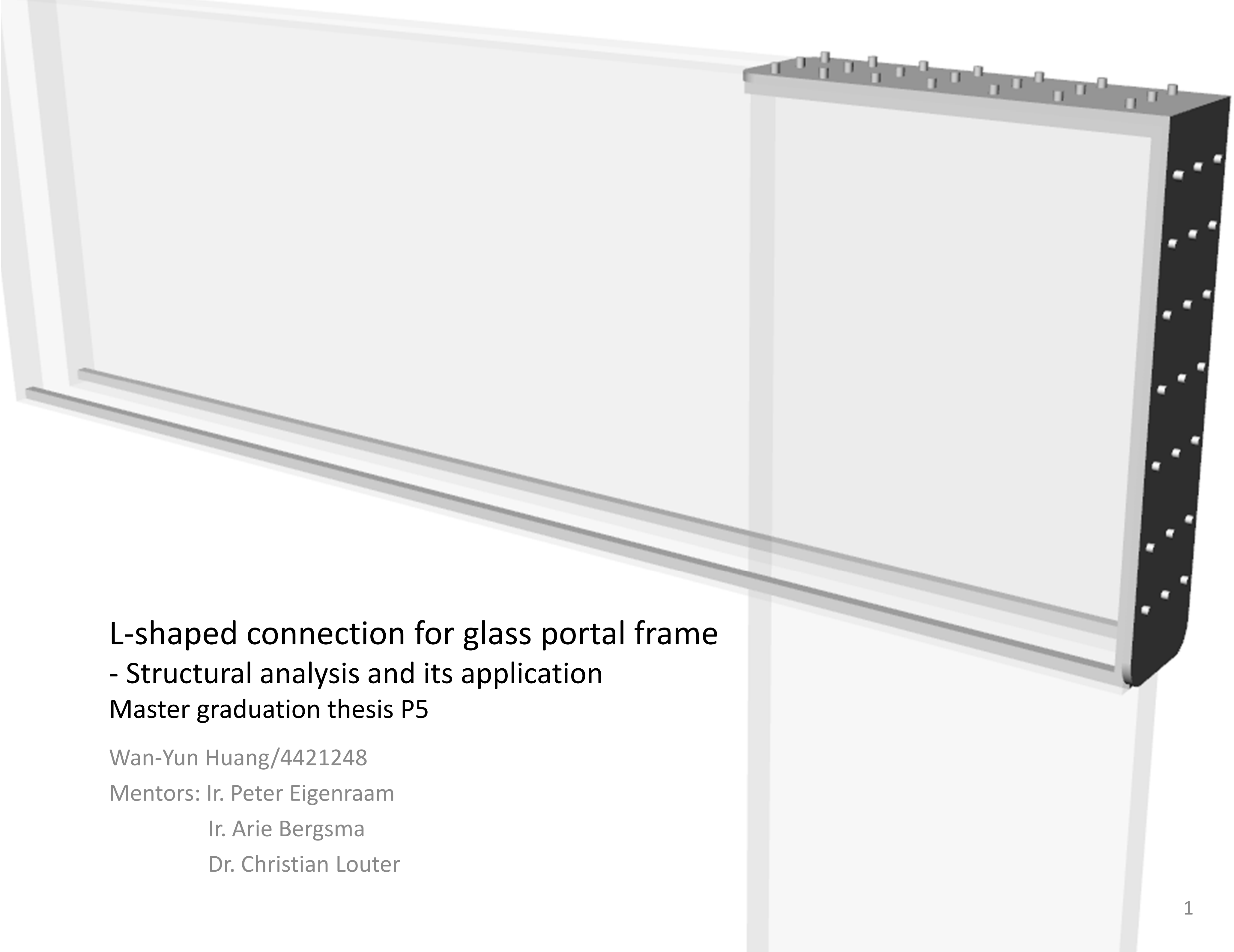

L-shaped connection for glass portal frame

- Structural analysis and its application

Master graduation thesis P5

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Ir. Arie Bergsma

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-Introduction
-Problem statement
-Research Objectives
-Research question
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-Hypothesis

Structural analysis

-Design parameters
-Analysis of glass structure
-Theoretical prediction
- Laboratory test

Design process

-Design process
-Case application

Discussion & Conclusion

-Discussion
-Conclusion

Introduction

Building with glass

- Architect's dream
- Light, lightness, transparency

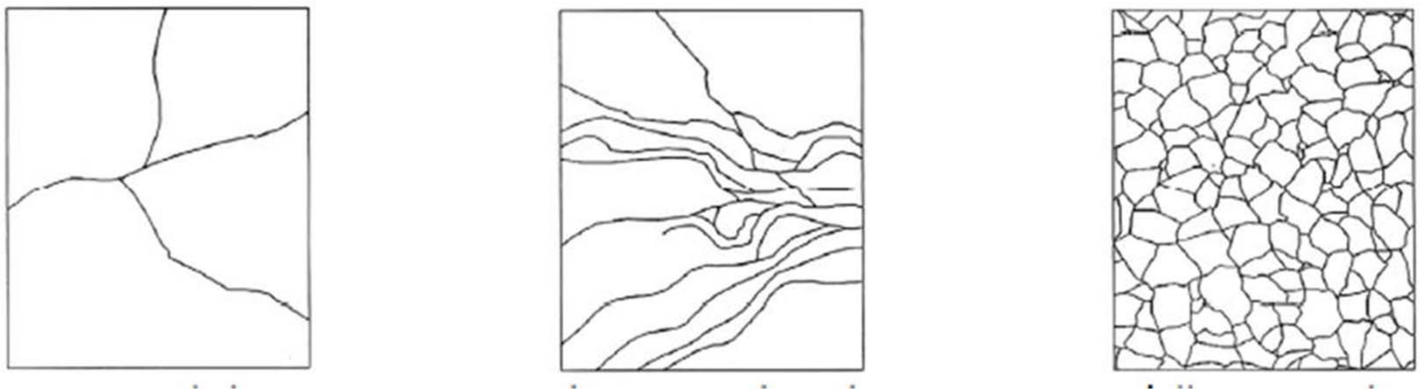
Introduction

Why is glass a challenging material for building structure?

-Brittle nature

-No warning of failure → a challenging material for building structure

-The subtle flaw will cause crack



Introduction

The development trend of structural glass in building

-Bigger production size

-Smaller connection

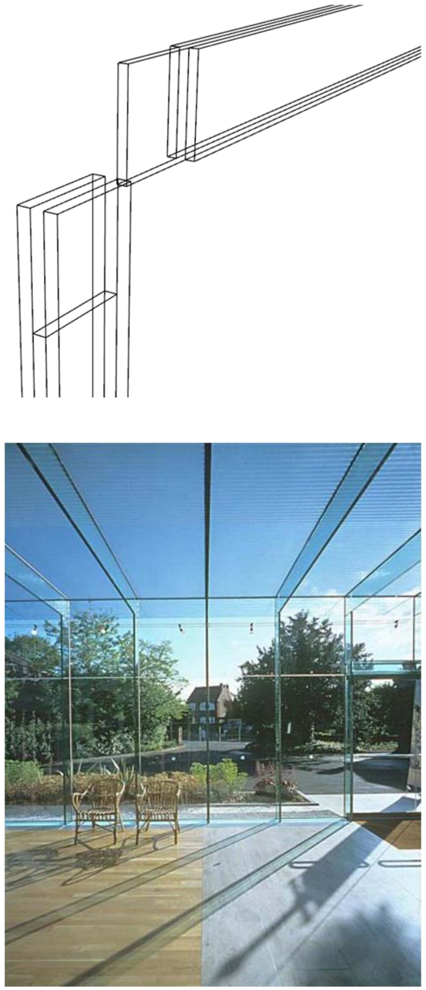
-More transparency

-Longer span

-Safety issue

Introduction

Existing **beam-column** connection types for glass portal frame



Adhesive
connection

Bolted
connection

Introduction

To improve the safety of glass structure , reinforced glass beam was invented.

