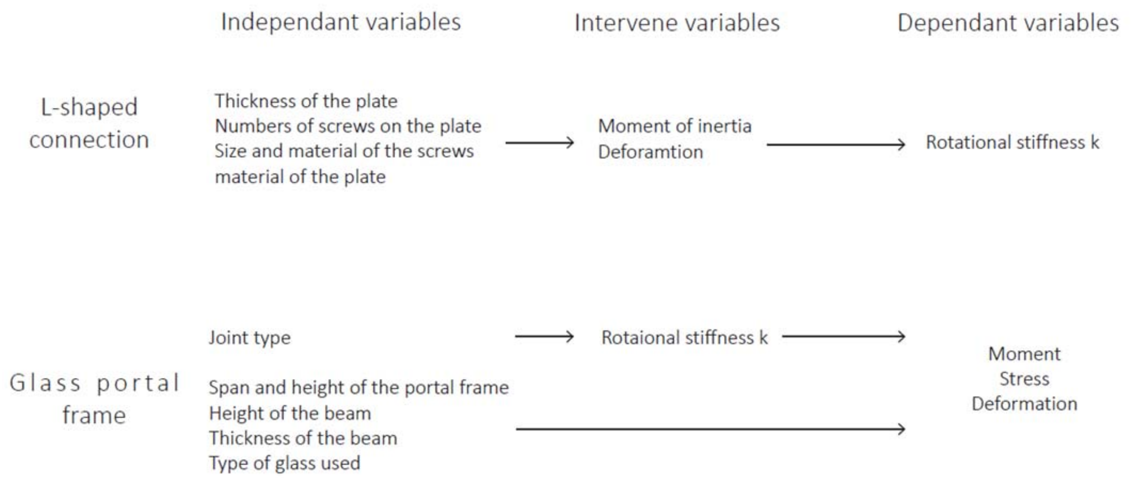


Figure 3-1 Overview of the relationship of rotational stiffness k in glasss portal frame and L-shaped connection

3.2 Glass portal frame structural design parameters

From the research goals, it states that one of the reason of this research is hope to reduce in the beam height through using semi-rigid joint in glass portal frame design; and since the section of the beam will determine how the beam can take the moment at that location, therefore, the moment at both end of the beam and mid-span of the beam are then the two main element we are focusing on. In the following paragraph, the parameter which will influence the moment of the beam, which will consequently affect the rotation stiffness k, will be discussed.

- The span and height of the glass portal frame

The span and the height of the portal frame are the essential parameters that affect the moment of the beam. The relationship of the span-height ratio and moment will be discussed in chapter 4.

- Joint type

Different types of joints in rigidness influence the moment diagram in a portal frame. Fixed joint has the highest rotational stiffness k, while the rotational stiffness k in hinge joint is zero. And from the figure 3.1.1 we can see that as the joint becomes more rigid, the moment curve will rise accordingly. Therefore, hinge has the biggest moment at the middle of the beam while the fixed joint has the smallest moment at the location. In contrast, at the ends of the beam, hinge has smallest moment and fixed joint has the largest moment. Semi-rigid joint is the only possible way to adjust the moment ratio between these two locations to the desired number we want.

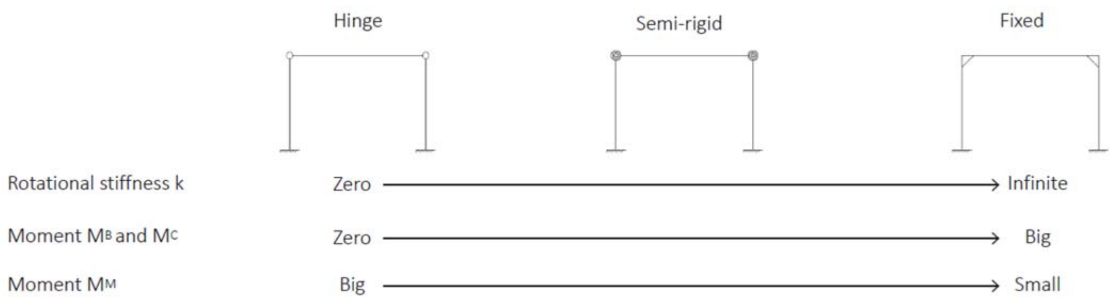


Figure3-2 Relationship of Rotational stiffness k and moment

- Type of glass used

The type of glass used is usually determined by the characteristic strength of glass chosen and the fracture fragment size after the glass is broken. For example, from the finite element analysis, if the maximum stress in beam is 90 N/mm^2, then according to the characteristic strength of glass, fully-tempered glass will be the choice.

-Thickness of the beam

The equivalent thickness is used for calculating the thickness of laminated glass when calculating deformation, stress and the properties related to moment of inertia. But the self weight will still be using the sum of adding all laminated layers t_{sum}.

For equivalent thickness t^*

$$t^* = \sqrt[3]{(t_1)^3 + (t_2)^3 + (t_3)^3 + \cdots}.$$

$$t_{sum} = t_1 + t_2 + t_3 + \cdots.$$

The beam which subjects to high slenderness ratio will have the possibility having lateral buckling, therefore, increase the thickness will help prevent the lateral buckling.

-The material choice of the intermediate layer

To avoid the stress concentration occur to the glass, a certain intermediate layer needs to apply between where the glass and the steel connection contacts. The modulus of elasticity of the material needs to be considered to have better performance of even-distribution of the force. For example, EPDM rubber.

3.3 L-shaped connection structural design parameters

The L-shaped connection is designed for reinforced glass beam as beam-column connection. Both glass beam and column are laminated with steel reinforcement bar and the stainless steel connection plate is fixed on the steel reinforcement by the bolts.

It is important to know what the parameters are that will influence the rotational stiffness k of the connection, in order to adjust the rotation stiffness that is desired in the connection design according to different glass portal frame design cases.

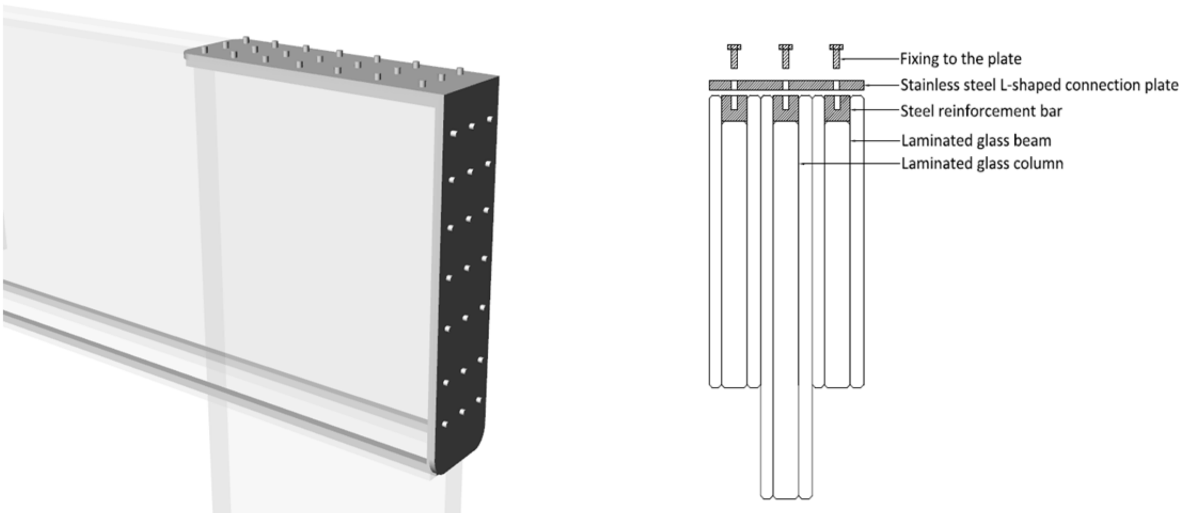


Figure 3-3 L-shaped connection drawing

- The Thickness of the plate

The thickness of the L-shape plate will influence the rotational stiffness k of the connection, as the thickness of the plate goes bigger, the connection is stiffer, therefore, the rotation stiffness k is also bigger.

- The amount of screws

It can be predicted that the increase numbers of screws in plate will make the connection more rigid. Never the less, as more screws means more holes need to be drilled in the plate, so the stiffness provide by the plate itself may decrease. Therefore, the level of increase in rigidness when increasing the bolts requires further research.

- The properties of the screws applied

It can be estimated that the properties of the screws, such as material, class and size, will affect the structural performance. However, in this research, these categories are not taken into analysis.

- The material choice of the connection

The material has higher Young’s modulus will give higher stiffness in connection itself and therefore results in higher rotational stiffness k.

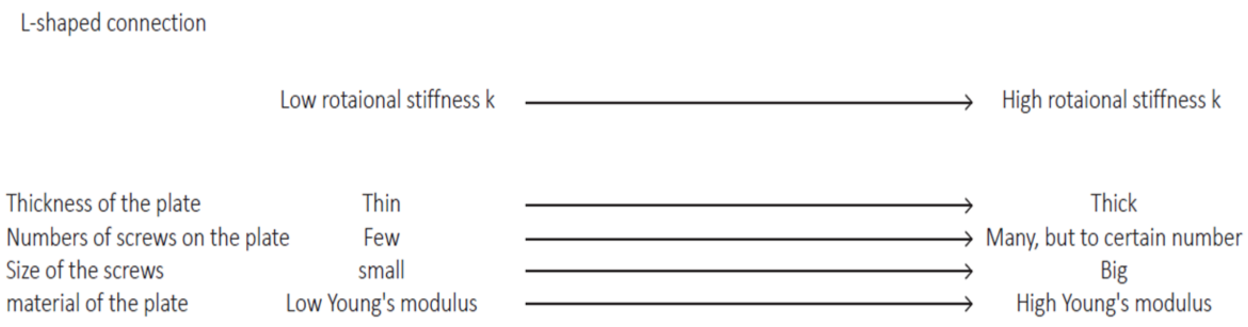


Figure 3-4 Relationships between parameters of L-shaped connection and rotational stiffness k

Chapter 4

Theoretical and FEM analysis of a glass portal frame

4.1 Theoretical prediction of behavior of glass portal frame

The portal frame calculated in the following is supported by hinge and with spring connection at B and C. M_B and M_C indicates the moment at both spring B and C respectively; M_M is the moment at the middle of the beam, which is crucial in this research. q1, q2and q3 are the distributed loads perpendicular respectively to its beam and column.

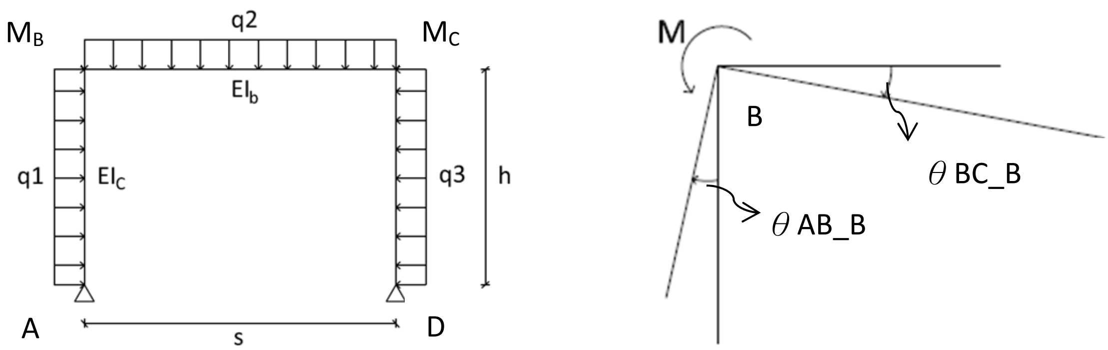


Figure 4-1 Portal frame diagram

The following formula indicate the rotation at point B in the member of AB and BC respectively, and θ B is what the spring contribute to the rotation change at point B.

$$\theta \text{ AB\_B} = \frac{M_B \cdot h}{3EI_c} + \frac{u}{h} - \frac{q1 \cdot h^3}{24 \cdot EI_c}$$

$$\theta \text{ BC\_B} = \frac{M_B \cdot s}{3 \cdot EI_b} + \frac{q2 \cdot s^3}{24 \cdot EI_b} + \frac{M_C \cdot s}{6 \cdot EI_b}$$

$$\theta \text{ RB} = \frac{M_B}{k}$$

Likewise, the following formula indicate the rotation at point C in the member of BC and CD respectively, and θ C is how the spring contribute to the rotation change at point C.

$$\theta \text{ BC\_C} = \frac{M_C \cdot s}{3 \cdot EI_b} + \frac{q2 \cdot s^3}{24 \cdot EI_b} + \frac{M_B \cdot s}{6 \cdot EI_b}$$

θ CD_C= $\frac{M_C \cdot h}{3EI_c}$ + $\frac{u}{h}$ - $\frac{q3 \cdot h^3}{24 \cdot EI_c}$

θ RB= $\frac{M_C}{k}$

The sum of rotational change of member AB and BC to point B and the rotational change caused by the moment at point B will be 0, as it is showed in the equation 1 and 2.

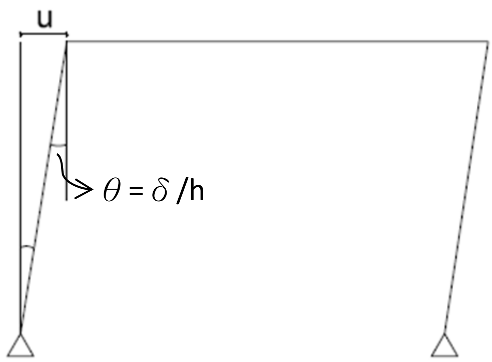
equation1: θ AB_B+ θ BC_B+ θ RB= 0

equation2: θ BC_C+ θ CD_C+ θ RC= 0

equation3: $\frac{q1 \cdot h}{2}$ + $\frac{M_B}{h}$ = $\frac{q3 \cdot h}{2}$ + $\frac{M_C}{h}$

Equation3 describes the theory of work, the sum of work done in a structure should be 0 and work equals to force times distance. The following graph and equation

$$\frac{q1 \cdot h \cdot \delta}{2} + \frac{M_B \cdot \delta}{h} = \frac{q3 \cdot h \cdot \delta}{2} + \frac{M_C \cdot \delta}{h}$$



Due to the complexity of the equation, the math calculation is done in Maple. With equation1, 2 and 3, the formula of M_B and M_C can be solved as the followings.

$$M_B = \left(\frac{1}{8}\frac{1}{2EIbhk+3EIcks+6EIbEIc}\right) \cdot [q1(3EI_bh^3k + 6EI_ch^2ks + 12EI_bEI_ch^2) -q2(2EI_cks^3) -q3(5EI_bh^2k + 6EI_ch^2ks + 12EI_bEI_ch^2)]$$

$$M_C = \left(\frac{1}{8}\frac{1}{2EIbhk+3EIcks+6EIbEIc}\right) \cdot [q1(5EI_bh^3k + 6EI_ch^2ks + 12EI_bEI_ch^2) -q2(2EI_cks^3) -q3(3EI_bh^2k + 6EI_ch^2ks + 12EI_bEI_ch^2)]$$

For M_m, the moment at the 1/2s of beam, the equation is derived from the basic differential equation of the deflection curve of a beam with eight boundary conditions.

In order to compare the results of theoretical calculation, FEM calculation and laboratory results, the dimension of portal frame in these calculations will be used the design of Dresden glass pavilion.

The dimension of the glass portal frame in Dresden glass pavilion is 4.4m wide and 2.5 m high, with the 250mm wide and 48 mm thick of beam and column. In our goal, we hope to have the M_M/M_B equals to 1, which is the ideal situation for the design to have smallest beam height. With this ratio equals to 1, the height of the beam will be at its smallest.

4.2 Relationships between rotational stiffness k and glass portal frame parameters

In the following paragraph, the relationship between k and other glass portal frame parameters will be discussed.

4.2.1 M_B and k relationship with vertical loads

From the graph 4.2.1, we can see that M_B has quadratic relationship with rotational stiffness k. Start from hinge connection, as the k increase, M_B also increases rapidly, but after certain level, M_B doesn't change much as the k gets bigger. Therefore, it means that after certain point, when the connection becomes more rigid, the moment would not change much for the beam.

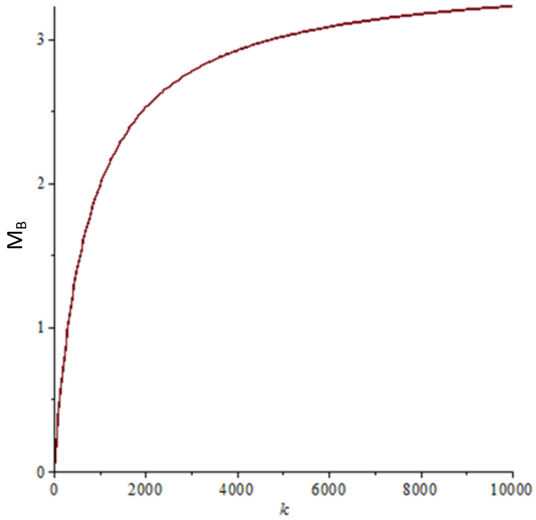


Figure 4-2 M_B and k relations with vertical loads

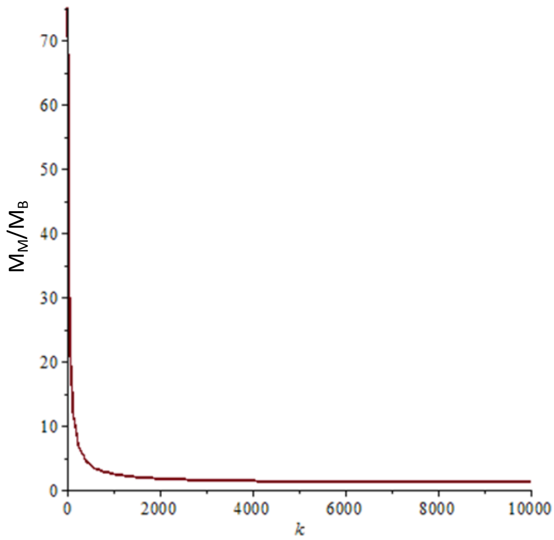


Figure 4-3 M_M/M_B and k relations with vertical loads

4.2.2 M_M/M_B and k relationship with vertical load

We can see from the graph 4.2.1-2 that M_M/M_B ratio is also a quadratic relationship with k. When the joint is a hinge that M_M/M_B is infinite, but as k increases after certain number the M_M/M_B ratio reach its constant value, which also indicates that it has reached the rotational stiffness that can be called as fixed joint. In this case, the M_M/M_B is 1.2 when the joint is fixed, so the assumption of having M_M/M_B=1 cannot be reached.

After finding out that M_M/M_B =1 may not be achieved in every case, I tried to find out what the possible dimension relationship of a portal frame is to reach M_M/M_B =1 scenario. The condition is explained as the following.

If M_M/M_B=1 is possible to achieve at fixed joint situation that M_M/M_B=1 will also be able to reach in a semi-rigid situation.