Reinforced laminated glass beam →Better post-breakage behavior

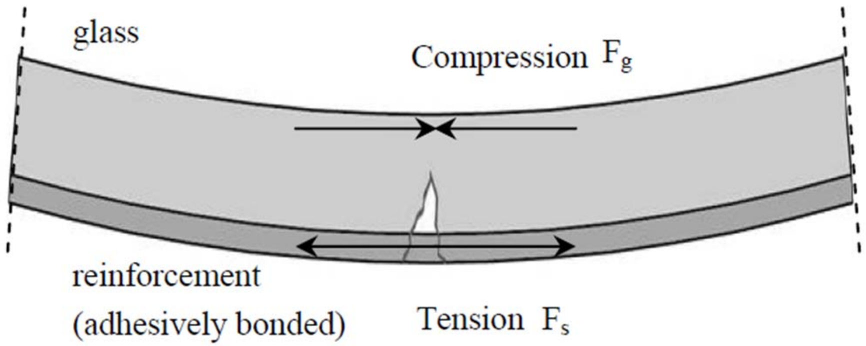


Figure Schematic overview of reinforced glass beam (Louter)

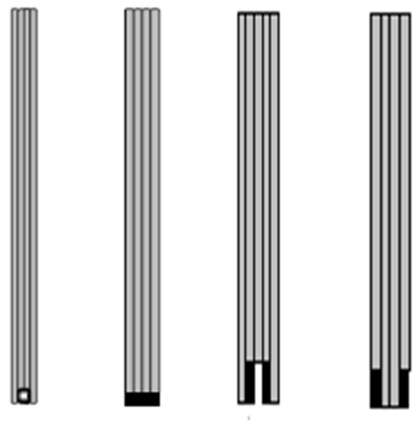


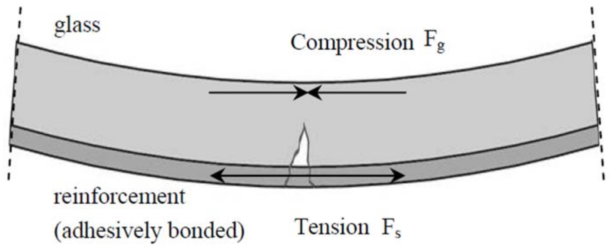
Figure Different cross section of reinforcement beam

Introduction

- To improve the safety
- Integrate reinforced glass beam

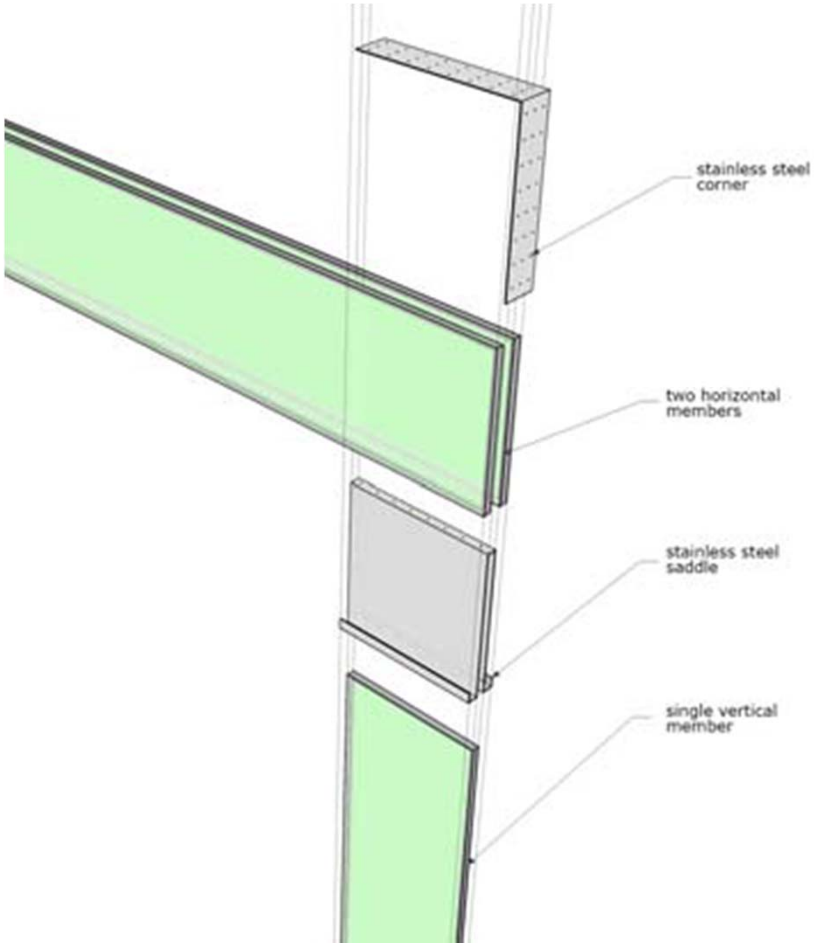
→ A new connection system is desired

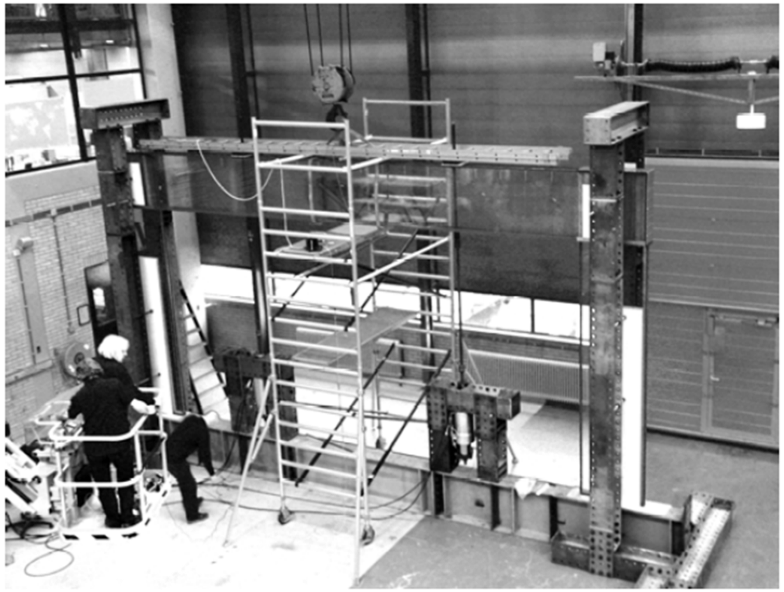
?



Introduction

Previous research- *"Designing and testing an eight meter span glass portal frame "*

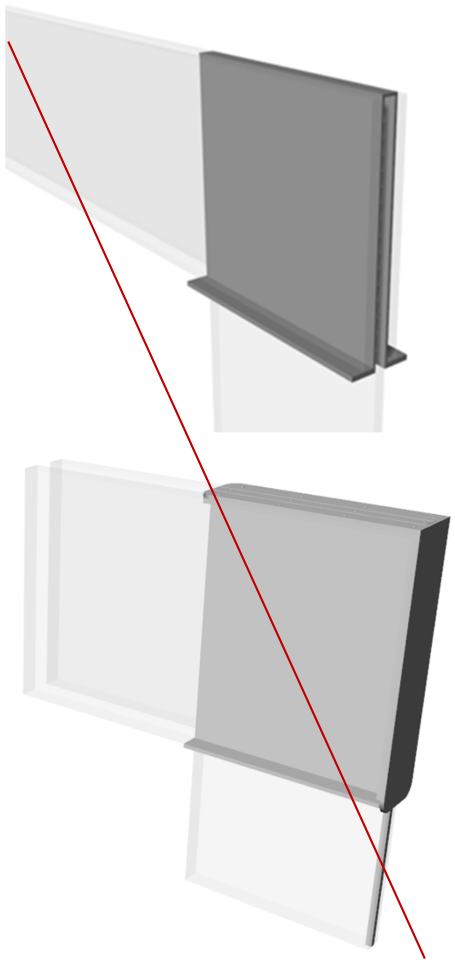




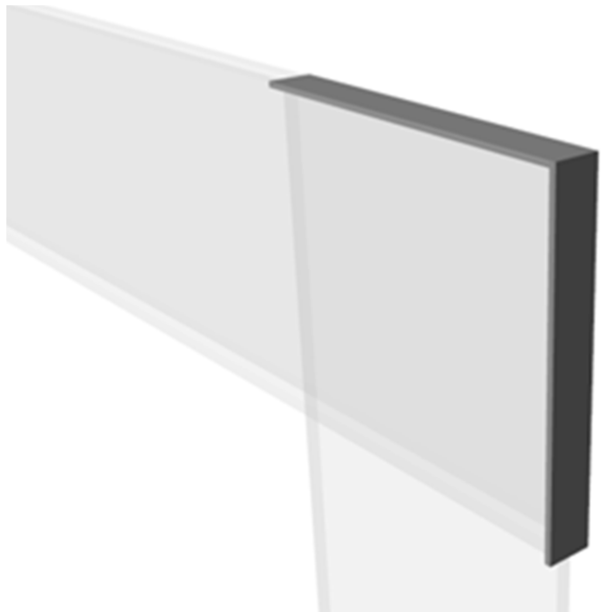
Introduction

Previous research- *"Designing and testing an eight meter span glass portal frame "*