Therefore, at fixed joint situation, the M_M and M_B can be written as

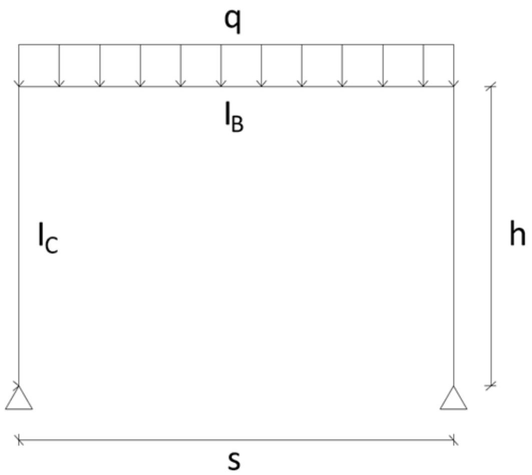


Figure 4-4 Pinned support frame with fixed joint

Coefficient $a = \frac{I_B}{I_C} \cdot \frac{h}{s}$

$$N = 2a + 3$$

$$M_B = M_C = -\frac{q \cdot s^2}{4N}$$

$$M_M = \frac{qs^2}{8} + M_B$$

(Steel designer's manual 6th edition 2003)

To reach the M_M/M_B=1 in a semi-rigid joint situation means that M_M/M_B is smaller than1 in the fixed joint situation.

$$\frac{M_M}{M_B} < 1$$

Therefore, to have M_M/M_B=1 in semi-rigid joints situation, the following condition needs to be met.

$$\frac{1}{2} > \frac{h \cdot I_B}{s \cdot I_C}$$

4.2.3 Deformation and k relationship with vertical load

The deformation at the 1/2s of the beam W is where the maximum deformation occurs when applying vertical loads. It is indicates in the graph that the W also has a quadratic relationship with rotational stiffness k. As k increases after the value at the vertex of the curve, which is 2300 in this case, the maximum deformation of the beam will not reduce much. Therefore, it can be conclude that k at this point is the optimum number in designing the portal frame as long as it does not exceed the maximum deformation at SLS (service limit state). In the case applied, the maximum deformation that this beam can have is 1/200 span, 0.022m, so k =2300 is the most preferable rotational stiffness for this portal frame design.

4.2.4 M_B and k relationship with horizontal loads

In the graph, we can also see that the relationship between M_B and k is also quadratic. However, compare to vertical load scheme, the horizontal load has less influence on the changes of the value M_B .

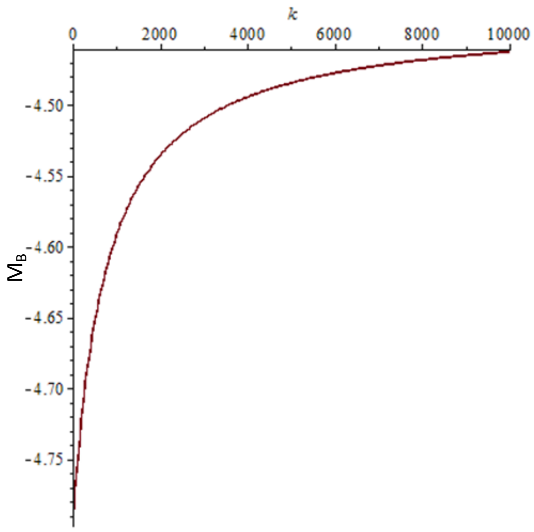


Figure 4-5 M_B and k relations with horizontal loads

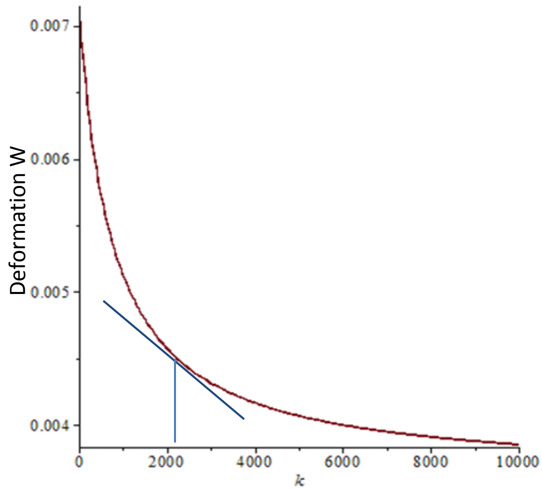


Figure 4-6 W and k relations with vertical loads

4.2.5 Moment and height-span relationship

As we can see from the equation, the height of the portal frame has a bigger influence on M_B and M_C than span. That is to say, when designing a glass portal frame, increasing the height of the frame will largely increase the moment at B and C. From an architectural design perspective, designing a glass portal frame in the future, the increase in height should be further considered.

4.3 FEM analysis of a glass portal frame

The finite element model is made in the same dimensions of portal frame as the theoretical calculation. The model is focusing on the relationship between rotational stiffness at the beam-column joint and the maximum deformation at the middle span of the beam. To see if the finite element model is matched with the theoretical analysis, the deformation level is modeled with various rotational stiffness k, which is 250, 500,1000,2000,4000 respectively. The figure 4.3 and 4.3-1 show the results of deformation when k is 1000 and 4000.

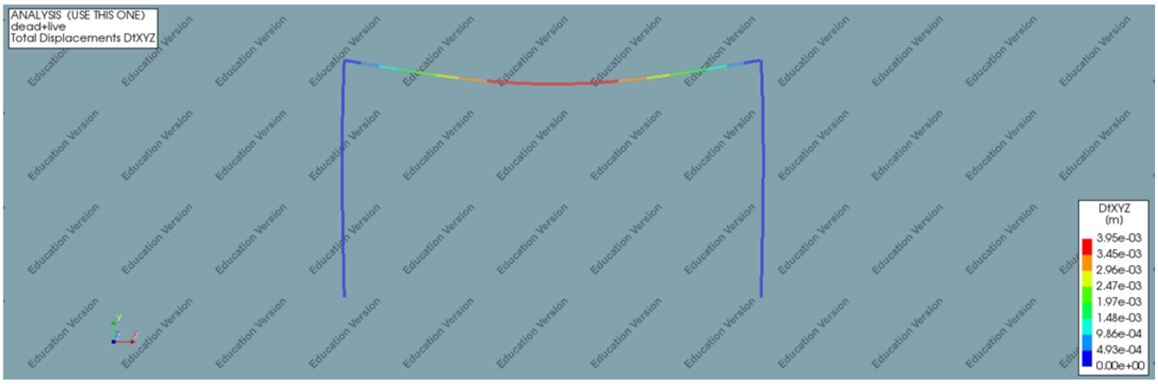


Figure 4-7 FEM analysis k=1000, deformation=0.00395m

Figure 4-8 FEM analysis k=4000, deformation=0.00307m

4.4 Comparison of theoretical and FEM analysis of a glass portal frame

The theoretical analysis and FEM analysis of a portal frame in the relationship of deformation and rotational stiffness k shows a similar curve, whereas the theoretical results have a slightly higher deformation then FEM results.

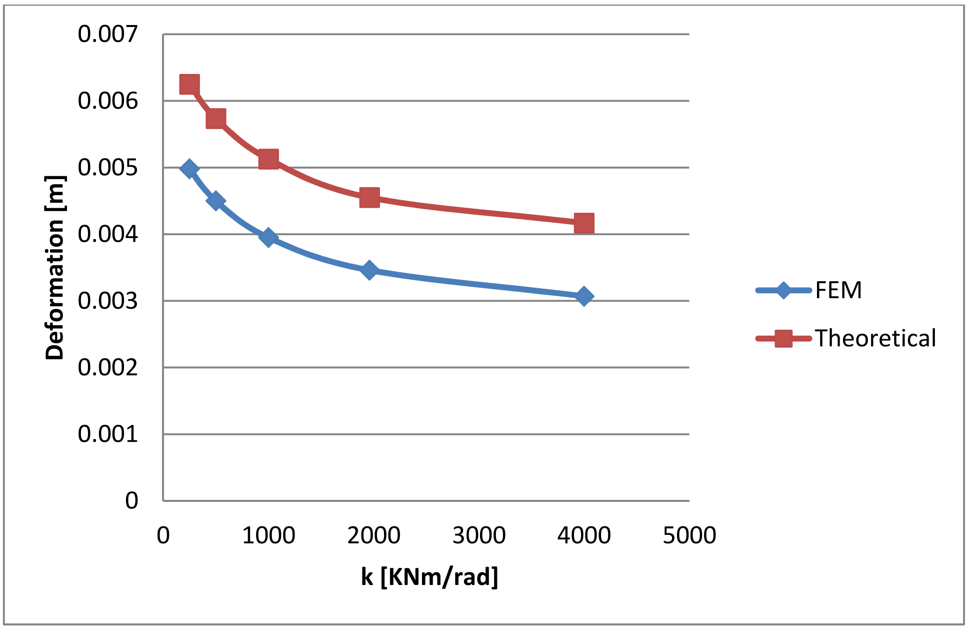


Figure 4-9 FEM and theoretical analysis comparison

4.5 Conclusion

In the theoretical analysis, it is certain that M_M/M_B=1 is the ideal situation to have a smallest height of the beam, however, it is not always possible to achieved. The possible situation to reach this ratio is when the dimension of the portal frame meets

$$\frac{1}{2} > \frac{h \cdot I_B}{s \cdot I_C}$$

this condition.

And in the comparison of the theoretical calculation and finite element analysis, it shows that they have similar curves with a slightly higher number for the FEA results.

Chapter 5

Structural analysis of L-shaped connection

To analyze the rotational stiffness k of current design of the L-shaped connection, sets of compression tests are performed according to the following method derived and the results are also compared with the acrylate adhesive connection used in Dresden pavilion. The goal is to understand what the range rotational stiffness is in the current developed L-shaped connection and the characteristics of both types of connection.

5.1 Method

The test method is developed to determine the rotational stiffness. The force can be applied in horizontal direction and vertical direction, and from the calculation for both model, from the conclusion in Eigenraam's it concludes that the vertical model is more preferable, due to that the horizontal model has 40% lower regarding the influence in self-weight. For this reason the method will only be explained in vertical model in the following.

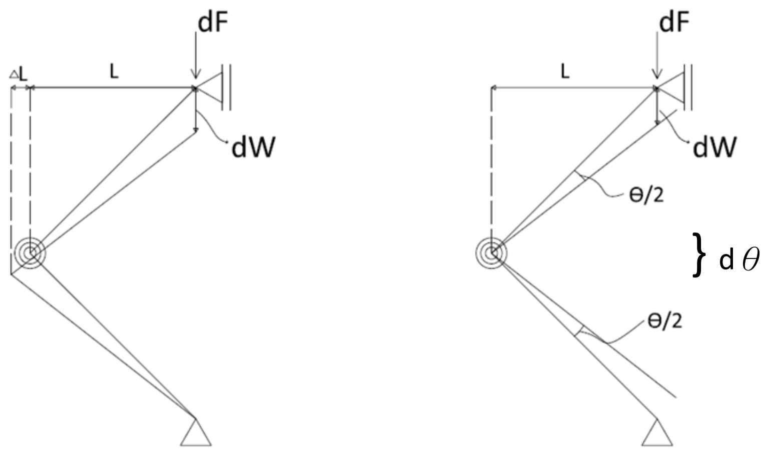


Figure 5-1 Test model

Here *F* is the applied force, *w* the displacement, ϑ the total rotation of the model, *k* the rotational stiffness of the connection. In the model, it is assumed that the deformation of the beam is small, therefore it is neglected. And the other assumption is that since the dispalcement are small, so it is considered tan $\theta = \theta$. As the force applied the beam rotates and L will become bigger, which is L+△L. Since the △L will keep changing but small , here we only take the original L in the following calculation to simplified the calculation.

$$\mathrm{k} = \frac{dM}{d\theta}$$

$$dM = dF \cdot L$$

$$d\theta = \frac{dW}{L}$$

$$k = \frac{F \cdot L^2}{dW}$$

5.2 Specimen material and design

In the test, two different thickness of L-shaped specimen, 3mm and 5mm thick, are tested. The L-shaped plate is made of stainless steel with a dimension of 503x38 mm or 505x38mm, depending on the thickness, and then bends it into L-shaped, which is 250mm on each side. The holes on the plate are in the size of m7 to give some tolerance for the m6 galvanized steel bolts class 10 that we used in the test. The design of the L-shaped connection also consider the tolerance for the manufacturing of the plate, so the distance between each role of the holes is designed to be 13mm apart from the center line of each other to give 1mm tolerance. Moreover, three 12mm thick aluminum plates are a substitution for the glass beams and column, the aluminum chosen has the same 70Gpa for young's modulus as glass, therefore, the characteristic strength of the material, which is the main focus in this test, will be enough to represent glass in this test. The dimension of the aluminum plate is 250x670mm with a hole at the end of the plate to fix on the test machine.

The specimens were made 5 identical ones for each thickness and the test is performed 5 times for each thickness to get a more reliable data.

	Beam	**L-shaped connection**
Material	aluminum	Stainless steel
Density	2700 kg/m^3	7680 kg/m^3
Young's modulus	70 GPa	180 Gpa
Poisson ratio	0.33	0.303

Table 5-2 Specimen material properties

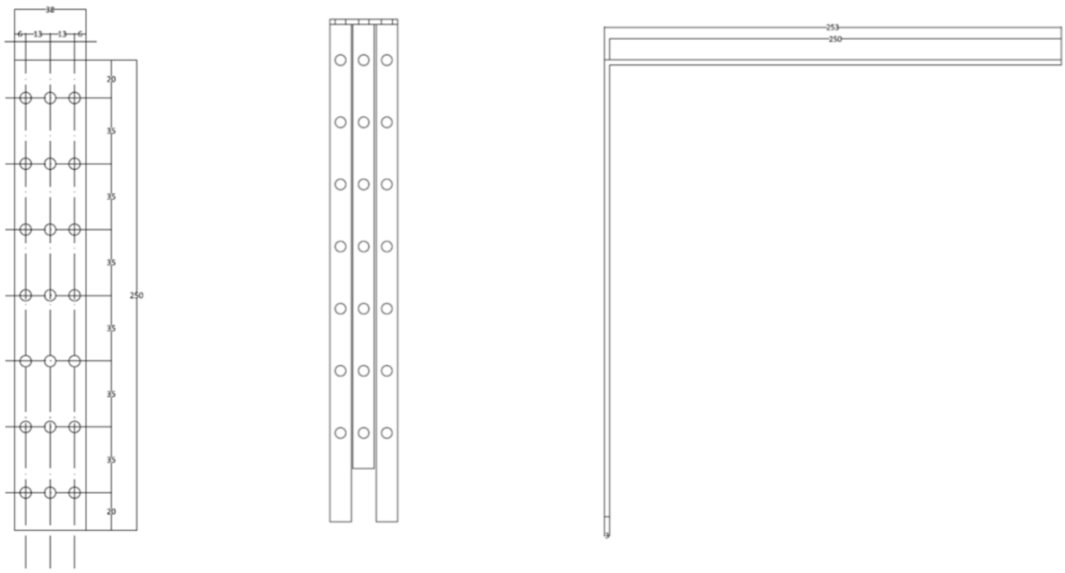


Figure 5-3 L-shaped connection specimen design

5.3 Test setup

The test setups that were used in this research are showed in Fig.5.4.1 and Fig 5.4.2&3, and the method is explained in the following paragraph.

The three aluminum plates were fixed by the L-shaped plate by M6 stainless steel screws. To consider the practical side of the experiment, the plate was only fixed with 4 lines of screws on each side, although 7 lines of holes were drilled in the plate. All the screws were fixed by the electrical screw driver, and in order to make sure all the screws are fixed in the same tightness, we set up the electrical screw driver to certain mode that when certain sound is heard we stopped the screw driver at that moment.

The specimen was fixed in the test machine by steel rods on top and bottom respectively, which allows the aluminum plate to rotate during the test. While two aluminum plates were fixed at the top and one aluminum plate is fixed at the bottom, the force was applied at the top point. During the test, the data of displacement and the force applied were collected. After each test, the screws were unscrewed to see how the condition of each screw, and recorded accordingly.

We decided to have 5 mm plates tested in two different screws patterns, since we found that the first three tests data for the 5mm plates we got are identical. The second scheme which is adding one extra line of screws on the second row of the holes to test a different pattern of the screws, this approach is to further understand how much can an extra line of screws contribute the increase of stiffness in this connection.

Designation		**3mm**	**5mm pattern 1**	**5mm pattern 2**
Specimen numbers		5	3	2
Specimen no.		Specimen 1-5	Specimen6-8	Specimen9-10
Overall geometry				
Beam length	[mm]	670	670	670
Beam height	[mm]	250	250	250
Beam thickness	[mm]	12	12	12
L-shaped plate				
Thickness	[mm]	3	5	5
Width	[mm]	38	38	38
Length (each side)	[mm]	250	250	250
Screws				
Screws size		M6	M6	M6
Screw numbers each side		12	12	15

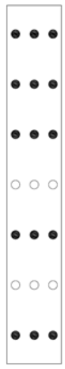
Bolt pattern (bottom is the corner)			

Table 5-4 Specimen configuration

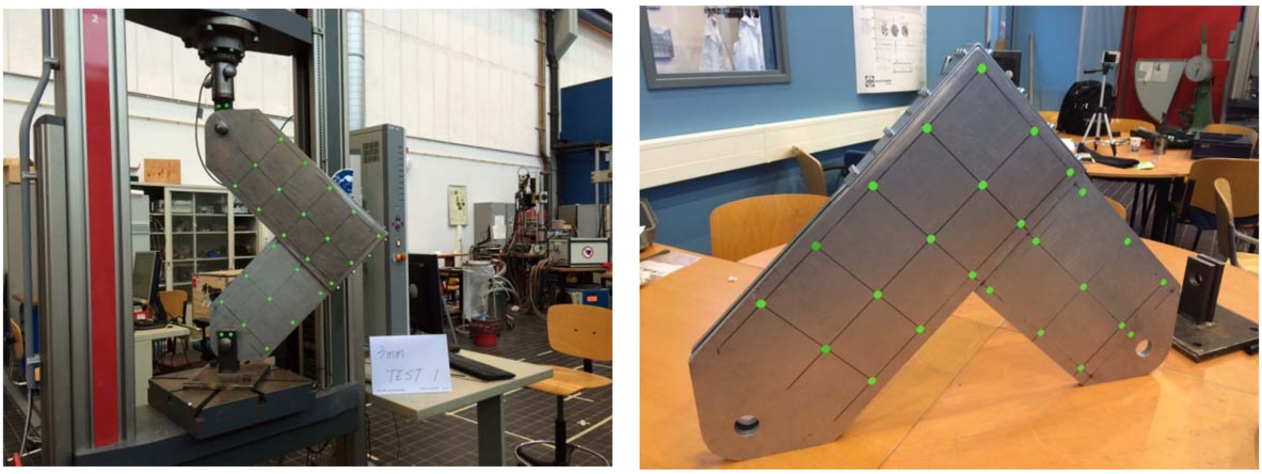


Figure 5-5&5-6 Test set up

5.4 Test results and discussion

From the test results, we chose the data of displacement when the applied force is the closest to 5000N and any other data after 5000N to 30000N. The difference of the displacement and the force are the number for dW and dF that we use in the derived formula for k. The reason to choose 5000N as a base point is that from 10 specimen results we can see that at this point the force-displacement curve is at a steady stage. L is determined by the location of rotation point, and it is explained in detail in the later chapter 5.5.1.

$$\Delta \mathrm{w} = w_x - w_{5000}$$

$$\Delta \mathrm{F} = F_x - F_{5000}$$

$$\mathrm{k} = \frac{dF \cdot L^2}{dW}$$

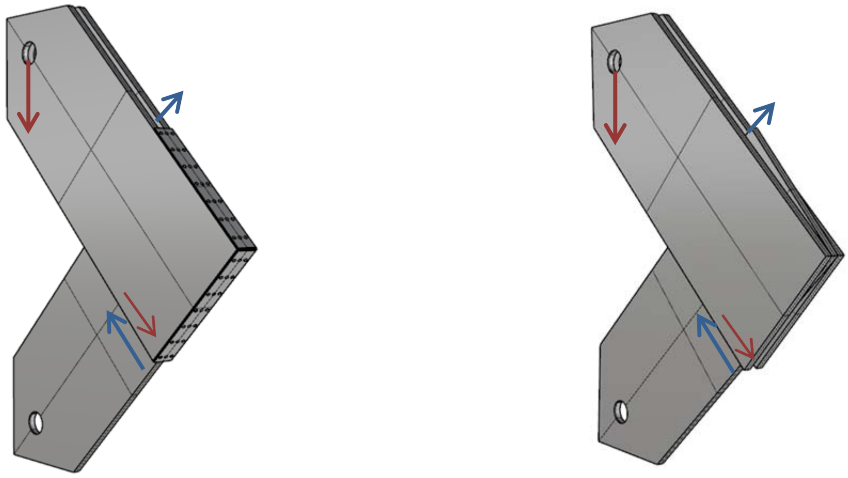


Figure 5-7 Indication of the rotation direction

From the 5 specimens of 3mm connection results, the results seem to be rather in a similar trend, only specimen 1 is not showed in the similar trend. For the 3mm specimens, the initial rotation stiffness k is in the range of 1200-1330 kNm/rad and ended at the range of 581-660 kNm/rad. The 3 mm specimens have significant visible deformation during the test. The most deformed location of the 3mm L-shaped connection is at the further end from the corner, and it is because that the relatively rotation of the upper aluminum plates and the lower aluminum plate is the biggest.