- The saddle doesn't work much
- Semi- rigid connection



Without saddle:
- More transparent



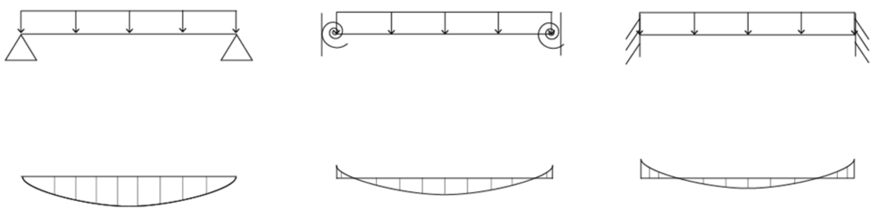
Semi rigid connection

Semi-rigid connection

- Rotational stiffness k= M/ θ

-Cost effective solution

-Most of the structure is designed to be fully rigid joint. Compared to rigid connection , semi rigid joint provides lower bending moment at the end of the beam , which can results in reducing the beam height



Pin-pin Spring- spring Fixed-fixed

Figure Moment diagram for beams subjected to uniform distributed load

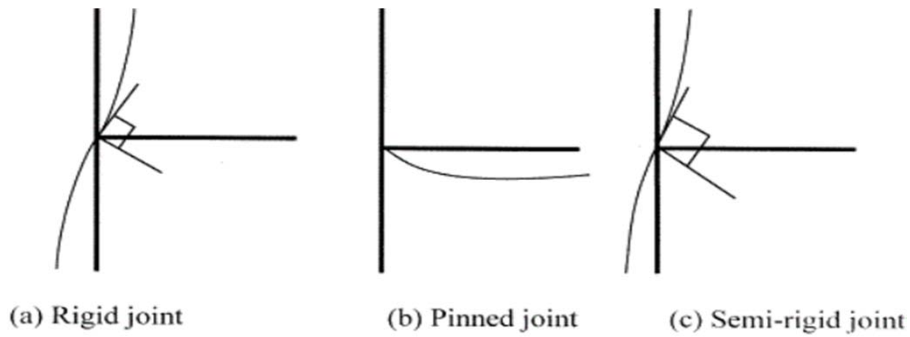


Figure Different joints according to rotational stiffness

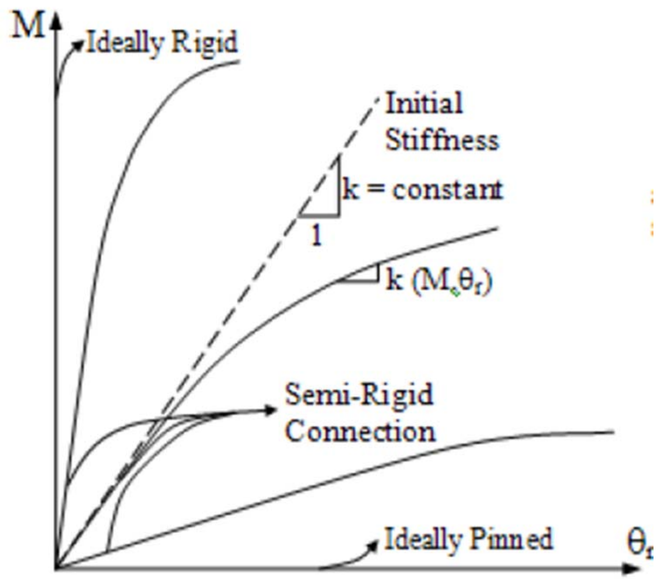
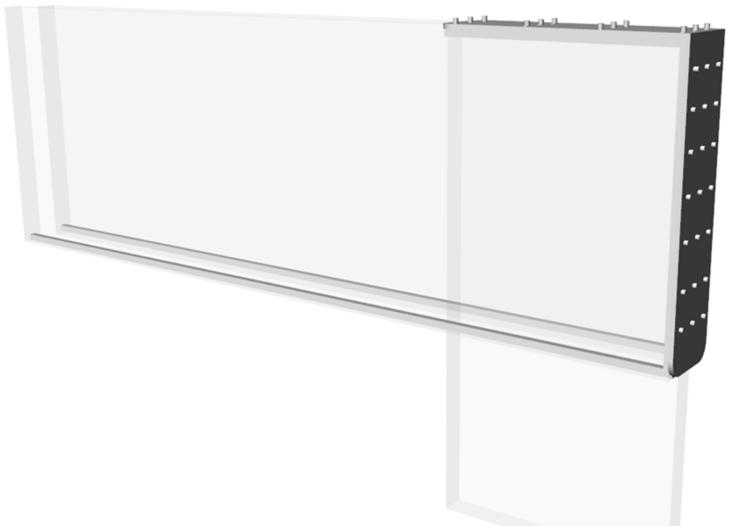


Figure Structural behavior of connections (Kartel 2010)

Potential of L-shaped connection

- Avoiding drilling holes in glass
- Higher safety
- Easier for construction
- Prevent over design the connection
- The desired rotation stiffness can be achieved by adjusting the parameters of L-shaped plate
- Smaller beam height



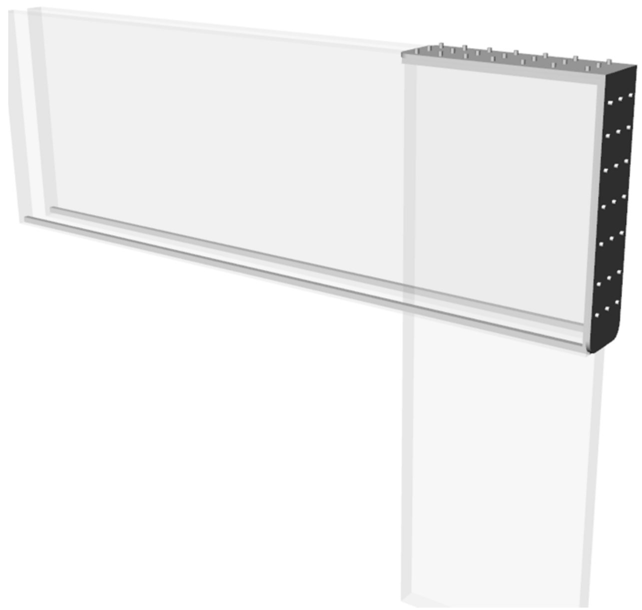
Research questions

Main question

“ How can we use the parameters of a L-shaped connection to determine the construction of a long-span all glass pavilion? ”