For the 3 sets of 5mm specimen in pattern 1, it shows the very identical test results. The initial rotation stiffness is at around 1790 kNm/rad and ended around 1300 kNm/rad, which the results are both much higher than the k of 3mm connection. The end rotation stiffness k of 5mm connection pattern 1 is about the same as the initial k of 3mm connection. It clearly indicates that the increase of thickness of the L-shaped plate has a significant positive effect on the increase of rotation stiffness k.

Since the 3 test results are identical, we tested the last 2 sets of 5 mm connection in a different screws pattern. Comparing with the 5mm connection in pattern 1, the 5mm connection in pattern 2 shows a less decline in k while adding the applied load, although the initial rotation stiffness k is slightly larger than the pattern1. The results proves that by adding screws at the place where most deformation occurs may help to increase the initial rotation stiffness and the reduction in stiffness along the test.

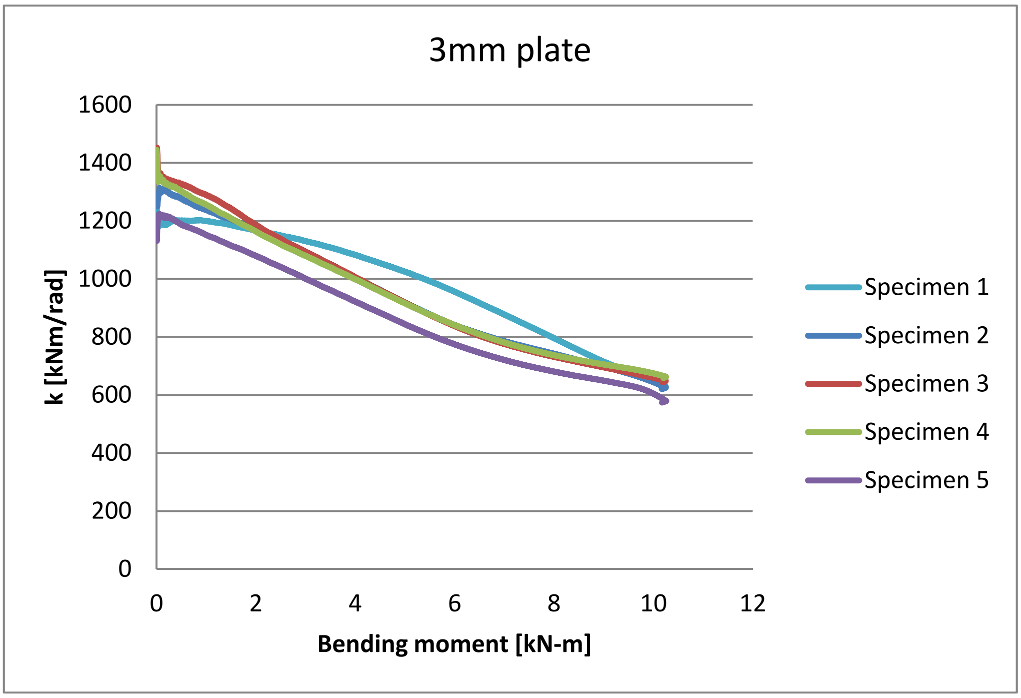


Figure 5-8 3mm L-shaped connection

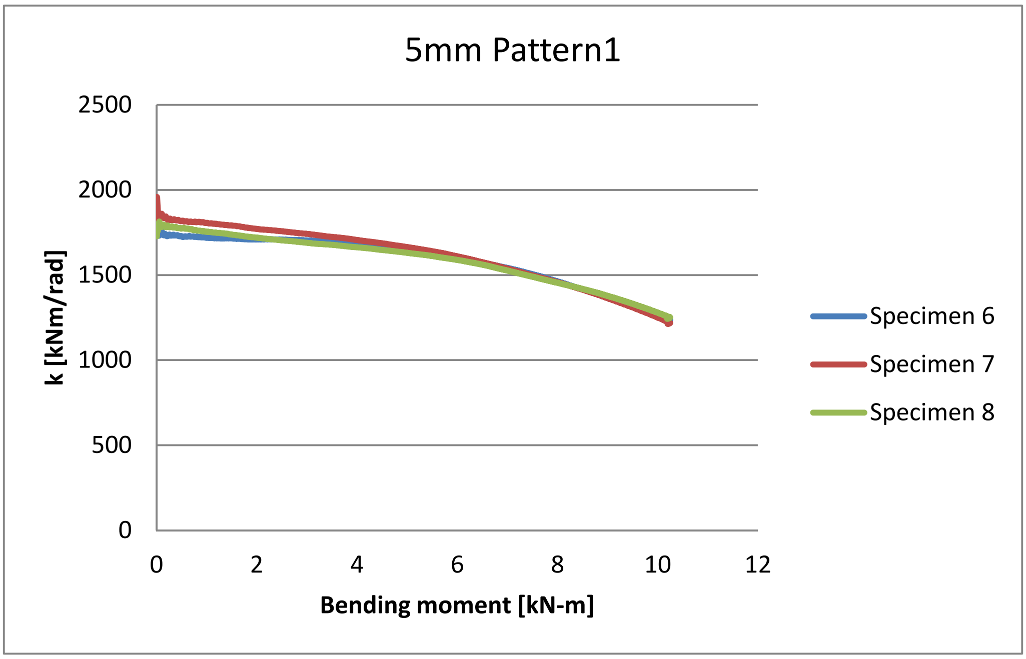


Figure 5-9 5mm L-shaped connection screw pattern 1

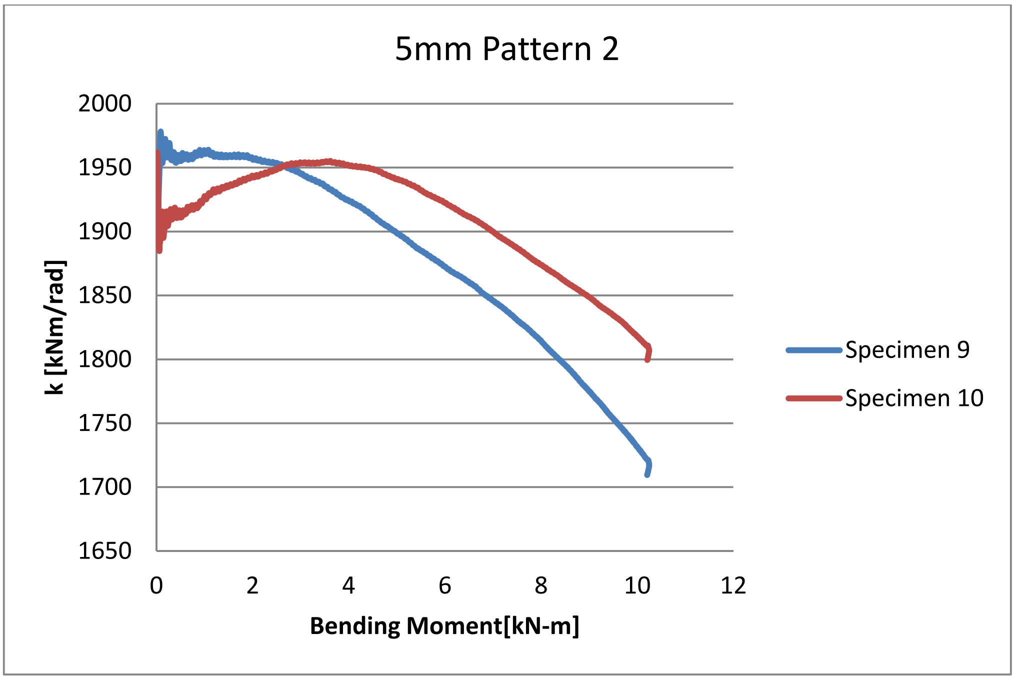


Figure 5-10 5mm L-shaped connection screw pattern 2

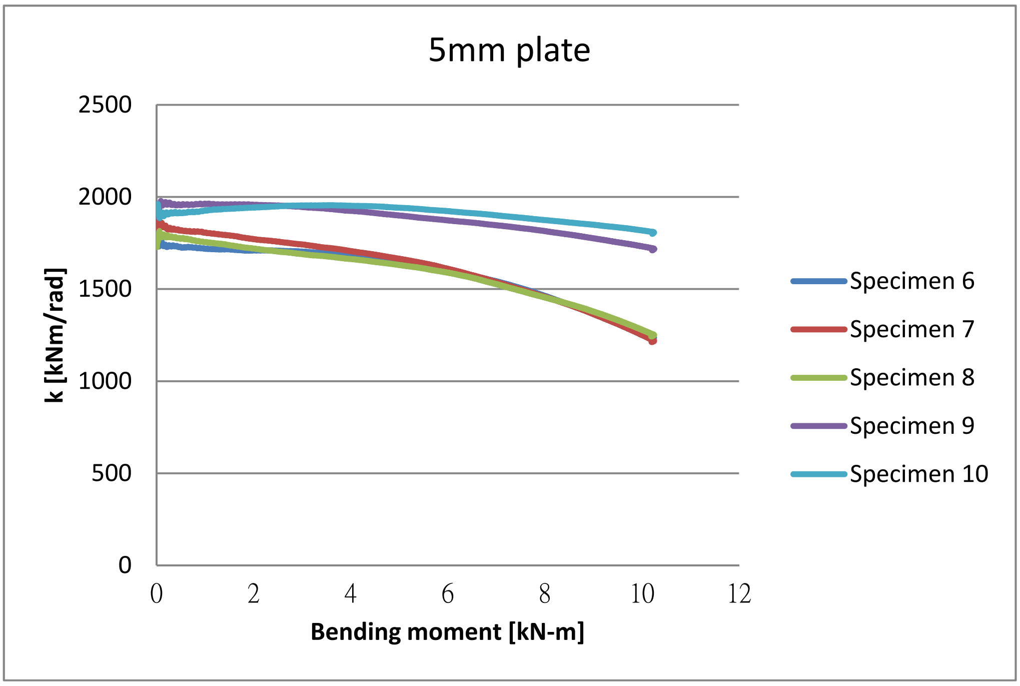


Figure 5-11 5mm L-shaped connection in screw pattern 1&2

From the test results, we can roughly see that the plastic deformation begins when the force applying reaching around 7000N for 3mm plate, 12500N for 5mm plate pattern 1 and 15000N for 5mm plate pattern 2. As it translates to moment- rotational stiffness graph, we see that 3mm plate reach its plastic deformation when the bending moment is at 0.94 with k= 1293, 5mm plate pattern 1 at moment is 3.08 with k=1738, and finally 5mm plate pattern 2 moment is 4.11 with k =1950. The force-deformation graph of each specimen can be found in appendix 4.

It can be concluded that increasing the thickness of connection plate and increasing the bolts number can largely increase the elastic phase of the plate, which results in having higher moment capacity for this beam-column connection.

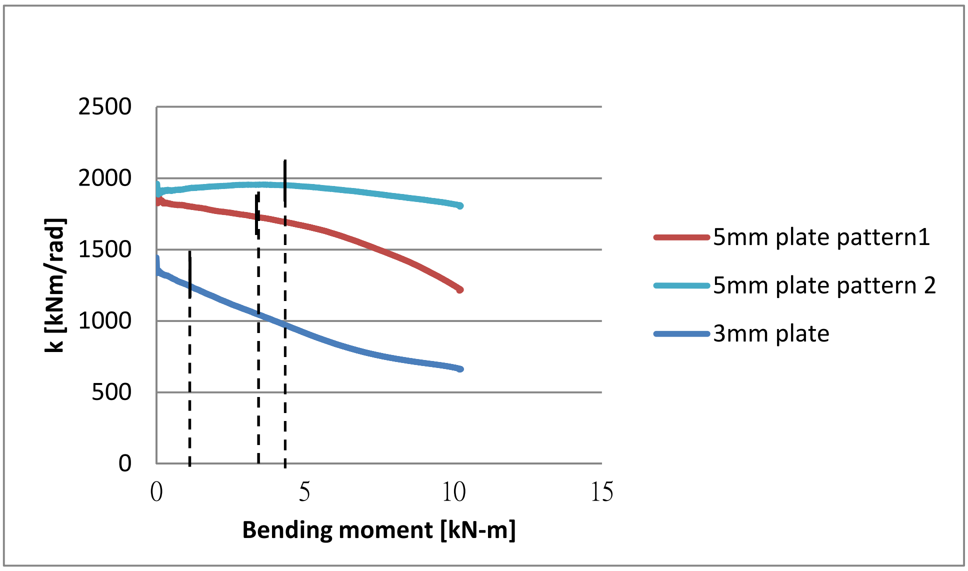


Figure 5-12 The bending moment and k when plastic deformation occurs in 3 types of specimens

5.4.1 The location of rotation point

The reason to identify the rotation point of the model is to find out the length of the actual arm of the beam and column and to give a more accurate result to the calculation.

In the test, the location of rotation point is further confirmed from the results. The method to find the rotation point is to use the screenshot of the video footage of the tests and trace the line to find it. First, the photo of starting position and the end position of the specimen in each test are captured. And in order not to influence by the distortion caused by the camera lens, the photo is adjusted in Photoshop by using the distortion correction. To find the precise coordinate of the center point of each green stickers on the test models, the processed pictures are then put in a program OCV3, a program developed to define center point of certain image, then the excel sheet of coordinated are defined. The coordinates of the center of these green dots were put into AutoCad to find the rotation point. First, to identify the rotation of the specimen, the fixing at the bottom of the machine is regarded as a rotation point for the lower beam, and as two sets of coordinates overlapped, the points of lower beam in the second photo is rotated to the same location as the one in the first photo. At this point, the rotation for the upper beam can be easily recognized. Then the points in the first and second photo are connected as a line, and then draw a perpendicular line to it. The location where those perpendicular lines intersect is where the rotation point of the specimen is.

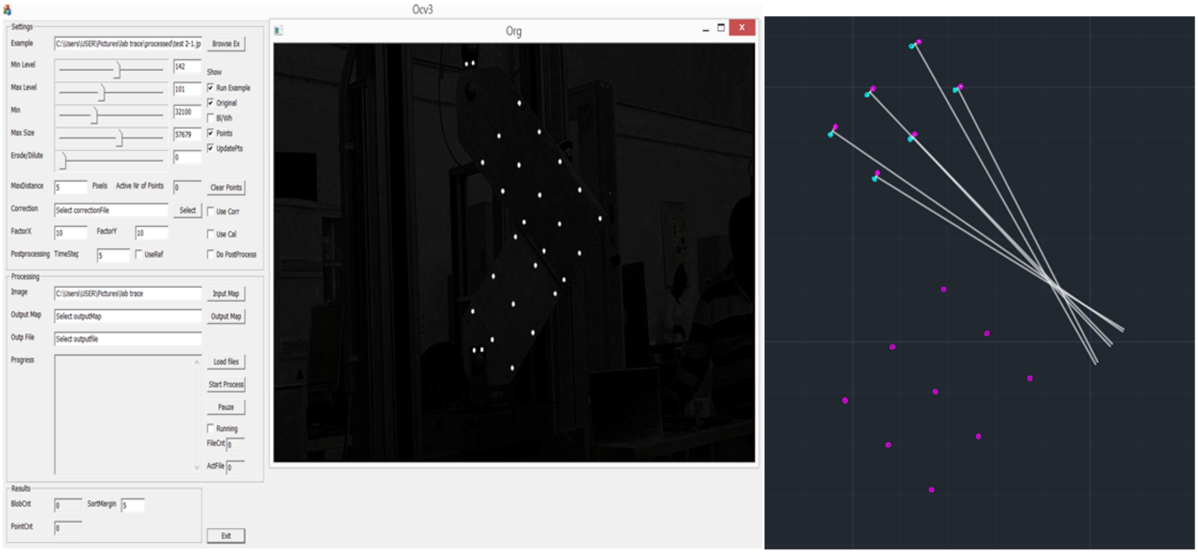


Figure 5-13 The process of finding the location of rotation point

From the results of 10 tests performed, it is showed that the rotation point is located around the top-right corner of the beam. It shows no difference where the location is regarding different thickness of the L-shaped connection used or the different screw- patterned performed. As a few more pictures are captured in the same test, it is showed that the rotation point is keep moving along the test, and the movement seems to be going to the corner side of the model. Moreover, the location of the rotation point also further confirms and explains the deformation pattern of the connection. The plastic deformation of the connection becomes bigger as it is further away from the rotation point.

As the rotation point is found, the length of the arm can be defined in the FEM in order to compare with the test results.

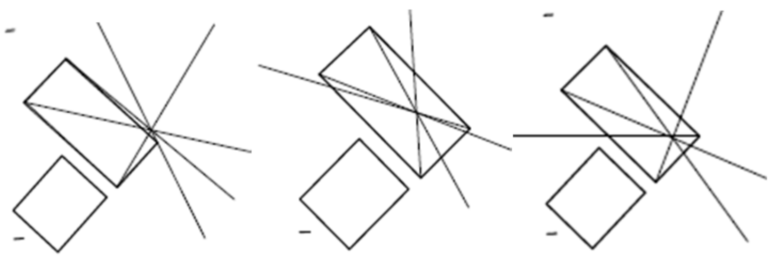


Figure 5-13 Location of rotation point in specimen 3mm, 5mm pattern1 &2

5.4.2 The deformation pattern and damage pattern

From the screws damage record, it shows that the 3mm and 5 mm plate in the same screws pattern has the similar pattern on the damage in screws. They both show the clear damage occurred in the first 2 rows of screws in the far end from corner and the center line of both side of the plate.

In 3mm plates, the damage of screws mainly occurs at the first two rows at the far end from the corner and the centerline of both plates. This can be explained by the movement of the upper two beams and the lower beam, since the lower plate has clockwise rotation, so at the upper side of the connection it shows a relatively upward movement; and in the lower side of the connection plate, it shows an small inward deformation, although it is not very visible to see the deformation, but from the clear damage pattern of centerline screws, the movement can be proved. Secondly, the deformation appears larger at the far end from the corner and so does the screw damage pattern, it describe the fact that it is further from the rotation point of the model.

In 5mm plates, the damage pattern remains similar to the 3mm specimens, but has smaller damages. It indicates that although the thickness of the plates is larger, the movement of the upper beams and lower beam are still significant to see from the small deformation and the damage pattern of the screws.

After seeing this damage patterns of 3mm and 5 mm plates and the identical test results of the first three 5 mm plates. It is decided to choose another screws pattern to be tested, an extra row of screws are added between the first row and second row of screws at the far end from corner on both side of plate. Since the extra screws are added to where the most deformation occurs, the 5mm plate in pattern 2 have barely any damage in screws and very small deformation visible. The complete screw damage record of each specimen can be found in appendix 5.

From the damage of screws record and deformation pattern, it can be concluded that the increase in thickness of L-shaped connection and adding more screws at the far end from the corner can reduce the movement of the beams and increase the stiffness of the connection.