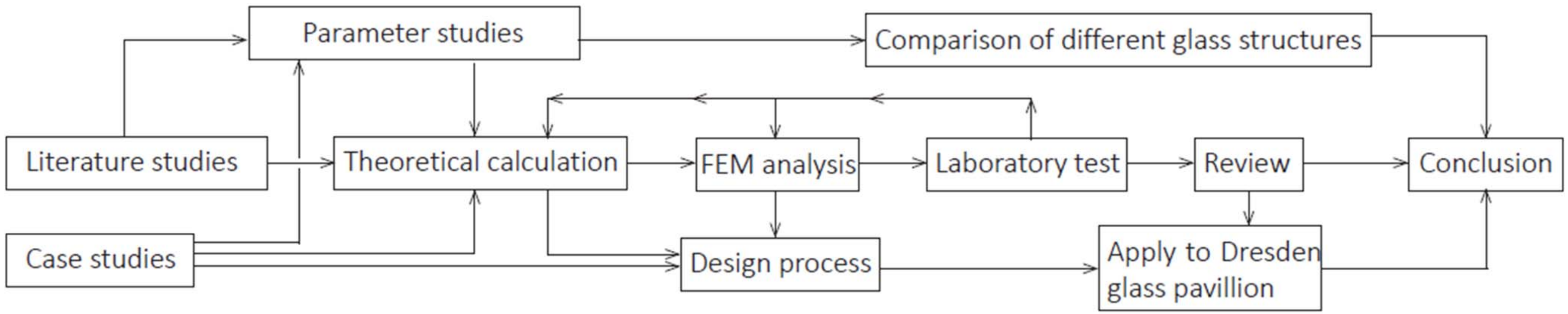
Research objectives

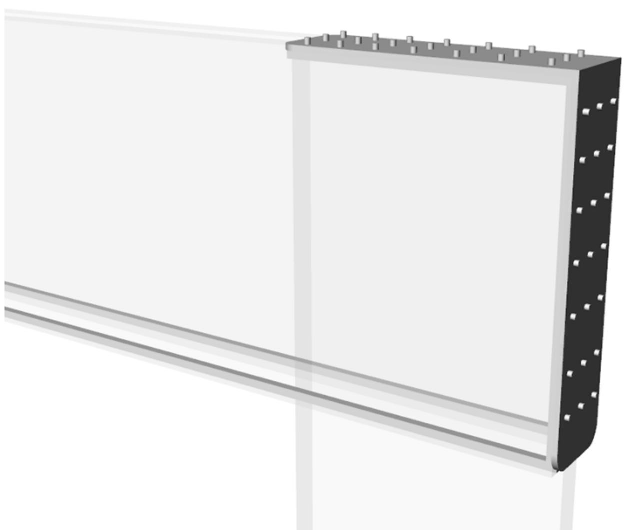
- The structural behavior of glass portal frame
- The parameter relationships
- To determine the rotation stiffness k of the connection.
- A new design procedure applying L-shaped connection.
- The comparison of existing glass column-beam connection in different aspects



Methodology

Research and design Methodology

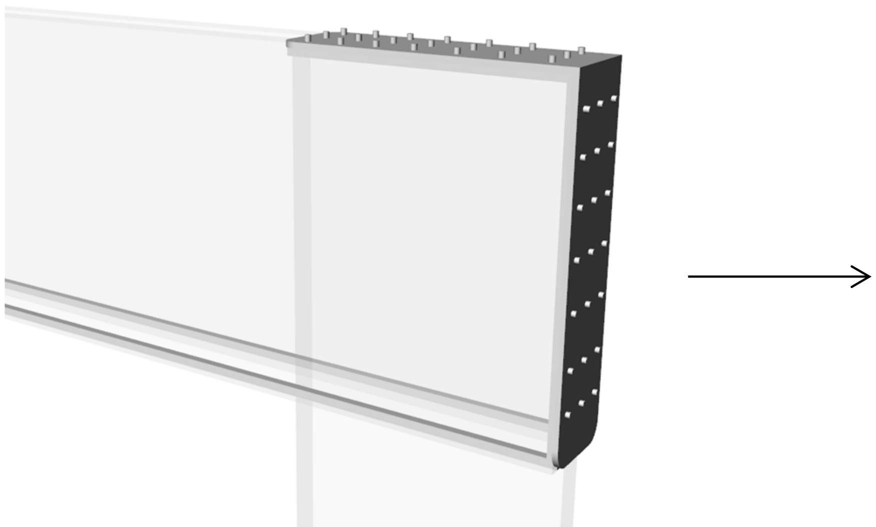




Hypothesis

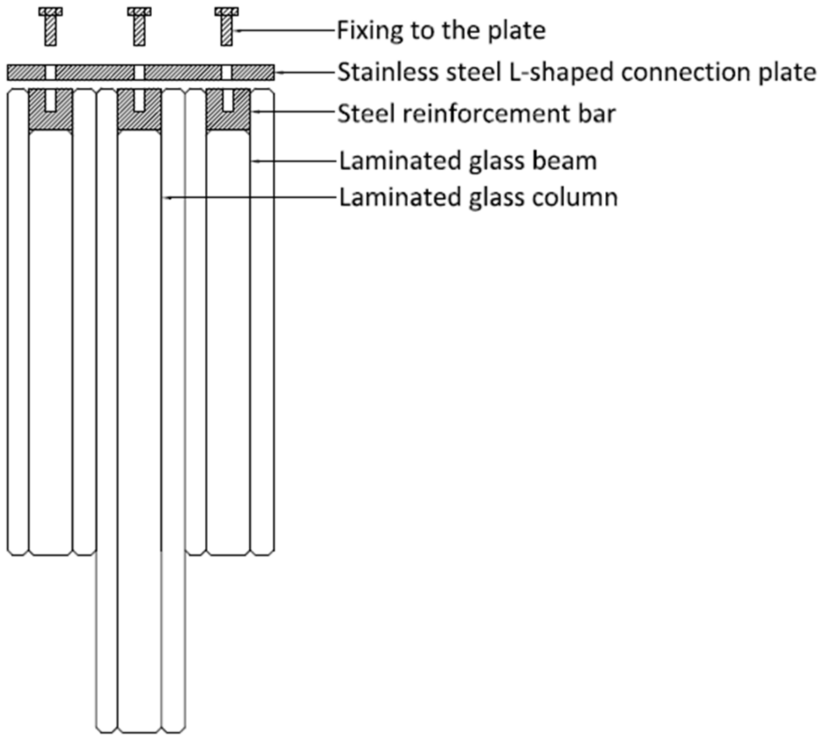
It is assumed that

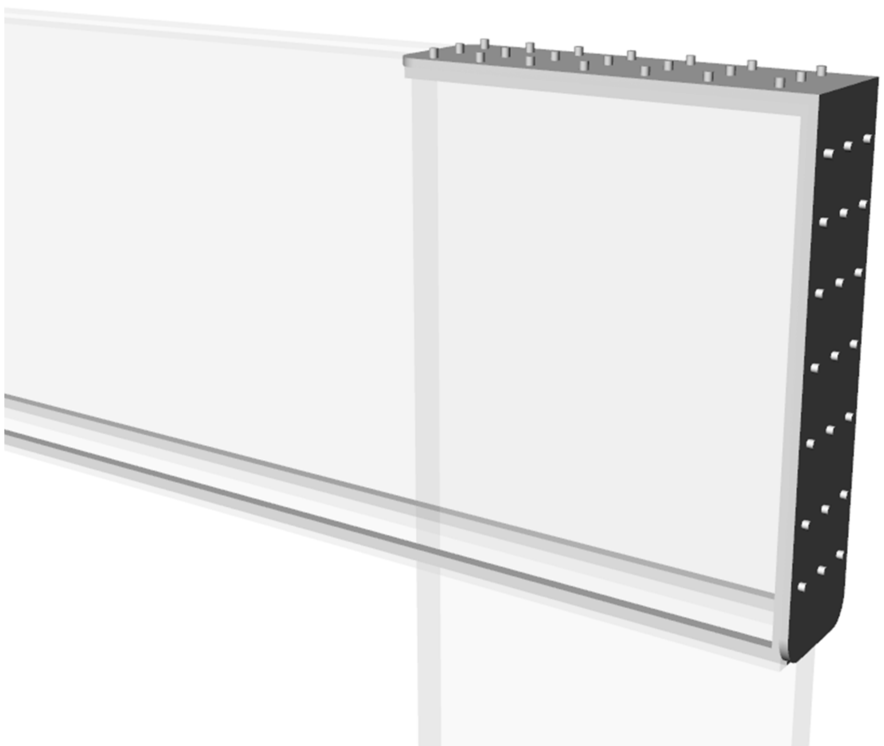
- The new design procedure will be **simpler and more efficient** to get **a smaller height of beam.**
- The L-shaped connection is **safer** .
- The L-shaped connection can be adjusted to the **desired value** to **prevent over design.**



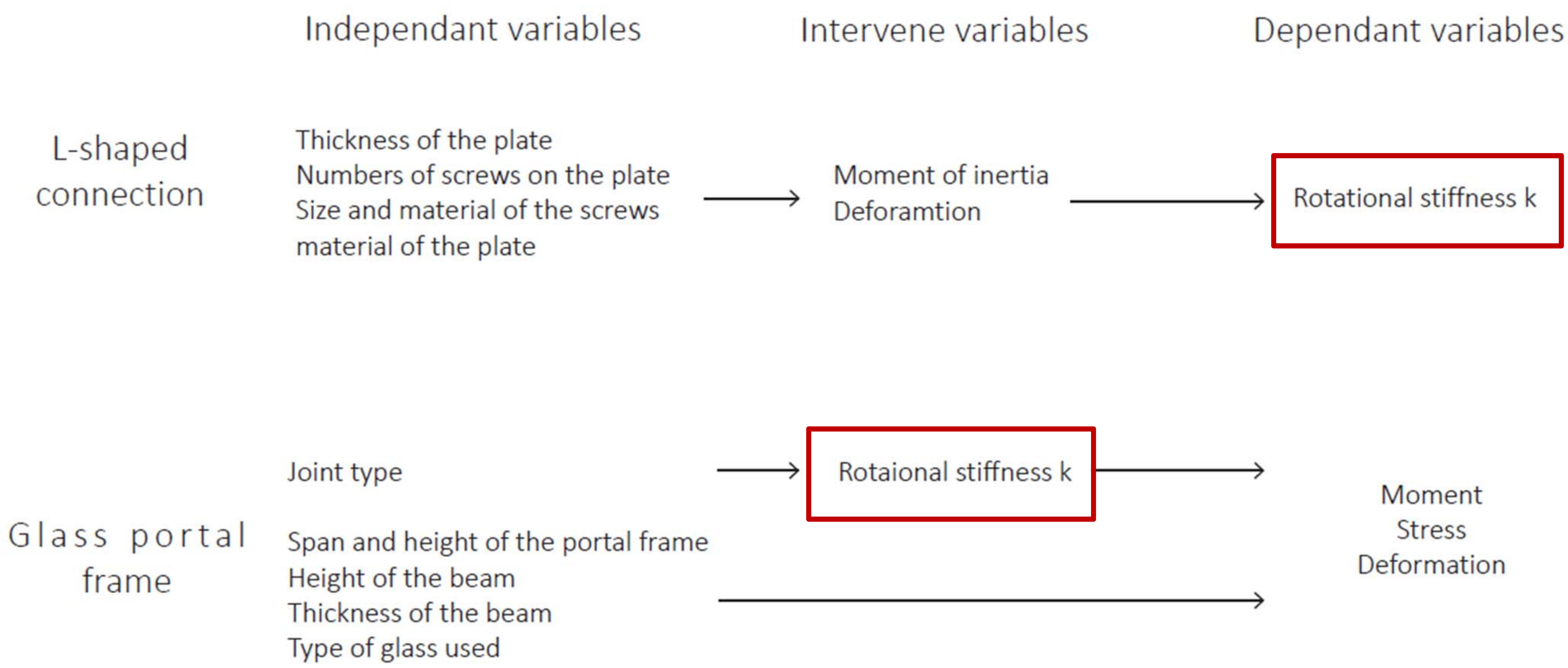
L-shaped connection principle

- Fix on steel reinforcement laminated in glass beam and column
- Both sides are fixed to the beam and column



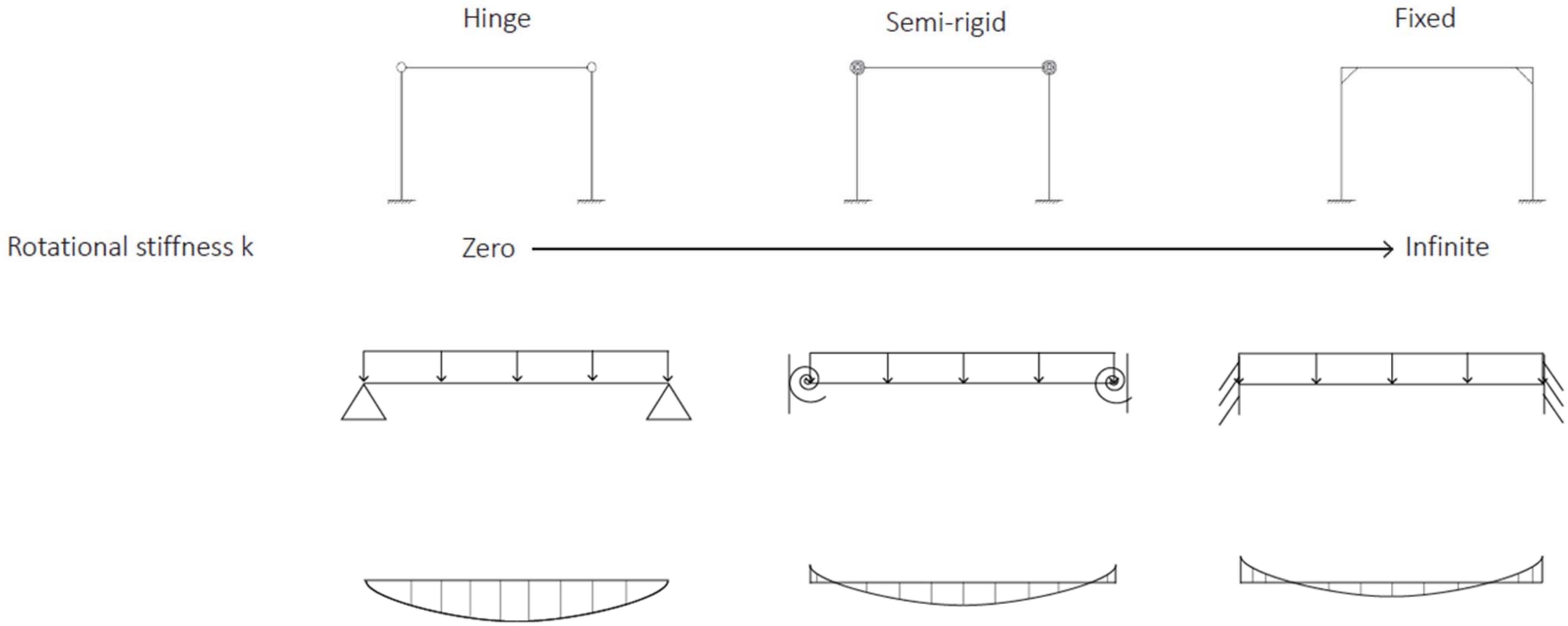


Design parameters relationship



Design parameter relationship

Design parameters relationship



Relationship of Rotational stiffness k and moment

Design parameters relationship

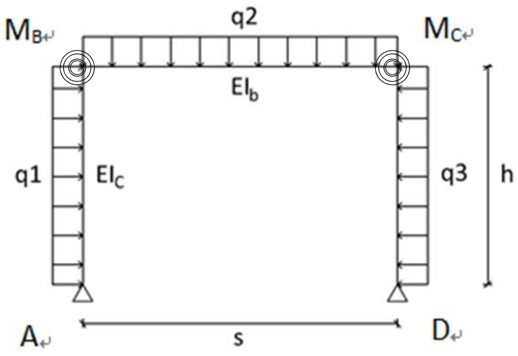
L-shaped connection

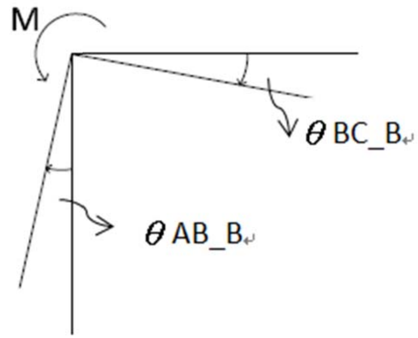
	Low rotaional stiffness k	→	High rotaional stiffness k
Thickness of the plate	Thin	→	Thick
Numbers of screws on the plate	Few	→	Many, but to certain number
Size of the screws	small	→	Big
material of the plate	Low Young's modulus	→	High Young's modulus

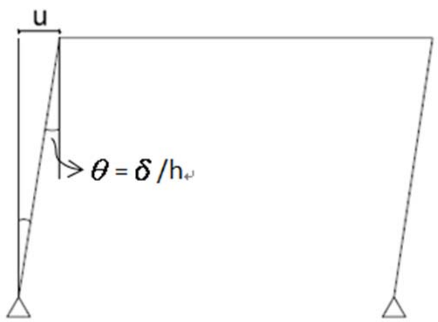
Relationships between parameters of L-shaped connection and rotational stiffness k

Structural analysis

Theoretical calculation







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

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

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

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

$$\theta CD\_C = \frac{M_C \cdot h}{3EI_c} + \frac{u}{h} - \frac{q3 \cdot h^3}{24 \cdot EI_c}$$

$$\theta RB = \frac{M_C}{k}$$

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

equation1: $\theta AB\_B + \theta BC\_B + \theta RB = 0$

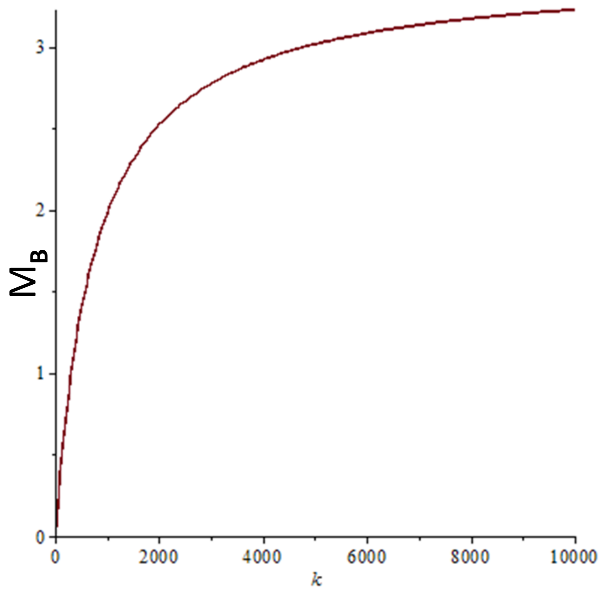
equation2: $\theta BC\_C + \theta CD\_C + \theta RC = 0$