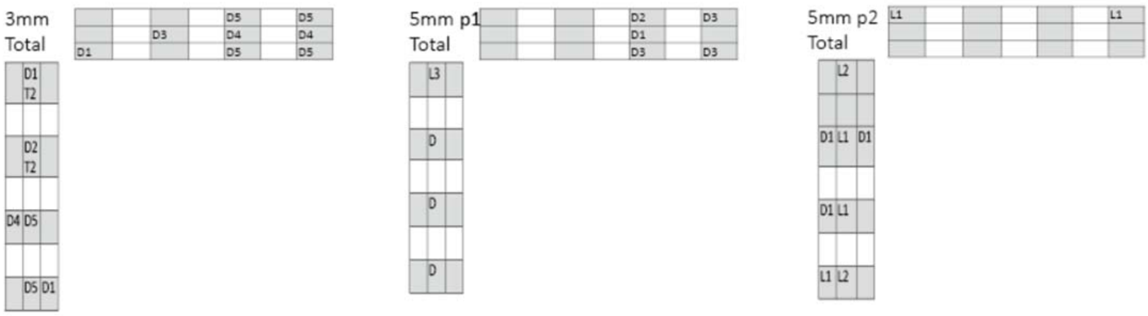


Figure 5-21 Screws damage pattern

Figure 5-14 Deformation of the 3mm L-shaped connection (1) Upper side (2)Lower side

Figure 5-15 Deformation of the 5mm L-shaped connection pattern 1 (1) Upper side (2) Lower side

Figure 5-16 Deformation of the 5mm L-shaped connection pattern 2 (1) Upper side (2) Lower side

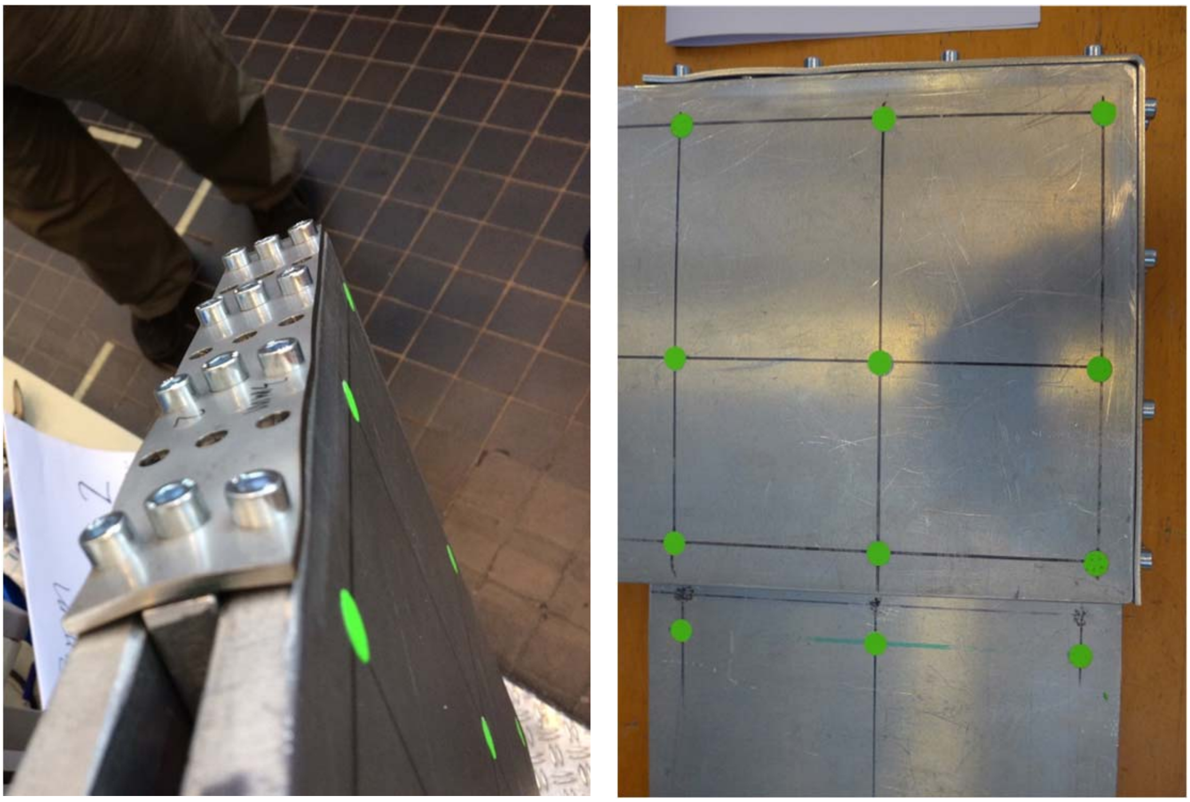


Figure 5-17 Deformation of the 3mm L-shaped connection (1) Upper side (2) full view

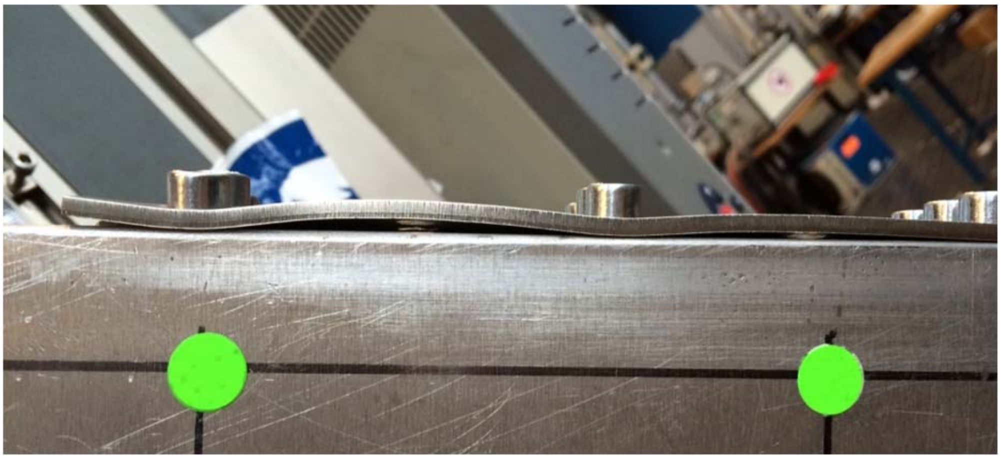


Figure 5-18 Deformation of the 3mm L-shaped connection side view

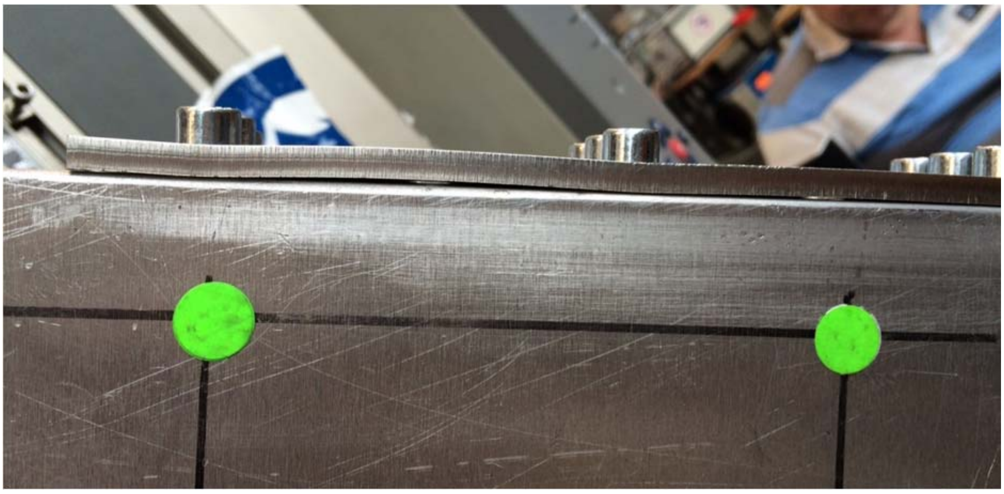


Figure 5-19 Deformation of the 5mm L-shaped connection pattern 1, side view

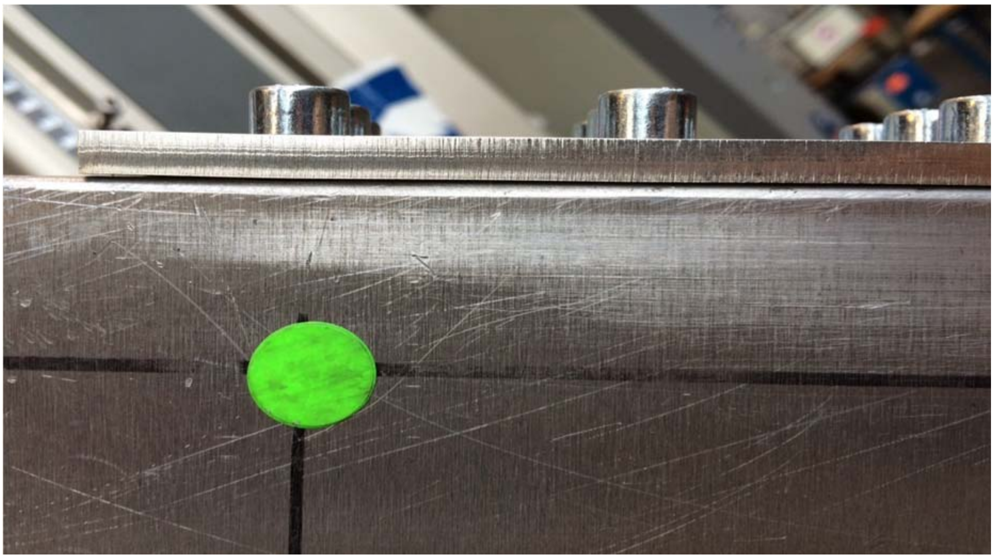


Figure 5-20 Deformation of the 5mm L-shaped connection pattern 2, side view

5.5 Test results comparison with FEM

To compare the lab test results with FEM, the model is made with 0.53m for both beams, which is the length from rotation point to the point where the force is applied in the physical lab model, according to the location of rotational point found previously. The rotation stiffness applied in the FEM is according to the test results of specimen 7, due to it is one of the three identical results in the 10 sets of tests. We use 5KN as the base point as it is mentioned previously. The values of rotation stiffness are chosen from when applied force is 6KN,7KN , 8KN, 9KN, 10KN,15KN, 20KN,25KN,30KN in the test respectively.

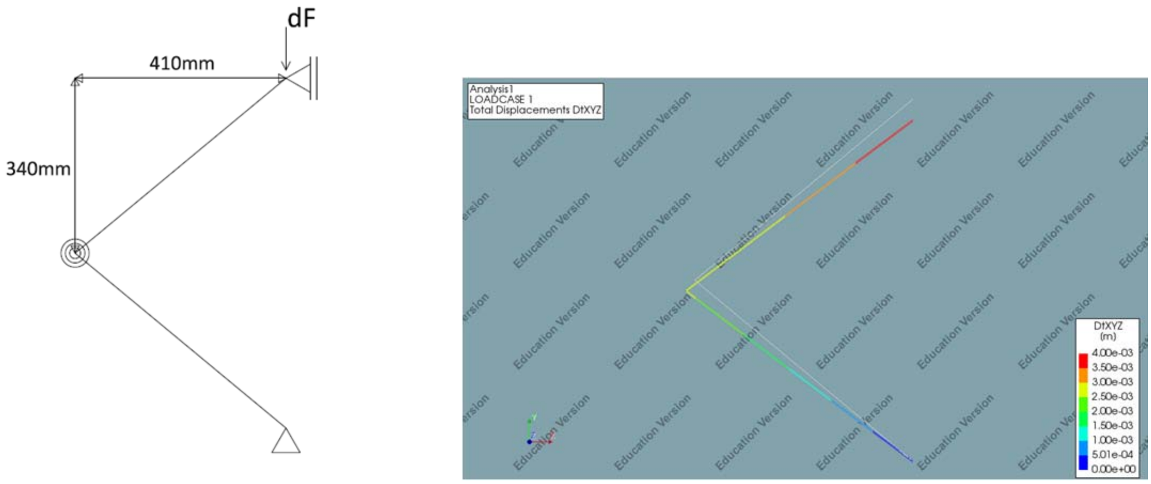


Figure 5-22 FEM set up and results

F [N]	K [kNm/rad]	Deformation[m] (Lab test)	Deformation [m] (FEM)	%
1000	1820	9.19×10^{-5}	1.33×10^{-4}	71
2000	1811	1.85×10^{-4}	2.44×10^{-4}	76
3000	1798	2.82×10^{-4}	3.63×10^{-4}	78
4000	1786	3.78×10^{-4}	4.81×10^{-4}	79
5000	1768	4.77×10^{-4}	6.01×10^{-4}	79
10000	1702	9.85×10^{-4}	1.21×10^{-3}	81
15000	1600	1.57×10^{-3}	1.91×10^{-3}	82
20000	1441	2.33×10^{-3}	2.77×10^{-3}	84
25000	1211	3.45×10^{-3}	4.00×10^{-3}	86

Table 5-23 The results comparison from Lab test and FEM

From the Figure 5-23, we can see that in the same rotation stiffness and applied force the deformation from the lab is always smaller than the FEM results. However, the similarity percentage of two data is rising as the applied force gets bigger. The reason behind it can be that the L is a changing value along the test process but we only take a single value for the calculation for k.

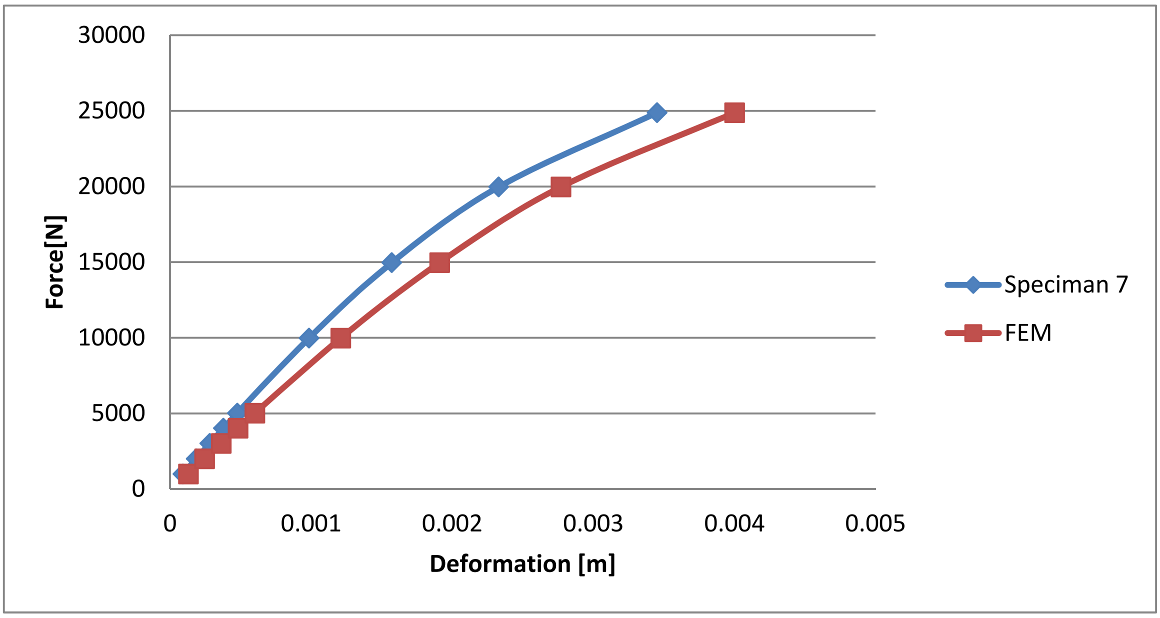


Figure 5-24 Comparison of lab model and FEM in applied force and deformation

5.6 Comparison with adhesive connection test results

The adhesive connection compared here is the application used in Dresden pavilion, the adhesive connection is made of acrylic based adhesive, more detail about the glass building case study can be found in chapter 2.6. Before the building construction some deformation tests were performed, from the results *(Weller, 2010)* as shown below, the test results presented in the paper is translated to an equation that is allowed us to compare the results from our own test. The goal is to compare the rotational stiffness k. The set up for the adhesive connection test was two 250x750mm glass beam and column with an overlapping area of 250x250mm by transparent adhesive, the column clamped and the force is applied at the end point of the glass beam. And it is coincidently that the dimension of the glass beam and column in this case is similar to the specimen we have, which is 250x670mm with an overlapping area of 250x250mm in our test.

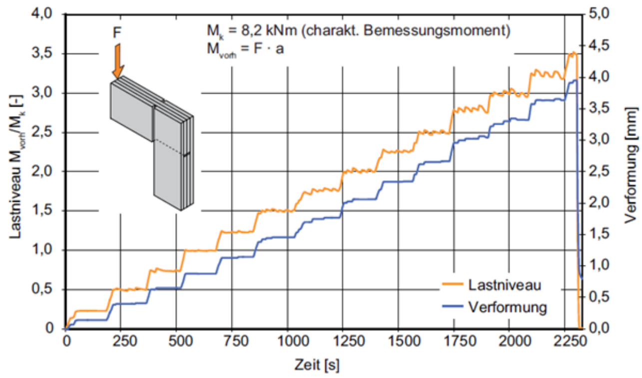


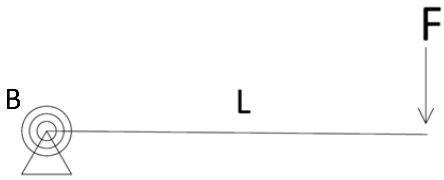
Figure5-25 Loading test set up (Weller 2010)

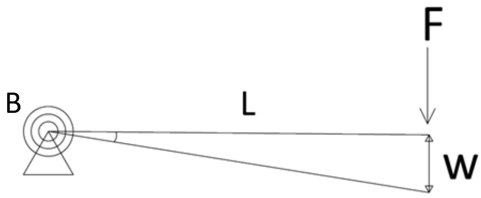
Figure 5-25 Verification of loadbearing capacity: Load and displacement versus test duration (Weller 2010)

5.6.1 Method

The method developed is translated from the test set up done in *Weller 2010.* Here F is the applied force in the test, L the length of both beam and column, which is a from the graph, and θ is the rotation angle according to point B, and w is the displacement of the beam. Form the test setup showed in the photo, the model is more like a cantilever beam with a semi-rigid support. The assumption is that the deformation of the beam is small, therefore it is neglected in the calculation. Only the displacement caused by rotation spring is taking into account in the total displacement of the whole model.

The data chosen are from the graph of test results of each middle point of each relatively flat line to be the number for the input in the formula.





Angle change caused by rotational spring θ_r

$$\theta_r = \frac{M}{k} = \frac{FL}{k}$$

Displacement caused by rotational spring W_r

$$W_r = \theta_r \cdot L = \frac{FL^2}{k}$$

The rotational stiffness k

$$k = \frac{FL^2}{W_r}$$

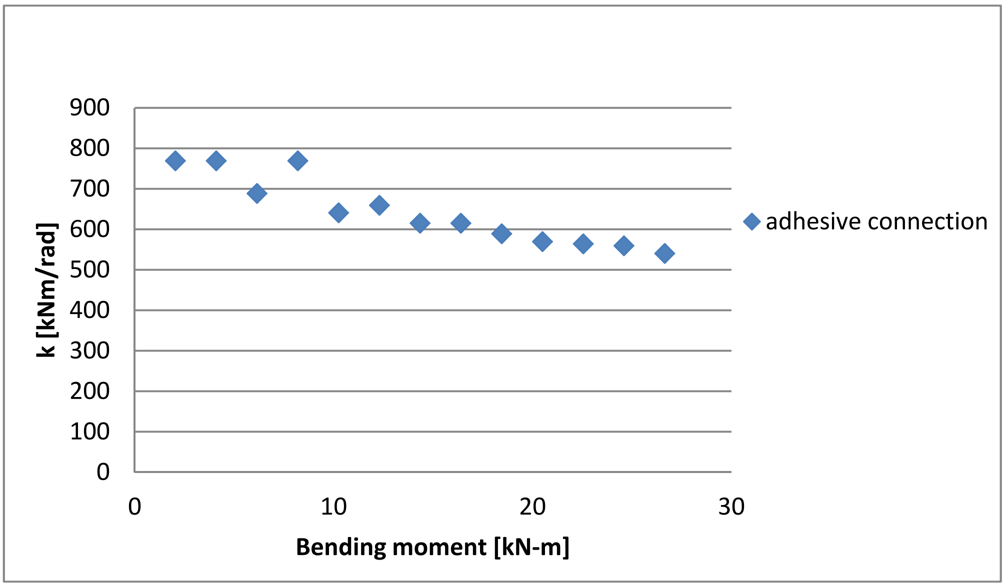


Figure5-26 Bending moment and Rotational stiffness k of adhesive connection

5.6.2 Adhesive connection and L-shaped connection rotation stiffness comparison conclusion

From the results, it clearly indicates that L-shaped connection has higher rotational stiffness then adhesive connection. However, the adhesive connection has a more gradual reduction in the level of rotational stiffness as the moment goes bigger compare to the L-shaped connection designed.

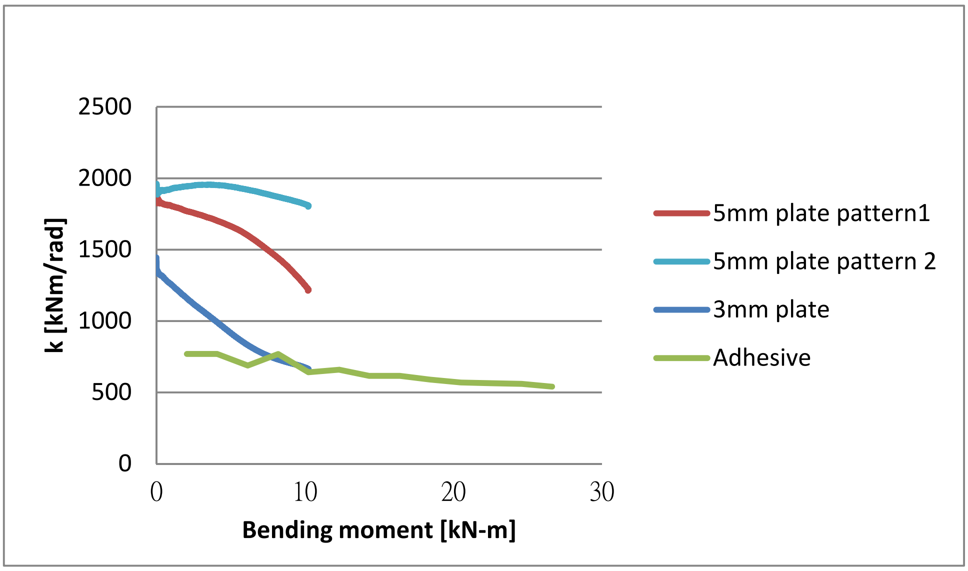


Figure 5-27 L-shaped connection and adhesive comparison in k and bending moment

5.7 Conclusion

From the lab test to find out the rotational stiffness that the current L-shaped connection design can provide and the location of rotation point. It can be concluded that as the thickness of the connection plates goes higher the initial rotation stiffness is bigger and the reduction of the rotational stiffness is more gradual. And from the confirmation of the location of rotation point, it is also described the deformation patterns of the plate. Finally, from the comparison of the L-shaped connection and adhesive, it can be concluded that L-shaped connection has much higher initial rotational stiffness k, whereas the adhesive has more constant rotational stiffness but a smaller one.

Chapter 6

Design process of a glass portal frame with L-shaped connection

6.1 The goal for new design process

In this chapter, the design procedure of a glass portal frame will be discussed and compared between the original design procedure and the design procedure when using L-shaped connection. The goal for the new design procedure is hoping to integrate this semi-rigid L-shaped connection into the design procedure to achieve a beam with desired height in a more easy way. By introducing rotational stiffness k in the procedure, the joint design is not just an estimation of either hinge or rigid joint anymore; it will give more precise information on what to expect on the structural behavior and to design a more optimal section of glass beam.

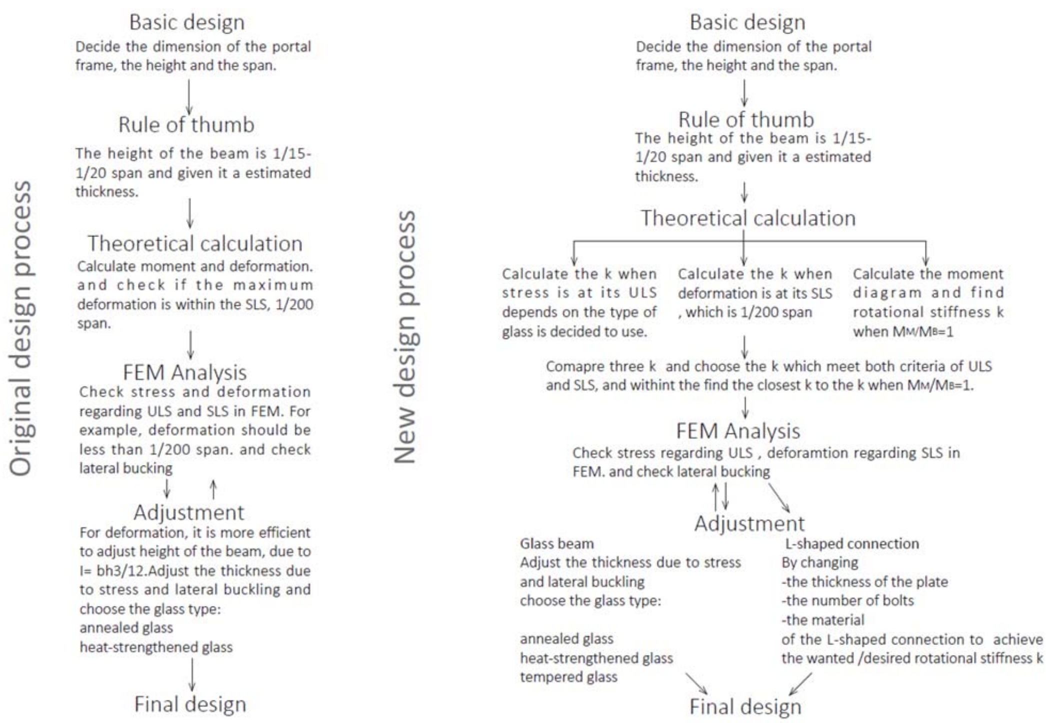


Figure 6-1 Original and New design process comparison

6.2 The original glass portal frame design process

The original glass portal frame design procedure that I categorized here is based on the reference the glass building case studies (Bijster, J., Noteboom, C., & Eekhout, M. 2016), the steel portal frame design cases, and the knowledge I learned from the course Technology of structure in master program in TU Delft.

Traditionally, the calculation for the dimension of the glass beam depends on the span of the beam. It is advised that the height of the beam is 1/15-1/20 of the span and give it an estimated thickness. For the thickness, according to the reference in the glass design, it is usually 8mm to 15mm for a single sheet of glass and the glass beam should contain at least 3 sheets in order to have 2 sacrificial glass panels on the outside when certain damage occurs. After this stage, it is time to check the peak stress and the deformation of the glass beam in FEM. The maximum deformation should not exceed 1/200 of span length, according to the SLS (service limit state) of beam design. When exceeding the limit of deformation and stress, it is more efficient to increase the height of the beam, due to the fact that h has bigger influence on the second moment of inertia is $bh^3/12$. At the same time, it is important to check the peak stress of the glass beam to determine what type of glass to use, ranging from the highest tension resistant fully-tempered glass to heat-strengthen glass and annealed glass. At this stage, the safety measure needs to be taken into consideration when choosing glass type. With the estimated thickness of glass beam, if a beam is too slender, we can then check the FEM to see if lateral buckling occurs then decide if adjusting the thickness of the panel is necessary.

6.3 The new design procedure of glass portal frame when using L-shaped connection

After the research and analysis about the relationship between rotational stiffness k and the glass portal frame, it is suggested that rotational stiffness k can be one of the factors to influence the design of the glass beam and be integrated in the glass portal frame design process.

In order to get the smallest beam height in a glass portal frame when using this semi-rigid L-shaped connection, the first step is to define the M_M/M_B ratio, as it mentioned in the earlier chapter, that only when

$$\frac{1}{2} > \frac{h \cdot I_B}{s \cdot I_C}$$

Then it is possible to have M_M/M_B =1. When the span and the height of a glass portal frame is decided, the next step is to define the I_B/I_C ratio. For a regular case when applying L-shaped connection, the thickness of the beam is twice the thickness of the column and now we have the h_B/h_C ratio. According to the rule of thumb, the height of the beam should be 1/15-1/20 span of the beam, so first use the 1/20 span as the ratio for the beam height. Once the beam height is set, the column width is defined too.

The next step is start calculating the moment diagram to find what is the rotational stiffness k when M_M/M_B=1 to achieve the goal of having a smallest beam. However, to fit in the limitation of SLS and ULS, it is also important to check what the k is at these criteria. Then chose the k which is the closest to when M_M/M_B=1 but within the SLS and ULS. One of the thing needs to be aware of is that the thickness of the glass , according to the reference in the laminated glass design, it is usually 6mm to 15mm for a single sheet of glass laminated and the glass beam should contain at least 3 sheets in order to have 2 sacrificial glass panels on the outside when certain damage occurs.

The rotational stiffness k at this scenario will be the rotational stiffness we are looking for in the L-shaped connection. To achieve this desired rotational stiffness k, the parameters of L-shaped connection, such as the thickness of plate, the number and the size of screws can be adjusted. And the last steps will be choosing the type of glass to apply according to the safety measures for this glass portal frame design.

6.5 Application of new design procedure to Helium Institute glass pavilion in Dresden

In the following structural analysis, the dimension of the glass building will use Dresden Helium institute as a reference; the reason to do so is because the result will also be compared with the structural analysis data from Dresden pavilion(Weller, 2010), which will be a comparison between adhesive connection and L-shaped connection on the same bases.

The Dresden pavilion is constructed with the glass portal frame of 4.4x2.5m. The glass beam and column has the same width of 250mm and composed of 4 layers of 12mm glass panels. However, in order to get the smallest beam height in a glass portal frame when using this semi-rigid L-shaped connection, the first step is to define the M_M/M_B ratio, as it mentioned in the earlier chapter, that only when

$$\frac{1}{2} > \frac{h \cdot I_B}{s \cdot I_C}$$

Then it is possible to have M_M/M_B =1. The following calculation shows that how the dimensions of the portal frame is derived. Here h is the height of the portal frame, s is the span, b_B and b_C is the thickness of the glass beam and column, and h_B and h_C is the height and width of the glass beam and column.

Since h=2.5, s=4.4

$$0.88 > \frac{I_B}{I_C}$$

$$0.88 > \frac{b_B \cdot {h_B}^3}{b_C \cdot {h_C}^3}$$

In the design using L-shaped connection the thickness of the beam will be twice the thickness of the column, in order to have the same composition of the beam and column for standardize manufacturing.

$$2 = \frac{b_B}{b_C}$$

$$0.44 > \frac{{h_B}^3}{{h_C}^3}$$

$$0.76 > \frac{h_B}{h_C}$$

The height of the beam is 1/15-1/20 span , so the smallest beam height h_B is 0.22m , while the h_C is 0.28m.

As the dimension of the glass portal frame is set, the rotational stiffness k can be found in the following calculation diagram when $M_M/M_B=1$. At the same time, the maximum deformation at SLS needs to be checked, in this case, it is 1/200 span, that is 0.22m; from the graph 6-3, the deformation is far from exceeding the limitation. Therefore, the desired rotational stiffness k for this portal frame design is 2300 kNm/rad. Here the parameters in L-shaped connection such as the thickness of the plate, or the numbers of screws on the plate can be adjusted to L-shaped connection to reach this desired rotational stiffness k=2300 kNm/rad. However, the L-shaped connection should have a slightly higher value of k for safety reason to prevent the reduction of rotational stiffness overtime, and this part will required further numerical studies on the L-shaped connection.

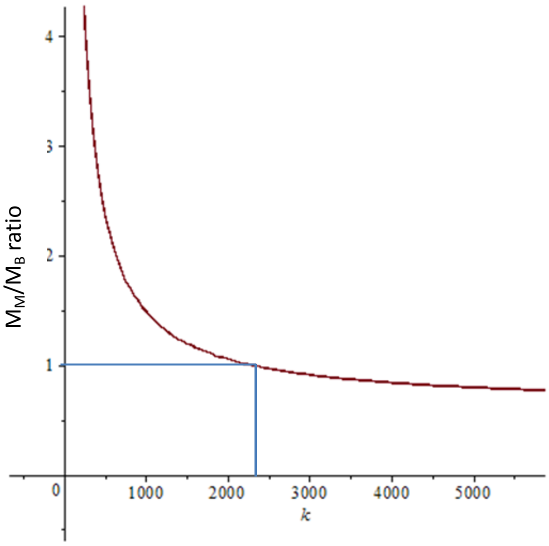


Figure 6-2 M_M/M_B *and k relationships*

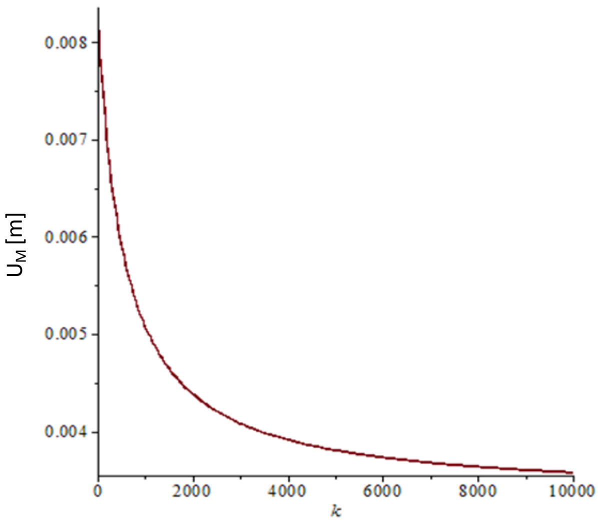


Figure 6-3 Deformation U_M *and k relationships*

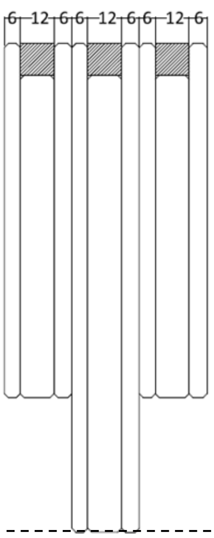
It is important to mentioned in the steps of estimated the thickness of the glass panels that for the L-shaped connection case, the layers of glass needs to be in odd number regarding the laminated reinforcement need to be in the center layer of glass, so the equivalent thickness will be different.

For equivalent thickness t^*

$$t^* = \sqrt[3]{(t_1)^3 + (t_2)^3 + (t_3)^3 + \cdots}.$$

The equivalent thickness is used for calculating the thickness of laminated glass when calculating deformation , stress and the properties related to moment of inertia. But the self weight will still be using the sum of adding all laminated layers t_{sum}.

$$t_{sum} = t_1 + t_2 + t_3 + \cdots.$$



	Thickness	Equivalent thickness
Beam	48mm	26mm
Column	24mm	13mm

Figure 6.5 Glass beam and column for L-shaped connection configuration

6.6 Conclusion

It is clear to see that the new design procedure integrating rotational stiffness k has the advantage of reducing the height of the beam and not to over design the connection. And as the L-shaped connection can be adjusted to its desired rotational stiffness by adjusting the parameters, it then can be found its initial rotational stiffness and its estimated reduction in k as force applied increases. However, the parameters relationship with the level of increase in rotational stiffness in L-shaped connection needs further research.

Chapter 7

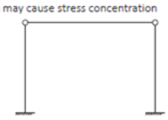
Comparison of existing all-glass building connection and L-shaped connection

For the glass beam-column connection, the existing connection are either bolted joint or adhesive joint, therefore, L-shaped connection is a new types of connection that will be applied on a laminated reinforcement in the glass.

The aim of this comparison table is to provide architects and engineer an overview of the advantages and disadvantage of different beam-column connections for glass portal frame, to help them understand what the options are and possibilities for the all-glass portal frame design.

7.1 Comparison of existing all-glass building connection and L-shaped connection

From the table of comparison below, the discussion is divided into the categories in the following paragraphs. The full page of the table can be found in Appendix 9.

	Dresden adhesive 	Apple v2 pin(mechenical fixing) 	Saddle connection 	L-shaped connection 
STRUCTURAL AND SAFETY	-Hinged / semi-rigid Pros - Constant value in rotation stiffness -Bridle joint method applied at beam-column connection to help remain structure integrity Cons -Perforamance totally rely on the quality of adhesive 	-Hinged Pros No moment capacilty at the hinge connection, so no need to worry about the reduction of rotational stiffness at the connection -Bridle joint method applied at beam-column connection to help remain structure integrity Cons - Holes need to be drilled in the glss beam, which may cause stress concentration 	-Semi-rigid Pros -Combined with reinforcement -No holes need to be drilled in glass Cons - Saddle does not contribute much 	-Semi-rigid Pros Combined with reinforcement -No holes need to be drilled in glass - Better post breakrage behavior with reinforced glass beam Cons 
BEAM-COLUMN CONNECTION TYPE	- Totally adhesive 	- Pin, mechenical fixing 	-Saddle with L-shaped plate fixes on the steel reinforcement laminated in glass. mechenical fixing 	-L- shaped plate fixes on the steel reinforcement laminated in glass. mechnical fixing 
CONSTRUCTION/ASSEMBLY	Pros -Use structural silicone to connect roof and facade, easy for installation. Cons -Requires onsite adhesive curing , which the temperature and the humidity will have influence on its structural perfromance - Labor intensive - Experienced labor , rely on labor technics - Torlerance problem?	Pros - Use mechenical fixing to connect roof and facade, less site environment sensitive	Pros -Easy to assemble the beam with saddle - Use mechenical fixing to connect roof and facade,less site environment sensitive	Pros - Use mechenical fixing to connect roof and facade,less site environment sensitive Cons - Need extra support before the coonection is applied

	Dresden adhesive	Apple v2 pin(mechenical fixing)	Saddle connection	L-shaped connection
TRANSPOTATION	- Standard size glass panel, which has no problem in transpotation	- Oversized glass panels has problem for transpotation	- Standard size glass panel, which has no problem in transpotation	- Standard size glass panel, which has no problem in transpotation
CONNECTION FACADE/ROOF	- Structural silicone 	- Embedded connection 	Embedded connection (suggest) 	- Embedded connection (suggest) 
AESTHETIC	- Adhesive connection is totally transparent	- With only mechenical pin fixing and small patch of embedded metal connection, the bulding is almost transparent	- With the metal saddle connection,it is totally not transparent at the beam-column overlapped area. therefore, as a whole building, it does not give the effect of transparent at all.	-With the L-shaped connection,it is transparent at the beam-column overlapped area. however, it has a bigger metal plate along the edges of beam and column. therefore , it provide a less transparency compare to Apple cube.
MAINTENANCE	- It can not be locally dissambled when one glass member is broken - Durability of the adhesive need to be ensured and tested	-It can be dissambled and replaced quickly when one glass member is broken	- it can not be easily replaced, due to the saddle need to be removed from top.	- it can be easily replaced, due to mechinal fixing
BENEFITS	-Provide total transparency -Bridle joint method provides safety - Relativley constant value of rotaional stiffness	-Provide high level of transparency - No need to worry about the reduction of rotaional stiffness at connection -Bridle joint method provides safety -Compare to adhesive joint, it is possible to replace and dissamble the glass member locally	- Applied with reinforced glass beam - Rotational stiffnessk can be estimated, which is beneficial for designing glass beam dimension and be integrated in the designing of L-shaped connection - Easy conestrcution with saddle element	-Rotational stiffnessk can be estimated, which is beneficial for designing glass beam dimension and be integrated in the designing of L-shaped connection -Compare to adhesive joint, it is possible to replace and dissamble the glass member locally - Provide high level of transparency

Figure 7-1 Comparison table of beam-column connections in glass building

7.2.1 Structural and safety

From the comparison table, the beam-column connection for the glass portal frame is designed to be hinge or semi-rigid connection. The bolted connection is a hinge for sure. However, the adhesive connection is initially designed as a hinge connection, but in reality it is a semi-rigid joint.