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

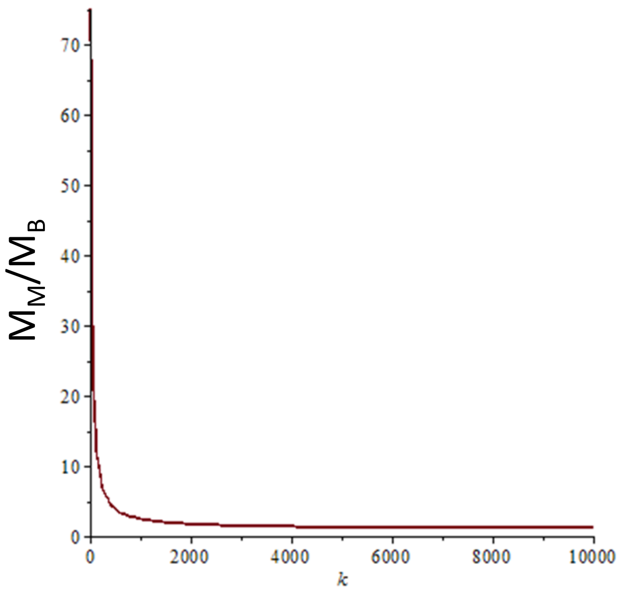
$$M_B = \left(\frac{1}{8} \frac{1}{2EIbhk + 3EIcks + 6EIbEIc}\right) \cdot [q1(3EI_b h^3 k + 6EI_c h^2 ks + 12EI_b EI_c h^2) - q2(2EI_c ks^3) - q3(5EI_b h^2 k + 6EI_c h^2 ks + 12EI_b EI_c h^2)]$$

Structural analysis

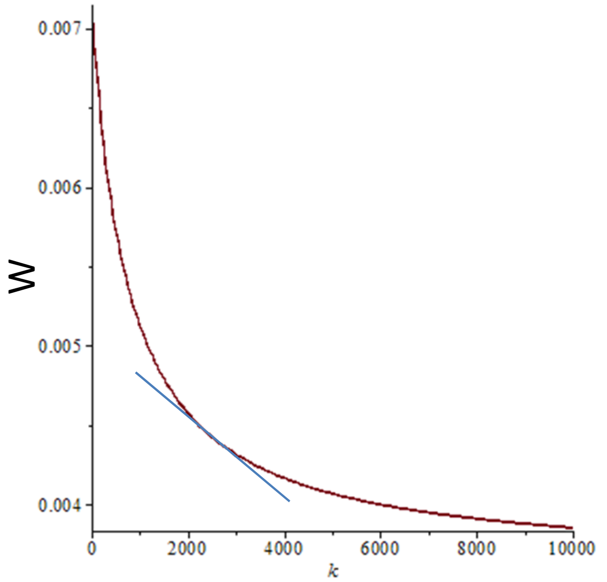
Parameter relationships
Case applied: 7.7x4.4x2.5m pavilion with 250mm beam height



M_B and k relationship



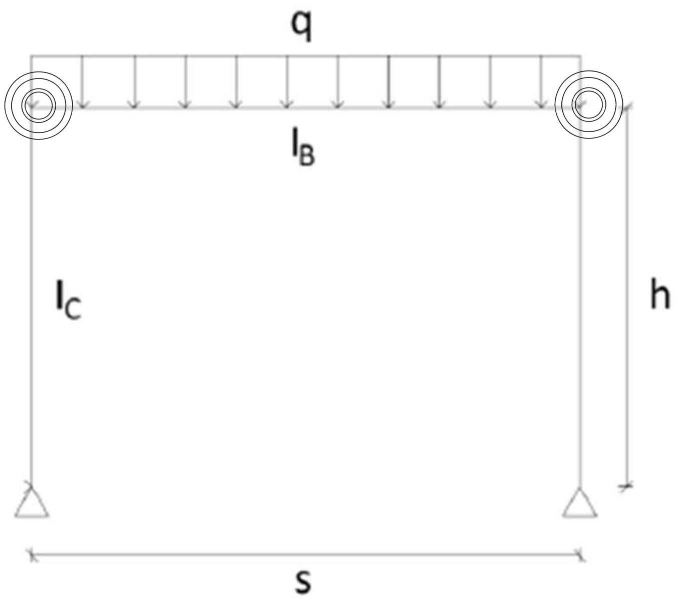
M_M/M_B and k relationship



Deformation and k relationship

Structural analysis

M_M/M_B =1 can be achieved when
M_M/M_B <1 at rigid –connection situation



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)

In semi-rigid joint, to reach the M_M/M_B=1,is when M_M/M_B is smaller than1 in fixed joint situation

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

Therefore,

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

Only under this condition, M_M/M_B =1 can be achieved

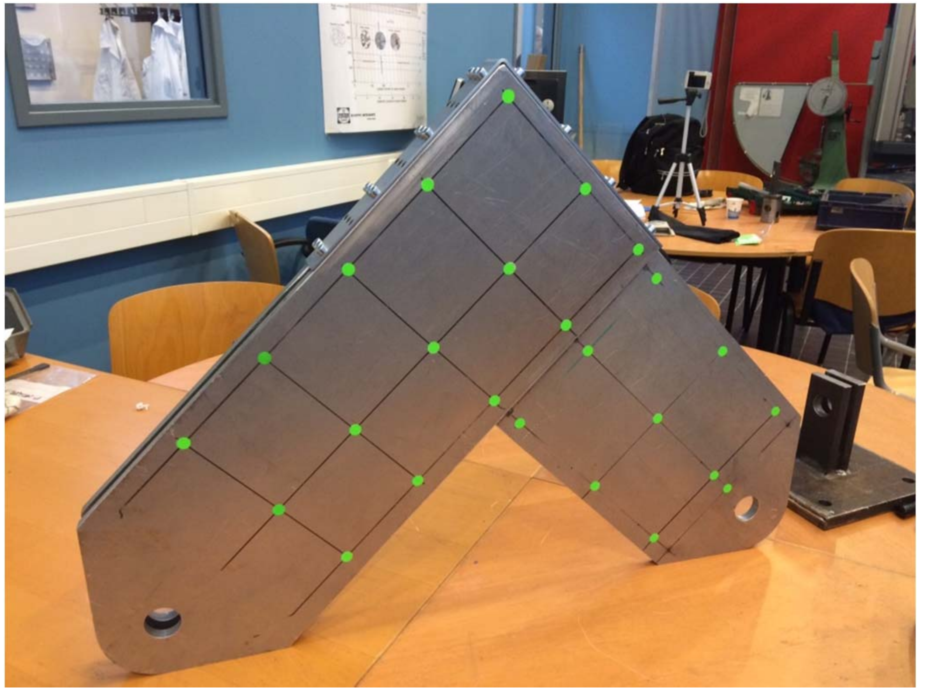
Introduction
Research outline
Structural analysis
Design process
Conclusion