The existing glass portal frame structures in glass buildings, the beam and column are joint together in a bridle joint method, like the often seen wooden construction, regardless of the connection types used. The reason behind it is to ensure the integrity of the structure not to have total collapse if failure of connection happens.

Since glass is brittle, it is preferable not to drill holes in glass to cause stress concentration, therefore in this case, the adhesive and L-shaped connections are preferable. Adhesive connection as it was mentioned in chapter 2 that the quality of the adhesive and the curing process condition will largely influence the connection performance. To compare adhesive connection and L-shaped connection, it can be concluded that the L-shaped has a higher initial rotational stiffness, whereas the adhesive has lower rotational stiffness but with a more gradual reduction in rotational stiffness as force applied becomes bigger.

For the safety aspect, it shows that the bridle joint method applied with either bolted joint or adhesive joint can reduce the possibility of total collapse of the structure. As L-shaped connection is designed for applying on the reinforced glass beam, so for the beam itself, it has a better post-breakage behavior, and it is believed that with the fixing on the both sides of the connection plate, the total failure may not be happened that easily.

7.2.2 Construction

Although transparent adhesive connection is much preferred in a glass building in aesthetic perspective, it is much more labor intensive and environment sensitive when construct it onsite. The onsite adhesive curing is one of the most concerned issues; the curing process is sensitive to the temperature and humidity, which will influence the structural performance of the building. And it also needs skilled and experienced workers to perform the adhesive application and curing, due to the fact that it is not easy to apply adhesive in a thin gap between glass panes without bubbles in a planner joint. For mechanical fixing, the connection pieces embedded in glass panels will be prefabricated and constructed on site, which the tolerance will be already considered in the design of mechanical connection to make sure that the installation onsite will be successfully processed.

For the installation process, the structure with bridle joint method, it is relatively easy to have the beam resting on both columns before connection is applied. The portal frame with saddle connection and L plate can also be constructed easily with the beams resting on the saddle joint before the set of connection is fixed to the reinforcement in the glass members. The glass portal frame with L-shaped connection, however, will need a temporary structure to keep the beams and columns in place prior the application of the connections.

7.2.3 Maintenance

For maintenance, mechanical fixing is usually better than only adhesive fixing. Adhesive fixing has a major problem of not possible to dissemble and replace the glass members. As for mechanical fixing, the glass members can be easily replaced by dissemble the connection and replace a new glass member and reconnect again. Furthermore, the quality of adhesive is also a big issue in the maintenance, the durability of the adhesive needs to be tested if it can have the same performance as it is in the next 15 or 20 years, since the glass structure is totally rely on the adhesive performance.

7.2.4 Transportation

As the glass production technology has become more advanced and some larger autoclave for tempering oversized glass panel has been built, it is possible to build the glass building with bigger glass panels from the original standard size 3.21x6m now up to 15x6m panels. Although produce such large glass panels is now possible, but the transportation issue is still one of the obstacle facing during the transportation of material and onsite assembly. The limitation for the largest size to transport in a lorry on road is 12x4m, therefore, using standard size glass panels like the Dresden pavilion or first version of apple cube will be more realistic for transportation.

7.2.5 Aesthetic (Transparency)

In this aesthetic category, the transparency will be the main focus to compare, due to the fact that transparency is the key reason to build in glass most of the time. The beam-column connection offers the most transparency will be the adhesive connection followed by the bolted connection, L-shaped connection and lastly the saddle connection with L plate. Comparing the bolted connection with the L-shaped connection, the bolted connection has the advantage of having less visible area than L-shaped connection from every perspective but just not in the front view of the portal frame. For the saddle connection with L plate, it is the least transparent in the above cases because it has a total block at the area where the beam and column overlapped.

7.2 Conclusion

The benefits of L-shaped connection is that it can be integrated in the reinforced glass beam, which can make good use of the embedded steel reinforcement section to have a better post-breakage behavior for the glass beam. In the aesthetic point of view, the connection can be quite compact by connecting glass beam, column, to reduce the visual disturbance and give a transparent view of the glass portal frame. In a structural point of view, since the rotational stiffness can be known by having laboratory test, the structural system and the design of the glass portal frame , for instance, its dimension and the type of glass used. And with the semi-rigid connection as this L-shaped connection provides, the joint design would be more efficient and not over designed. For construction aspect, compare to the totally transparent adhesive connection, this L-shaped connection is possible for replacing and dissemble the glass member locally. All in all, the L-shaped connection has the potential of developing into a connection product for the future all glass portal frame in real life.

Chapter 8

Conclusion and recommendations

8.1 Conclusion

The starting point of this research was to find out what the potential of this L-shaped connection regarding offering a semi-rigid connection to a glass portal frame design. During the process, literature studies about glass elements, connection types for structural glass and rotational stiffness have been done; parameters of glass portal frame design and L-shaped have been defined, and sets of tests have been performed to find out the rotational stiffness and location of the rotation point. And finally, a design procedure for glass portal frame when applying L-shaped connection has been developed and verified in the case of Dresden pavilion.

From the lab test to find out the rotational stiffness that the current L-shaped connection design can provide and the location of rotation point. It can be concluded that as the thickness of the connection plates goes higher the initial rotation stiffness is bigger and the reduction of the rotational stiffness is more gradual. And from the confirmation of the location of rotation point, it is also described the deformation patterns of the plate. Finally, from the comparison of the L-shaped connection and adhesive, it can be concluded that L-shaped connection has much higher initial rotational stiffness k, whereas the adhesive has more constant rotational stiffness but a smaller one.

From the new design procedure for a glass portal frame developed to integrate L-shaped connection in the process, it shows rather efficient steps to get to the optimal joint design for a glass portal frame. From the new design procedure applied on the Dresden pavilion, it is clear to see that the new design procedure integrating rotational stiffness k has the advantage of reducing the height of the beam and not to over design the connection. And as the L-shaped connection can be adjusted to its desired rotational stiffness by adjusting the parameters, it then can be found its initial rotational stiffness and its estimated reduction in k as force applied increases. However, the parameters relationship with the level of increase in rotational stiffness in L-shaped connection needs further research.

The benefits of L-shaped connection is that it can be integrated in the reinforced glass beam, which can make good use of the embedded steel reinforcement section to have a better post-breakage behavior for the glass beam. In the aesthetic point of view, the connection can be quite compact by connecting glass beam, column, to reduce the visual disturbance and give a transparent view of the glass portal frame. In a structural point of view, since the rotational stiffness can be known by having laboratory test, the structural system and the design of the glass portal frame , for instance, its dimension and the type of glass used. And with the semi-rigid connection as this L-shaped connection provides, the joint design in a glass portal frame would be more efficient and not over designed. For construction aspect, compare to the totally transparent adhesive connection, this L-shaped connection is possible for replacing and dissemble the glass member locally. However, the detailed design of the L-shaped connection needs to be further developed and verify in different laboratory tests.

8.2 Recommendations

It is recommended that further research can be done in the future as following subjects.

- The numerical studies of L-shaped plate of rotational stiffness k when changing different parameters, such as plate thickness, screw number and size.
- The improvement on the reduction of rotational stiffness k to a smaller constant value.
- Improved version of the connection design based on the same connecting principle to the reinforced glass beam.

Appendices

Appendix 1

Maple sheet for glass portal frame calculation

> Parameters

$h := h:$
$s := s:$
$q1 := q1:$
$q2 := q2:$
$q3 := q3:$
$EIc := EIc:$
$EIb := EIb:$
$k := k:$

$$> t\_AB\_B := \frac{MB \cdot h}{3 \cdot EIc} + \frac{u}{h} - \frac{q1 \cdot h^3}{24 \cdot EIc};$$
$$t\_BC\_B := \frac{MB \cdot s}{3 \cdot EIb} - \frac{q2 \cdot s^3}{24 \cdot EIb} + \frac{MC \cdot s}{6 \cdot EIb};$$
$$dt\_B := \frac{MB}{k};$$
$$t\_BC\_C := \frac{MC \cdot s}{3 \cdot EIb} - \frac{q2 \cdot s^3}{24 \cdot EIb} + \frac{MB \cdot s}{6 \cdot EIb};$$
$$t\_CD\_C := \frac{MC \cdot h}{3 \cdot EIc} - \frac{u}{h} - \frac{q3 \cdot h^3}{24 \cdot EIc};$$
$$dt\_C := \frac{MC}{k};$$

$$t\_AB\_B := \frac{1}{3}\,\frac{MB\,h}{EIc} + \frac{u}{h} - \frac{1}{24}\,\frac{q1\,h^3}{EIc}$$
$$t\_BC\_B := \frac{1}{3}\,\frac{MB\,s}{EIb} - \frac{1}{24}\,\frac{q2\,s^3}{EIb} + \frac{1}{6}\,\frac{MC\,s}{EIb}$$
$$dt\_B := \frac{MB}{k}$$
$$t\_BC\_C := \frac{1}{3}\,\frac{MC\,s}{EIb} - \frac{1}{24}\,\frac{q2\,s^3}{EIb} + \frac{1}{6}\,\frac{MB\,s}{EIb}$$
$$t\_CD\_C := \frac{1}{3}\,\frac{MC\,h}{EIc} - \frac{u}{h} - \frac{1}{24}\,\frac{q3\,h^3}{EIc}$$
$$dt\_C := \frac{MC}{k} \qquad (1)$$

$$> eq1 := t\_AB\_B + t\_BC\_B + dt\_B = 0;$$
$$eq2 := t\_BC\_C + t\_CD\_C + dt\_C = 0;$$
$$eq3 := \frac{q1 \cdot h}{2} + \frac{MB}{h} - \frac{MC}{h} - \frac{q3 \cdot h}{2} = 0;$$

$$eq1 := \frac{1}{3}\,\frac{MB\,h}{EIc} + \frac{u}{h} - \frac{1}{24}\,\frac{q1\,h^3}{EIc} + \frac{1}{3}\,\frac{MB\,s}{EIb} - \frac{1}{24}\,\frac{q2\,s^3}{EIb} + \frac{1}{6}\,\frac{MC\,s}{EIb} + \frac{MB}{k} = 0$$
$$eq2 := \frac{1}{3}\,\frac{MC\,s}{EIb} - \frac{1}{24}\,\frac{q2\,s^3}{EIb} + \frac{1}{6}\,\frac{MB\,s}{EIb} + \frac{1}{3}\,\frac{MC\,h}{EIc} - \frac{u}{h} - \frac{1}{24}\,\frac{q3\,h^3}{EIc} + \frac{MC}{k} = 0$$

$$eq3 := \frac{1}{2}\, q1\, h + \frac{MB}{h} - \frac{MC}{h} - \frac{1}{2}\, q3\, h = 0 \tag{2}$$

> solution := solve({eq1, eq2, eq3}, {MB, MC, u});
> assign(solution);

$$solution := \Big\{ MB = -\frac{1}{8}\, \frac{1}{2\, EIb\, h\, k + 3\, EIc\, k\, s + 6\, EIb\, EIc} \big(3\, EIb\, h^3\, k\, q1 - 5\, EIb\, h^3\, k\, q3 + 6\, EIc\, h^2\, k\, q1\, s - 6\, EIc\, h^2\, k\, q3\, s - 2\, EIc\, k\, q2\, s^3 + 12\, EIb\, EIc\, h^2\, q1 - 12\, EIb\, EIc\, h^2\, q3\big),$$
$$MC = \frac{1}{8}\, \frac{1}{2\, EIb\, h\, k + 3\, EIc\, k\, s + 6\, EIb\, EIc} \big(5\, EIb\, h^3\, k\, q1 - 3\, EIb\, h^3\, k\, q3 + 6\, EIc\, h^2\, k\, q1\, s - 6\, EIc\, h^2\, k\, q3\, s + 2\, EIc\, k\, q2\, s^3 + 12\, EIb\, EIc\, h^2\, q1 - 12\, EIb\, EIc\, h^2\, q3\big),$$
$$u = \frac{1}{48}\, \frac{1}{EIb\, EIc\, k} \big((5\, EIb\, h\, k\, q1 - 5\, EIb\, h\, k\, q3 + 2\, EIc\, k\, q1\, s - 2\, EIc\, k\, q3\, s + 12\, EIb\, EIc\, q1 - 12\, EIb\, EIc\, q3)\, h^3 \big) \Big\} \tag{3}$$

> MB − MC;

$$-\frac{1}{8}\, \frac{1}{2\, EIb\, h\, k + 3\, EIc\, k\, s + 6\, EIb\, EIc} \big(3\, EIb\, h^3\, k\, q1 - 5\, EIb\, h^3\, k\, q3 + 6\, EIc\, h^2\, k\, q1\, s - 6\, EIc\, h^2\, k\, q3\, s - 2\, EIc\, k\, q2\, s^3 + 12\, EIb\, EIc\, h^2\, q1 - 12\, EIb\, EIc\, h^2\, q3\big) - \frac{1}{8}\, \frac{1}{2\, EIb\, h\, k + 3\, EIc\, k\, s + 6\, EIb\, EIc} \big(5\, EIb\, h^3\, k\, q1 - 3\, EIb\, h^3\, k\, q3 + 6\, EIc\, h^2\, k\, q1\, s - 6\, EIc\, h^2\, k\, q3\, s + 2\, EIc\, k\, q2\, s^3 + 12\, EIb\, EIc\, h^2\, q1 - 12\, EIb\, EIc\, h^2\, q3\big) \tag{4}$$

> q1 := 1 :
  q2 := 0 :
  q3 := −1 :

$$EIc := 7 \cdot 10^5 \cdot \frac{0.05 \cdot 1^3}{12} :$$

EIb := EIc :

> simplify(MB);
  simplify(MC);

$$-\frac{0.1250000000\, (23333.33334\, h\, k + 35000.\, k\, s + 2.041666667\, 10^8)\, h^2}{5833.333334\, h\, k + 8750.000001\, k\, s + 5.104166667\, 10^7}$$
$$\frac{0.1250000000\, (23333.33334\, h\, k + 35000.\, k\, s + 2.041666667\, 10^8)\, h^2}{5833.333334\, h\, k + 8750.000001\, k\, s + 5.104166667\, 10^7} \tag{5}$$

> MB − MC;

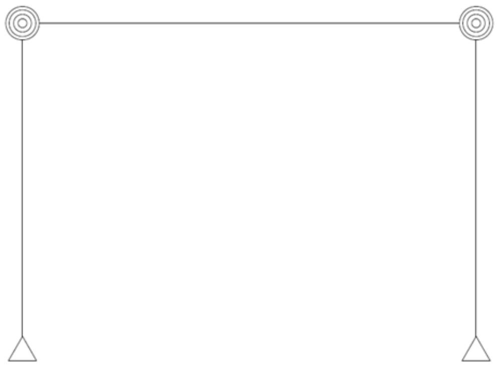
$$-\frac{1}{4}\, \frac{23333.33334\, h^3\, k + 35000.00000\, h^2\, k\, s + 2.041666667\, 10^8\, h^2}{5833.333334\, h\, k + 8750.000001\, k\, s + 5.104166667\, 10^7} \tag{6}$$

```
s := 10 :
k := 1000000 :
> MB;
MC;
u;
                    -12.50000000
                    12.50000000
                    0.08041964285                                   (7)
> w1 := q1·y^4/(24·EIc) + C1·y^3 + C2·y^2 + C3·y + C4;
phi1 := diff(w1, y);
M1 := -EIc·diff(phi1, y);
V1 := diff(M1, y);
      w1 := 0.00001428571428 y^4 + C1 y^3 + C2 y^2 + C3 y + C4
      φ1 := 0.00005714285712 y^3 + 3 C1 y^2 + 2 C2 y + C3
      M1 := -0.5000000000 y^2 - 17500.00000 C1 y - 5833.333334 C2
      V1 := -1.000000000 y - 17500.00000 C1                        (8)
> y := 0 :
eq4 := w1 = 0 :
eq5 := M1 = 0 :
> y := h :
eq6 := w1 = u :
eq7 := M1 = MB :
> solution := solve({eq4, eq5, eq6, eq7}, {C1, C2, C3, C4});
assign(solution);
      solution := {C1 = 0., C2 = 0., C3 = 0.01429821428, C4 = 0.}  (9)
> y :='y':
w1;
P1 := plot(w1, y = 0 ..h, color = cyan);
      0.00001428571428 y^4 + 0.01429821428 y
      P1 := PLOT(...)                                               (10)
> w2 := q2·x^4/(24·EIc) + C5·x^3 + C6·x^2 + C7·x + C8;
phi2 := diff(w2, x);
M2 := -EIb·diff(phi2, x);
V2 := diff(M2, x);
      w2 := C5 x^3 + C6 x^2 + C7 x + C8
      φ2 := 3 C5 x^2 + 2 C6 x + C7
      M2 := -17500.00000 C5 x - 5833.333334 C6
      V2 := -17500.00000 C5                                        (11)
> x := 0 :
eq8 := w2 = 0 :
eq9 := M2 = MB :
> x := s :
eq10 := w2 = 0 :
```

```
eq11 := M2 = MC :
> solution := solve({eq8, eq9, eq10, eq11}, {C5, C6, C7, C8});
assign(solution);
solution := {C5 = -0.0001428571429, C6 = 0.002142857143, C7 = -0.007142857140, C8 = 0.}   (12)
> x :='x':
w2;
P2 := plot(w2, x = 0 ..s, color = cyan);
      -0.0001428571429 x^3 + 0.002142857143 x^2 - 0.007142857140 x
      P2 := PLOT(...)                                               (13)
>
```

Appendix 2

FEM input for glass portal frame with spring connection



The finite element model of frame with rotational spring is modeled according to the example provided by DIANA FEA BV.

Material		
Glass	Density [kg/m^3]	2520
	Young's modulus [GPa]	70
	Poisson ratio	0.22
Dimension		
Frame	Span [m]	4.4
	Height [m]	2.5
Beam	Height of beam[m]	0.22
	Thickness[m]	0.048
	Equivalent thickness [m]	0.026
	Cross section[m^2]	0.00572
	Moment of Inertia[m^4]	2.31x10^{-5}
Column	Width of column[m]	0.28
	Thickness[m]	0.024
	Equivalent thickness [m]	0.013
	Cross section[m^2]	0.00364
	Moment of Inertia[m^4]	2.38x10^{-5}

Diana 10.1 software

Model type: 2D model

Geometry: Line element

Load: Line load

Support: Hinge support

Connection type: Spring connection

- Element class: springs and dashpots
- Mode: auto connect

Tying:

- Slave type: point
- Fixed translation: T1 &T2

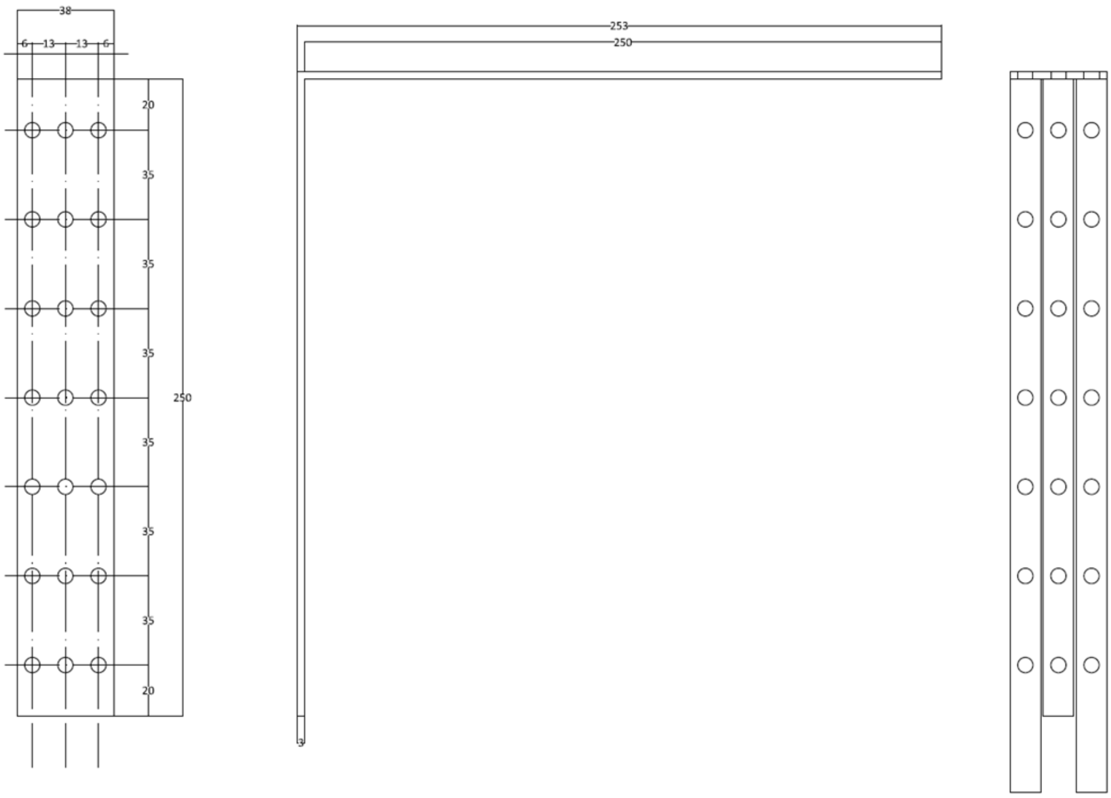
Mesh type: Hex/quad

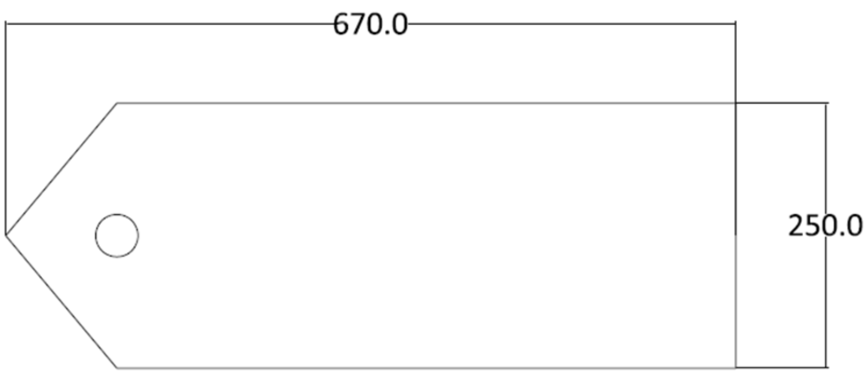
Analysis: Linear analysis

Appendix 3

Specimen design drawing and material properties

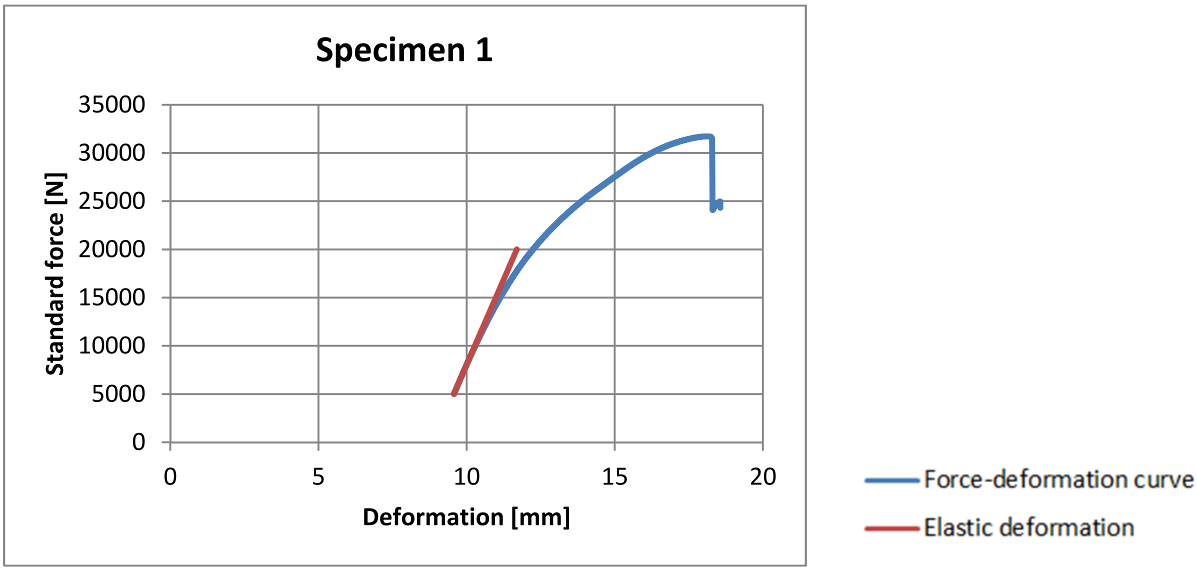
	Beam	L-shaped connection
Material	Aluminum	Stainless steel
Density	2700 kg/m^3	7680 kg/m^3
Young's modulus	70 GPa	180 Gpa
Poisson ratio	0.33	0.303
Thickness	3 &5 mm	12 mm

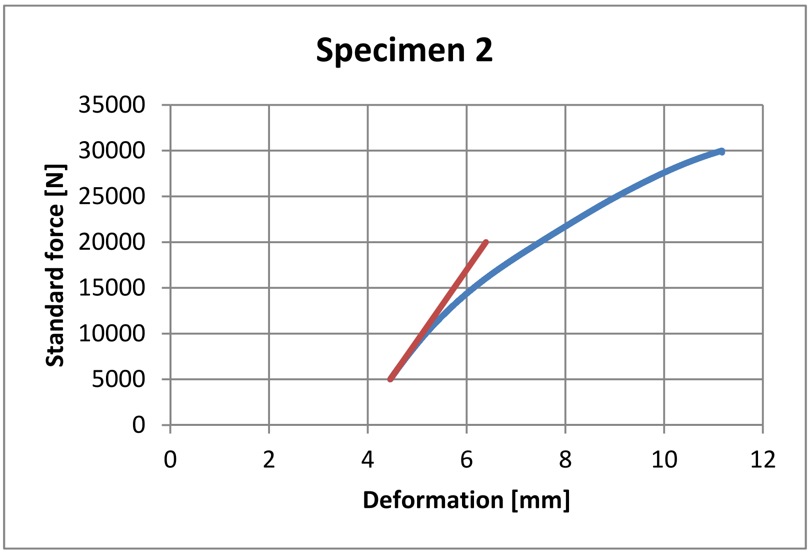




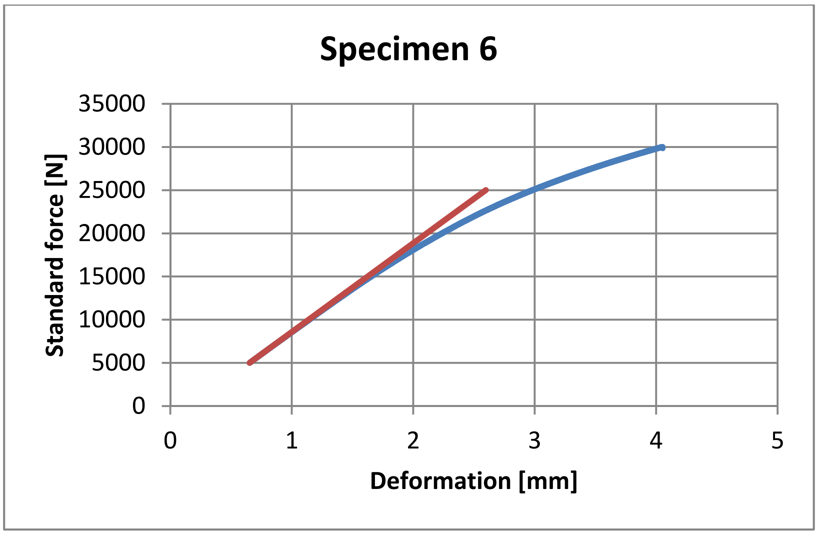
Appendix 4 Lab tests results

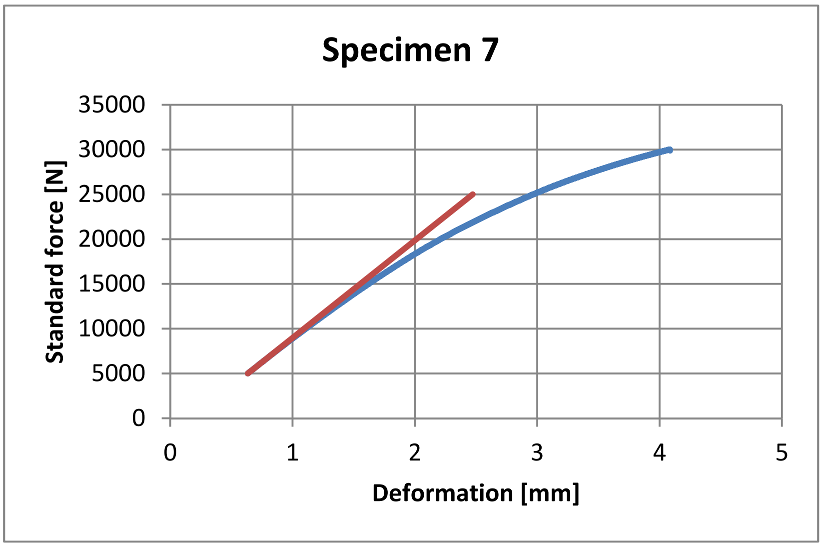
3mm plate (Specimen 1-5)

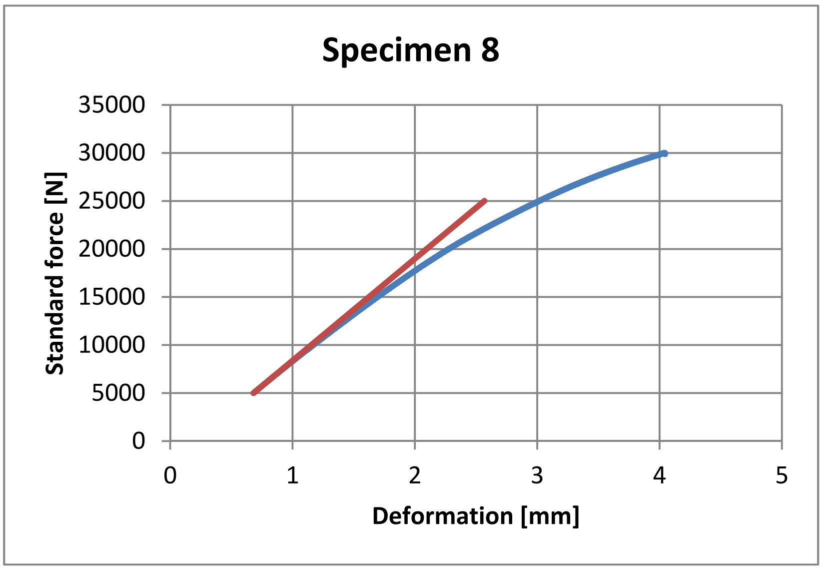




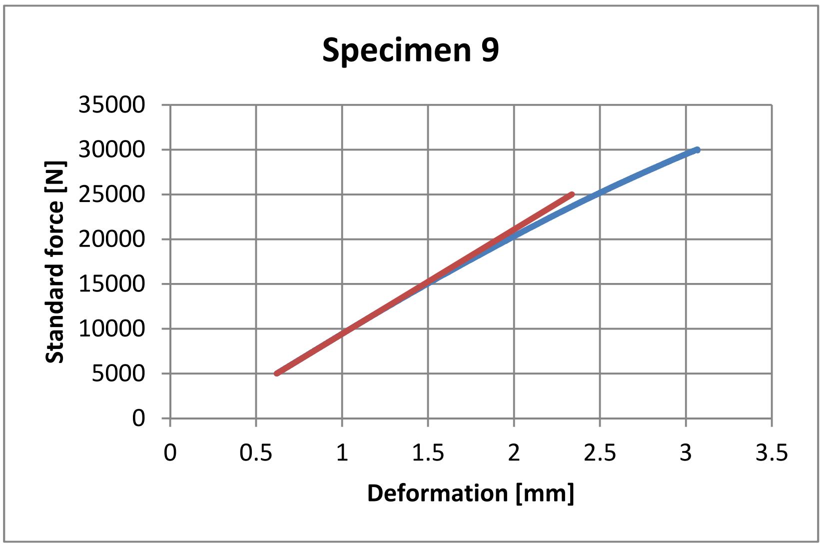
5mm plate, pattern 1 (Specimen 6-8)

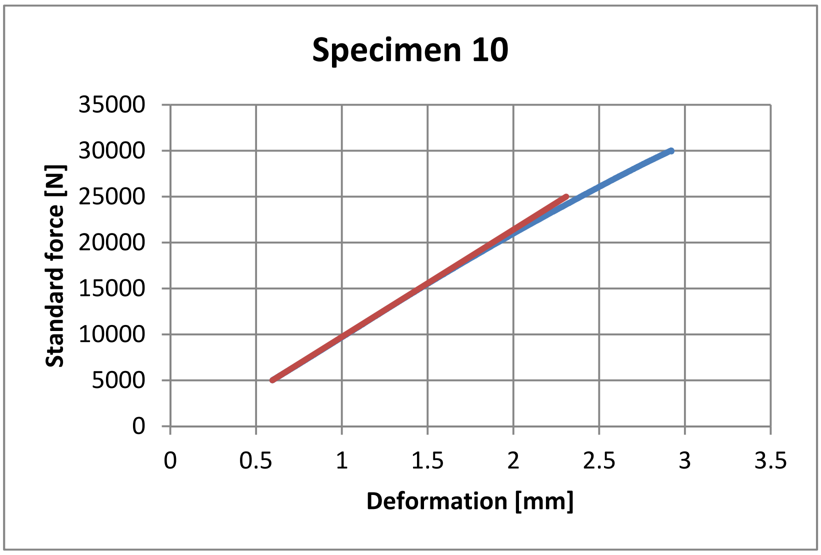






5mm plate, pattern 2 (Specimen 9-10)



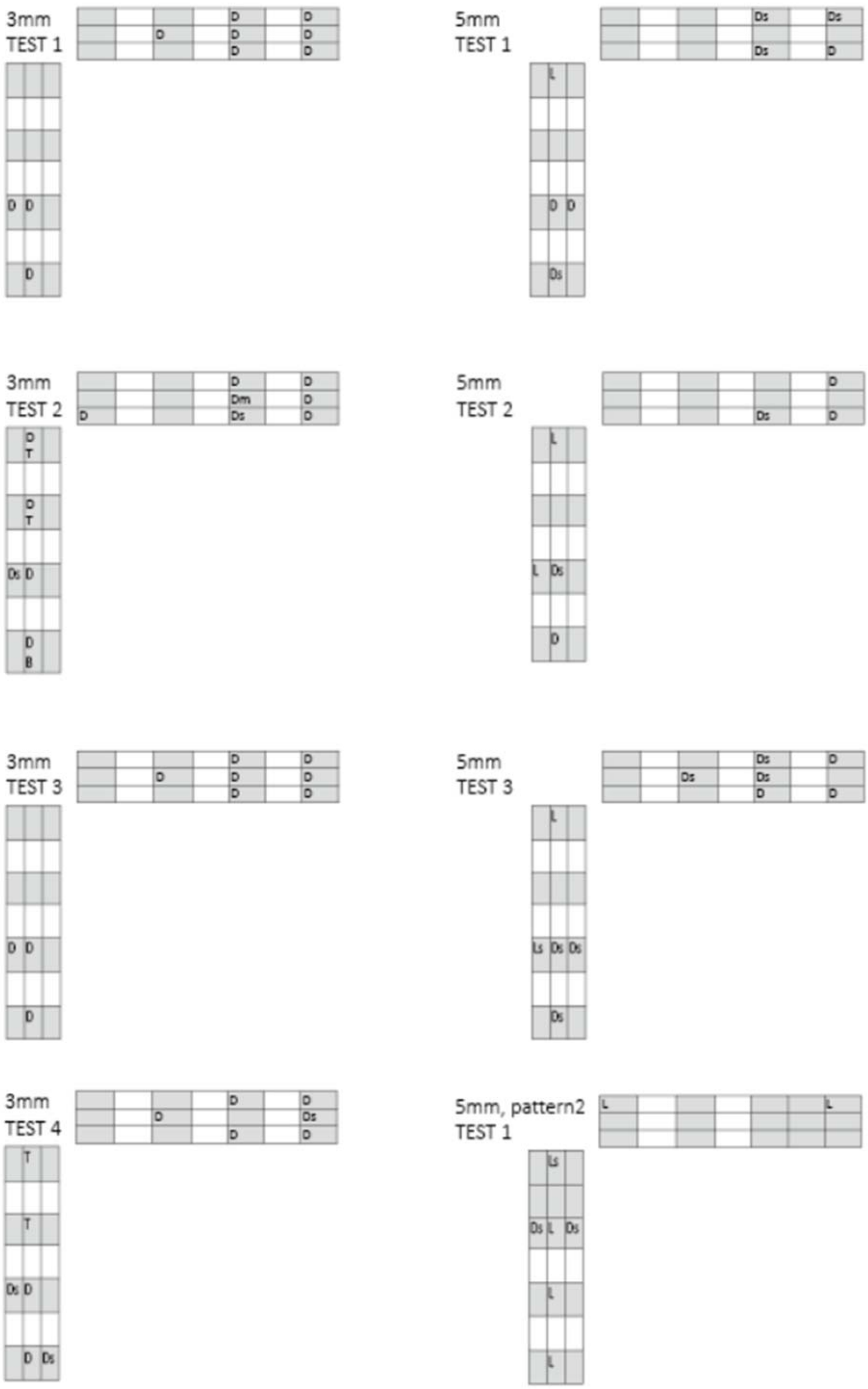

Specimen 10
Standard force [N]
35000
30000
25000
20000
15000
10000
5000
0
0
0.5
1
1.5
2
2.5
3
3.5
Deformation [mm]