Structural analysis –theoretical calculation conclusion

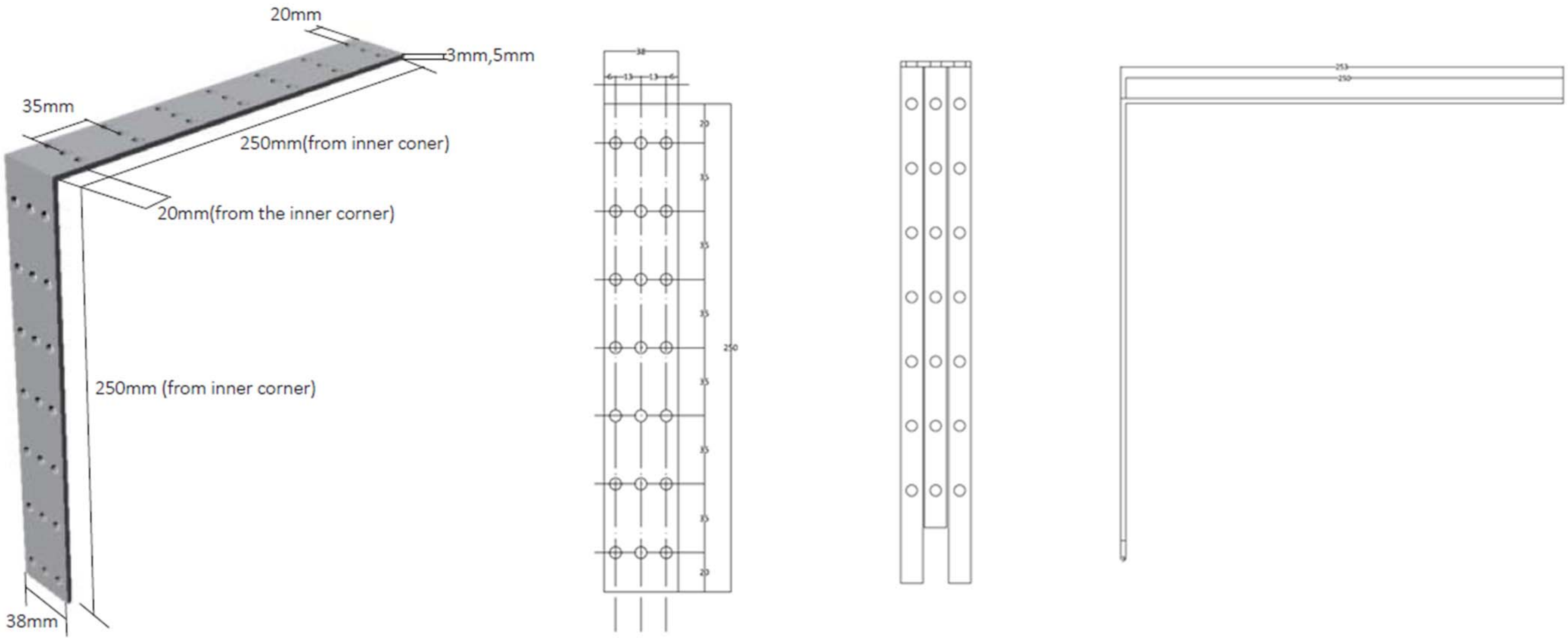
- Both deformation and moment reach a constant value as the rotational stiffness goes higher after certain value. So it won't be efficient to have a more rigid connection after that value k .

- Only under this condition $\frac{1}{2} > \frac{h \cdot I_B}{s \cdot I_C}$, M_M/M_B =1 can be achieved