Appendix 5

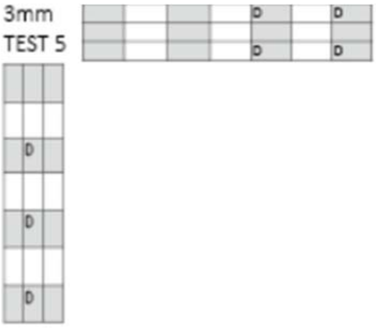
Screws damage record

D= Damage L=Loose

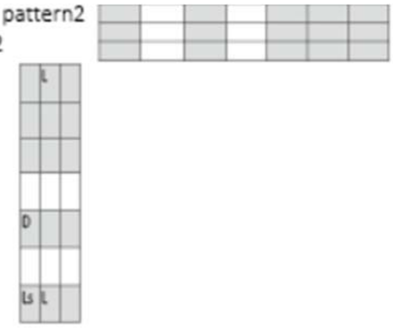
DS= Small damage T= Flat thread



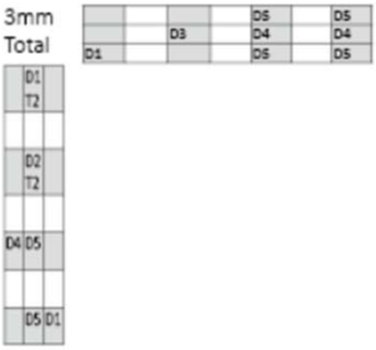
3mm
TEST 5



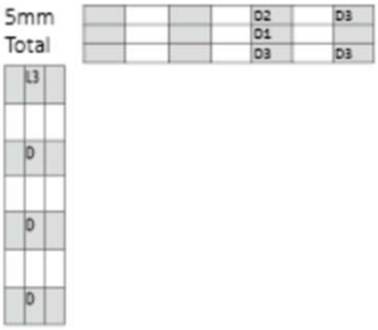
5mm, pattern2
TEST 2



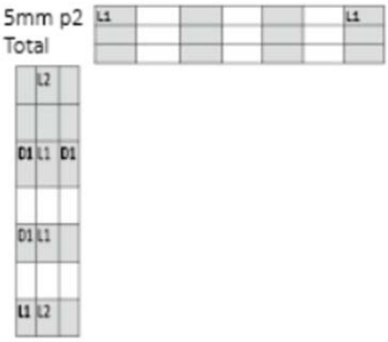
3mm
Total



5mm
Total

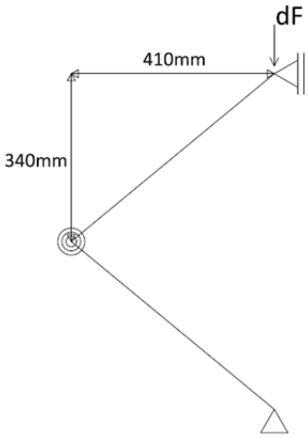


5mm p2
Total



Appendix 6

Comparison of Lab results and FEM



Material		
Aluminum	Density [kg/m^3]	2700
	Young's modulus	70
	[GPa]	0.33
	Poisson ratio	
Upper beam	Cross section[m^2]	0.006
	Moment of	
	Inertia[m^4]	
Lower beam	Cross section[m^2]	0.003
	Moment of	
	Inertia[m^4]	

Figure 3.7.2 FEM set up and input properties

Deformation	Standard force	Ux-U0	Fx-f0	Fx-f0	θ	M	K	FEM	LAB	%
[mm]	[N]	[m]	[kN]	[N]	[rad]	[kNm]	[kNm/rad]	[m]	[m]	
0.634343088	5000									
0.726246774	5995	0.000092	0.995125	995.125	0.000224	0.408001	1820.17	0.00013	0.0000919	71%
0.819508493	6996	0.0001852	1.99525	1995.25	0.000452	0.818053	1811.36	0.000244	0.0001852	76%
0.914616525	7998	0.0002818	3.014897	3014.897	0.000687	1.236108	1798.28	0.000363	0.0002818	78%
1.010919452	9001	0.0003781	4.018272	4018.272	0.000922	1.647492	1786.26	0.000481	0.0003781	79%
1.109292865	9999	0.0004767	5.015772	5015.772	0.001163	2.056467	1768.85	0.000601	0.0004767	79%
1.617647052	14959	0.000985	9.974147	9974.147	0.002403	4.0894	1702.11	0.00121	0.0009850	81%
2.204389095	19953	0.0015718	14.96591	14965.91	0.003834	6.136023	1600.54	0.00191	0.0015718	82%
2.961191177	24960	0.0023285	19.96911	19969.11	0.005679	8.187337	1441.61	0.00277	0.0023285	84%
4.085888386	29885	0.0034515	24.87463	24874.63	0.008418	10.1986	1211.46	0.004	0.0034515	86%

Table of FEM and Lab results

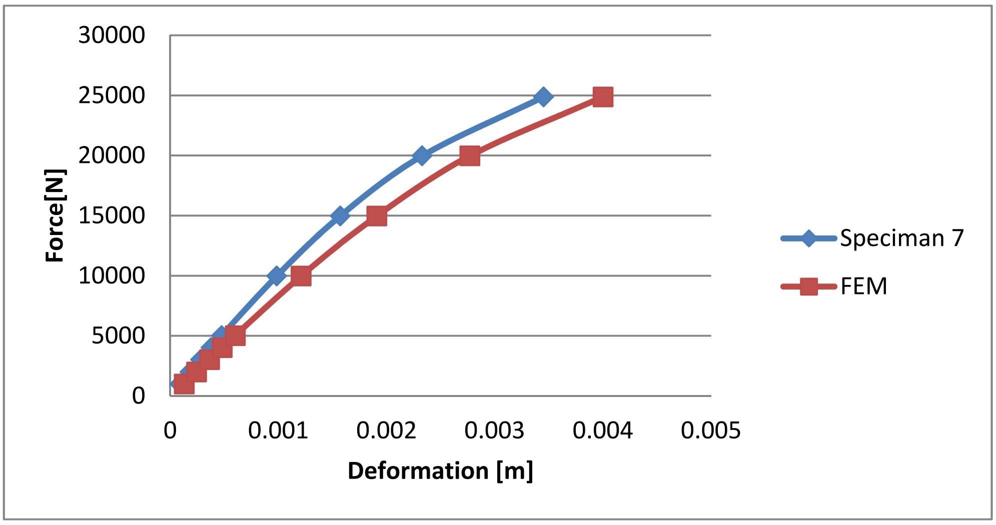


Figure: Comparison of Lab test results and FEM in force and deformation

Appendix 7

Adhesive connection translation

L=0.75m

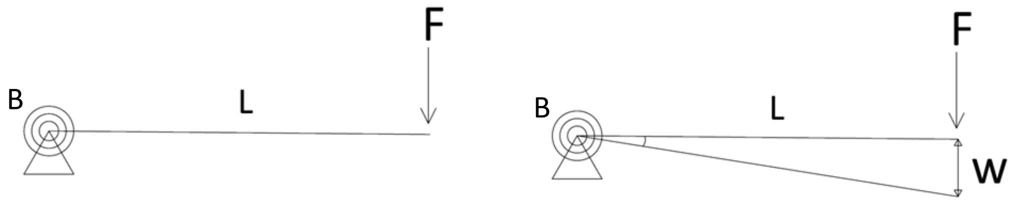


Figure: Calculation model

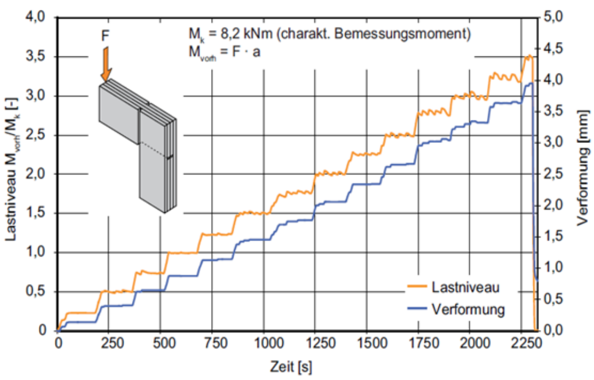


Figure: test results from Weller 2010.

mvorh/m	F	Displacemen	k	Moment
	[kN]	[m]	[kNm/rad]	[kNm]
0.25	2.733333	0.002	768.75	2.05
0.5	5.466667	0.004	768.75	4.1
0.75	8.2	0.0067	688.432836	6.15
1	10.93333	0.008	768.75	8.2
1.25	13.66667	0.012	640.625	10.25
1.5	16.4	0.014	658.928571	12.3
1.75	19.13333	0.0175	615	14.35
2	21.86667	0.02	615	16.4
2.25	24.6	0.0235	588.829787	18.45
2.5	27.33333	0.027	569.444444	20.5
2.75	30.06667	0.03	563.75	22.55
3	32.8	0.033	559.090909	24.6
3.25	35.53333	0.037	540.202703	26.65

Table: Translation results

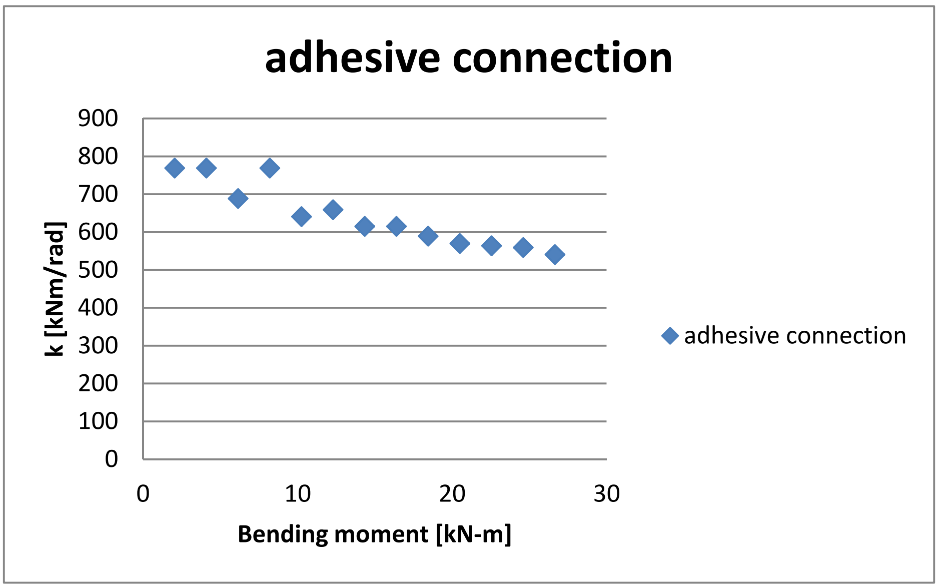
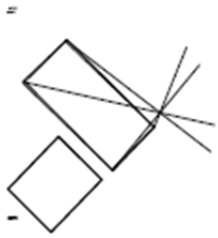


Figure: Bending moment and Rotational stiffness k of adhesive connection

Appendix 8

Location of rotation point of all specimens

Specimen 1



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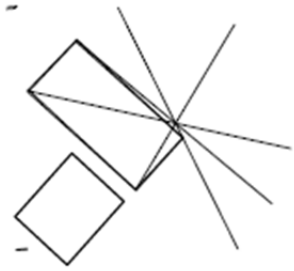

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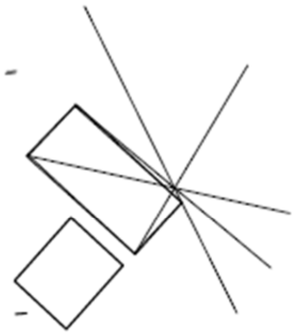

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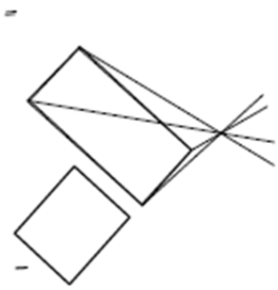

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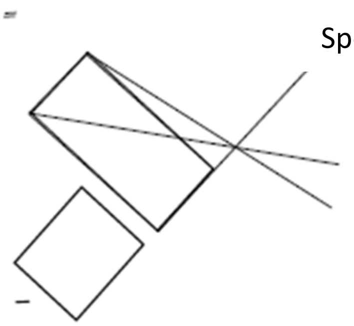

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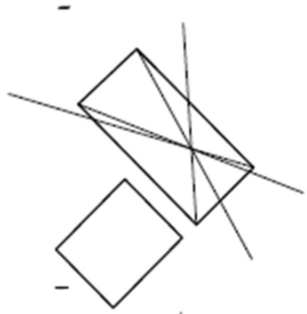

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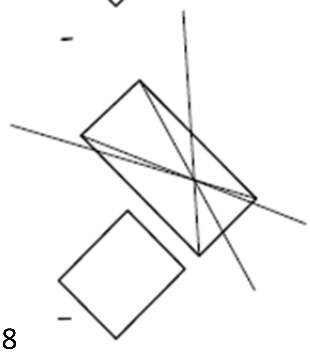

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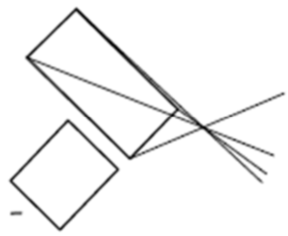

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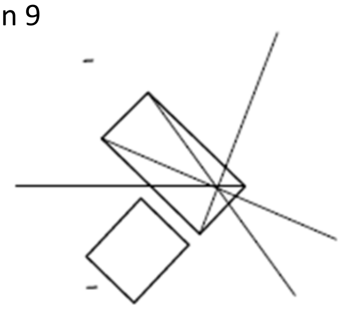
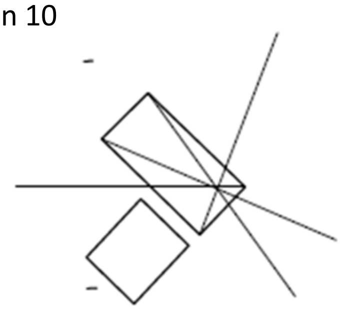


Specimen 10



Appendix 9

Comparison table

	Dresden adhesive 	Apple v2 pin(mechenical fixing) 	Saddle connection 	L-shaped connection 
STRUCTURAL AND SAFETY	-Hinged / semi-rigid Pros - Constant value in rotation stiffness -Bridle joint method applied at beam-column connection to help remain structure integrity Cons -Perforamance totally rely on the quality of adhesive 	-Hinged Pros No moment capacilty at the hinge connection, so no need to worry about the reduction of rotational stiffness at the connection -Bridle joint method applied at beam-column connection to help remain structure integrity Cons - Holes need to be drilled in the glss beam, which may cause stress concentration 	-Semi-rigid Pros -Combined with reinforcement -No holes need to be drilled in glass Cons - Saddle does not contribute much 	-Semi-rigid Pros Combined with reinforcement -No holes need to be drilled in glass - Better post breakrage behavior with reinforced glass beam Cons 
BEAM-COLUMN CONNECTION TYPE	- Totally adhesive 	- Pin, mechenical fixing 	-Saddle with L-shaped plate fixes on the steel reinforcement laminated in glass. mechenical fixing 	-L- shaped plate fixes on the steel reinforcement laminated in glass. mechnical fixing 
CONSTRUCTION/ASSEMBLY	Pros -Use structural silicone to connect roof and facade, easy for installation. Cons -Requires onsite adhesive curing , which the temperature and the humidity will have influence on its structural perfromance - Labor intensive - Experienced labor , rely on labor technics - Torlerance problem?	Pros - Use mechenical fixing to connect roof and facade, less site environment sensitive	Pros -Easy to assemble the beam with saddle - Use mechenical fixing to connect roof and facade,less site environment sensitive	Pros - Use mechenical fixing to connect roof and facade,less site environment sensitive Cons - Need extra support before the coonection is applied

	Dresden adhesive	Apple v2 pin(mechenical fixing)	Saddle connection	L-shaped connection
TRANSPOTATION	- Standard size glass panel, which has no problem in transpotation	- Oversized glass panels has problem for transpotation	- Standard size glass panel, which has no problem in transpotation	- Standard size glass panel, which has no problem in transpotation
CONNECTION FACADE/ROOF	- Structural silicone 	- Embedded connection 	Embedded connection (suggest) 	- Embedded connection (suggest) 
AESTHETIC	- Adhesive connection is totally transparent	- With only mechenical pin fixing and small patch of embedded metal connection, the bulding is almost transparent	- With the metal saddle connection,it is totally not transparent at the beam-column overlapped area. therefore, as a whole building, it does not give the effect of transparent at all.	-With the L-shaped connection,it is transparent at the beam-column overlapped area. however, it has a bigger metal plate along the edges of beam and column. therefore , it provide a less transparency compare to Apple cube.
MAINTENANCE	- It can not be locally dissambled when one glass member is broken - Durability of the adhesive need to be ensured and tested	-It can be dissambled and replaced quickly when one glass member is broken	- it can not be easily replaced, due to the saddle need to be removed from top.	- it can be easily replaced, due to mechinal fixing
BENEFITS	-Provide total transparency -Bridle joint method provides safety - Relativley constant value of rotaional stiffness	-Provide high level of transparency - No need to worry about the reduction of rotaional stiffness at connection -Bridle joint method provides safety -Compare to adhesive joint, it is possible to replace and dissamble the glass member locally	- Applied with reinforced glass beam - Rotational stiffnessk can be estimated, which is beneficial for designing glass beam dimension and be integrated in the designing of L-shaped connection - Easy conestrcution with saddle element	-Rotational stiffnessk can be estimated, which is beneficial for designing glass beam dimension and be integrated in the designing of L-shaped connection -Compare to adhesive joint, it is possible to replace and dissamble the glass member locally - Provide high level of transparency

Appendix 10

The configuration of the laminated reinforcement section

To consider the bonding of the steel reinforcement, it is more preferable to have more bonding faces with the glass panes, it is concluded from the research (Louter et al 2010.) that 3-face bonding is preferable to achieve the satisfied results regarding residual strength.

Therefore, in the three types of reinforcement section with more than 3-face bonding showed in figure 3.7.3 is compared. In the literature studies, it is concluded from Louter that the increase of reinforcement percentage will increase the post-breakage strength and the stiffness of the glass beam. Although the moment of inertia (I) of solid section and the hollow section only has small difference, if comparing the (c) solid section with 1mm thick (b)hollow section in both 10mmx10mm section, the (c) solid section is still more preferable. However, in our case, to fix the L-shaped connection to the laminated reinforcement, it is preferable to have solid section to have a better grip and larger attaching area with the screws.

As for the 5-face bonding solid section (a) seems to have it all, but to consider the transparency of the glass beam, this option is discarded.

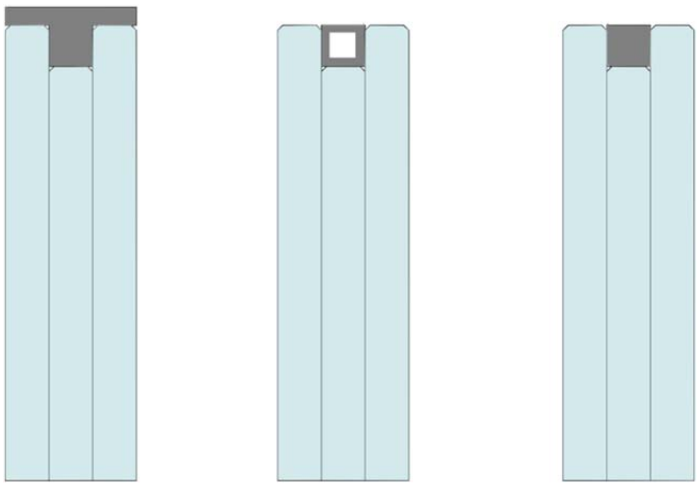


Figure 3.7.3 three types of steel reinforcement section for glass

(a) 5-face bonding (b) 3-face bonding with hollow section(c) 3-face bonding with solid section

One of the concerns of the connection is that it is not certain if the steel reinforcement laminated in the glass panel will be detached before the L-shaped connection deforms plastically. Since our test has limited data to clarify this concern, it is suggest to have further research on this topic.

Appendix 11

Sway check for in-plane stability

For the in-plane stability, it is important to check the horizontal displacement of the portal frame.

In the finite element model of the new design portal frame of Dresden pavilion , k =2300, the maximum horizontal displacement at top of the column is 0.017 m, which is beyond the limit h/500 of Eurocode(NEN EN-1990). That is to say the portal frame at this condition is not stable, and it is suggested that other stability measure needs to be implemented for this design.

In NEN EN-1990 Annex A1.4.3

The maximum horizontal displacement u for the entire building is h/500

Appendix 12

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