Laboratory test set up



Laboratory test: L-shaped connection specimen

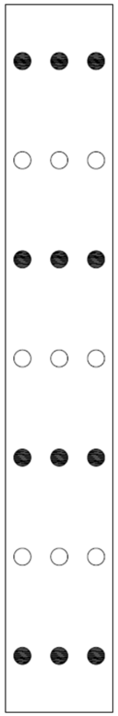


Material :
Stainless steel

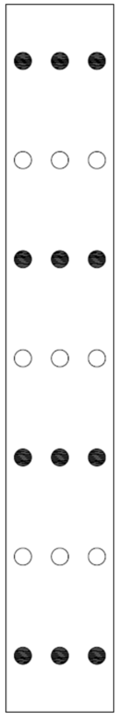
Thickness:
3mmx5
5mmx5

Bolt :
M6 bolts

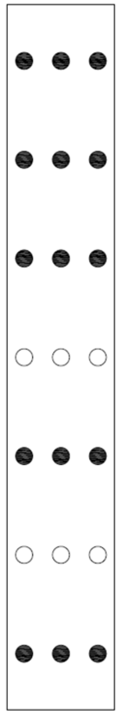
Laboratory test set up



Specimen 1-5
3mm plate



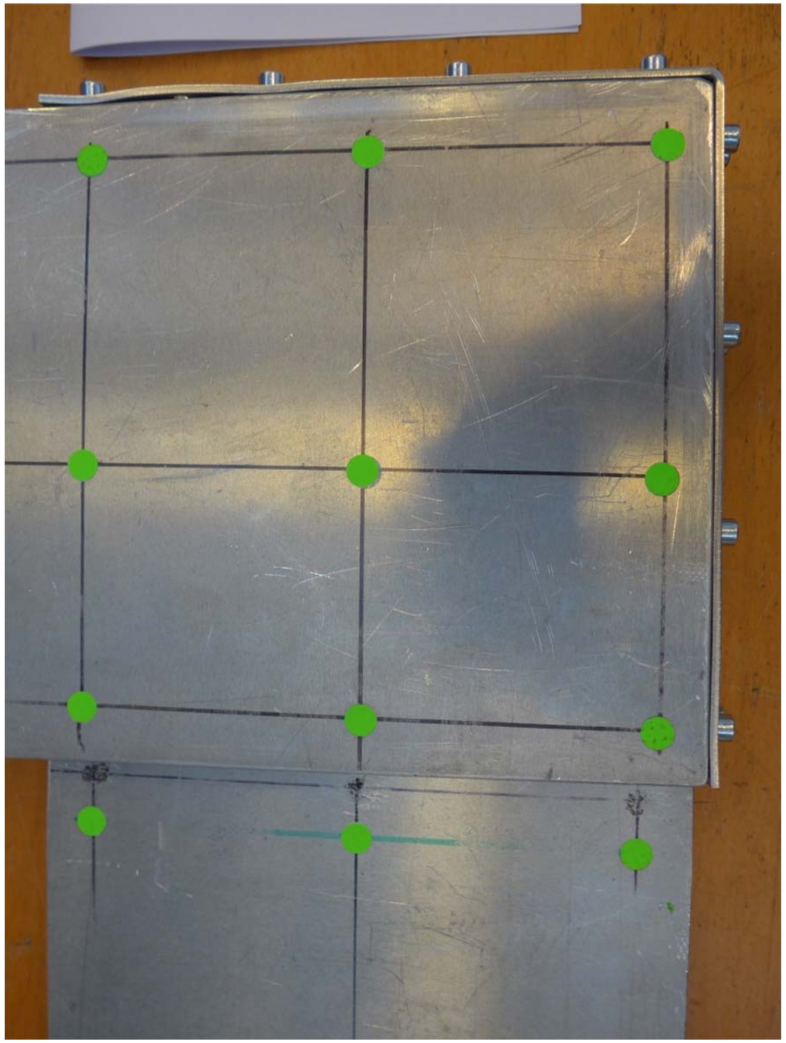
Specimen 6-8
5mm plate
Pattern 1



Specimen 9-10
5mm plate
Pattern 2

Laboratory test results

3mm plate

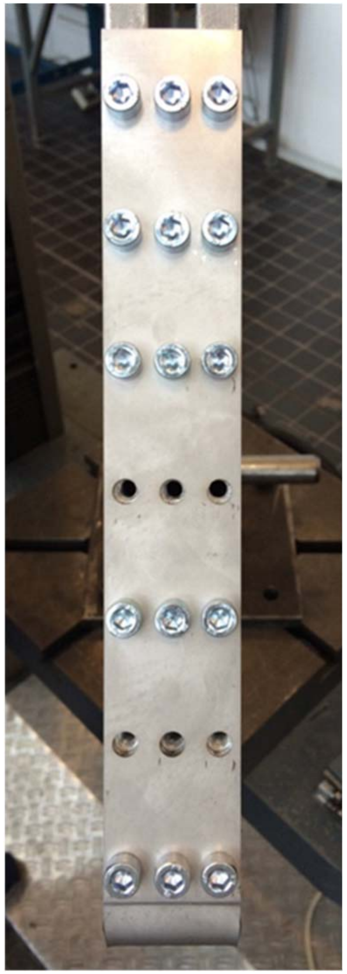


Deformation pattern

Laboratory test results- Deformation

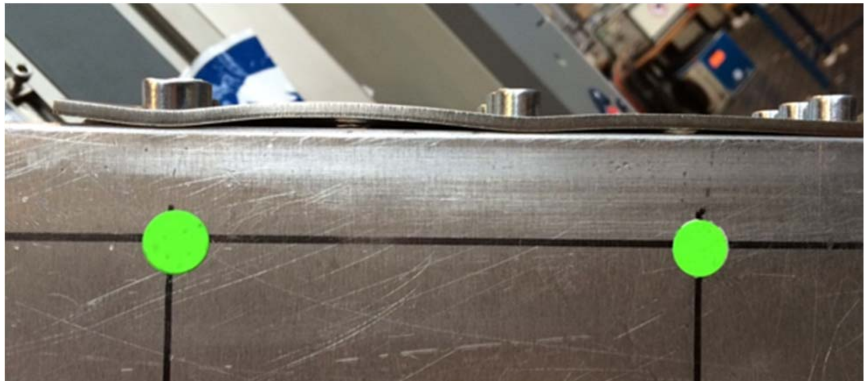
3mm plate

5mm plate, pattern1



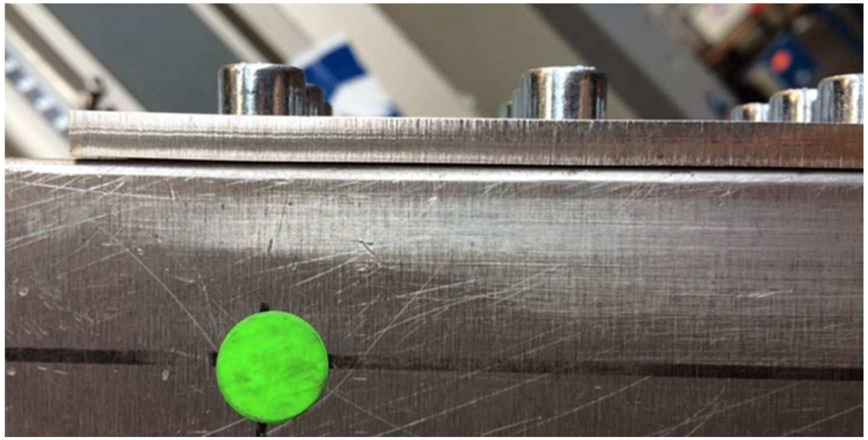
5mm plate, pattern2

Laboratory test results- Deformation



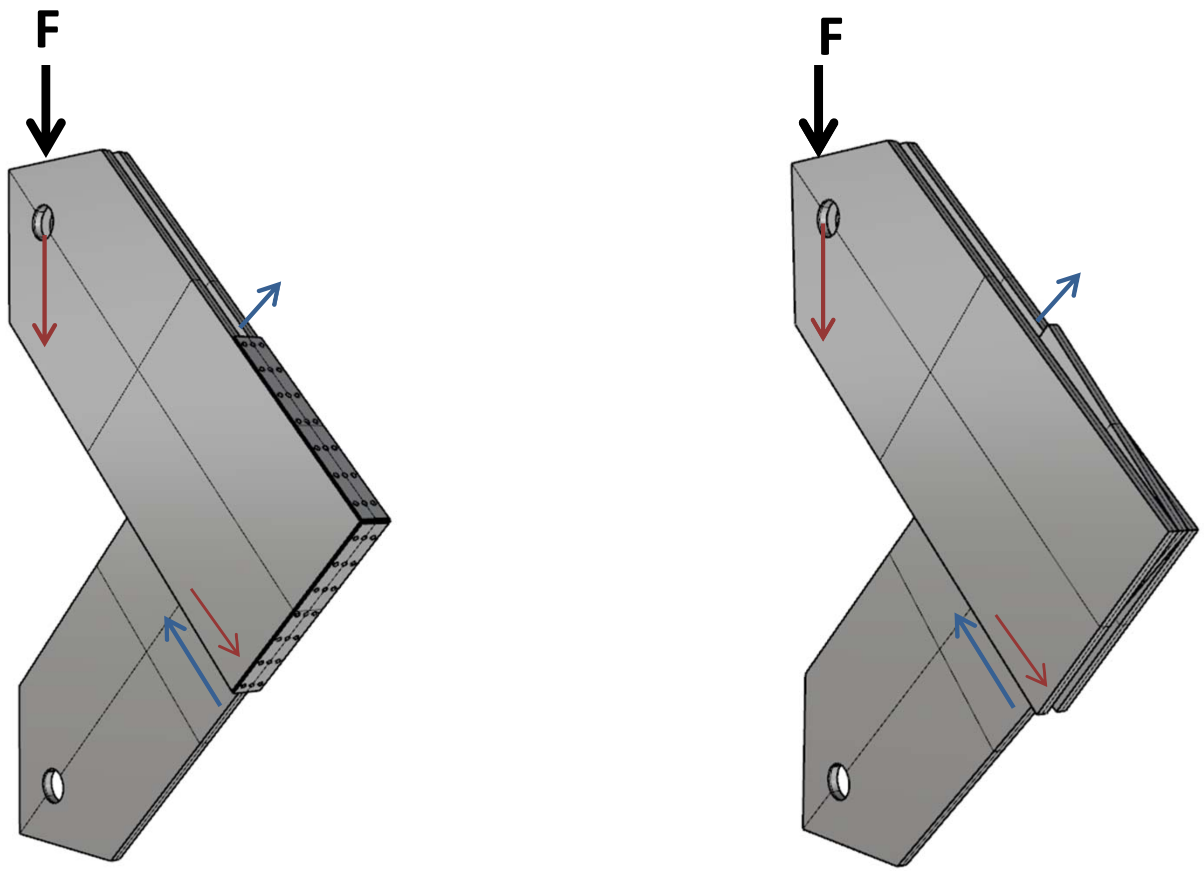
3mm plate

5mm plate, pattern 1



5mm plate, pattern 2

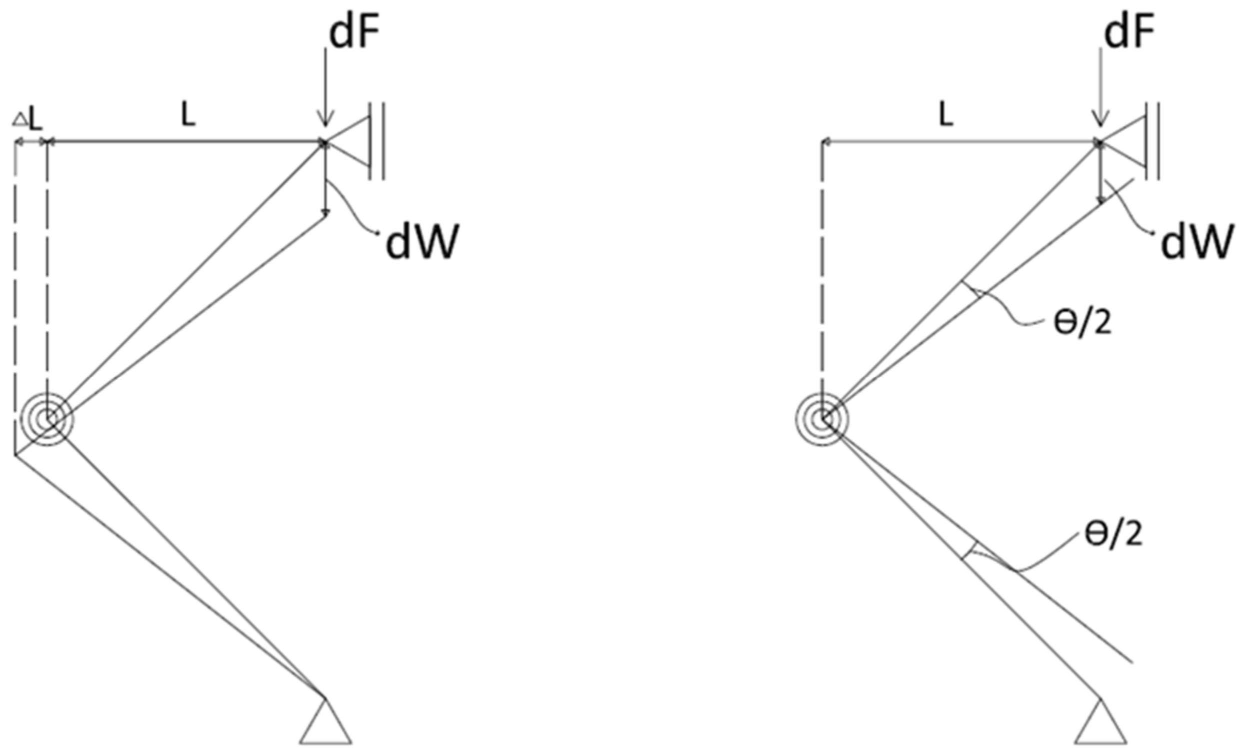
Laboratory test results



The rotation direction of the model

Laboratory test method

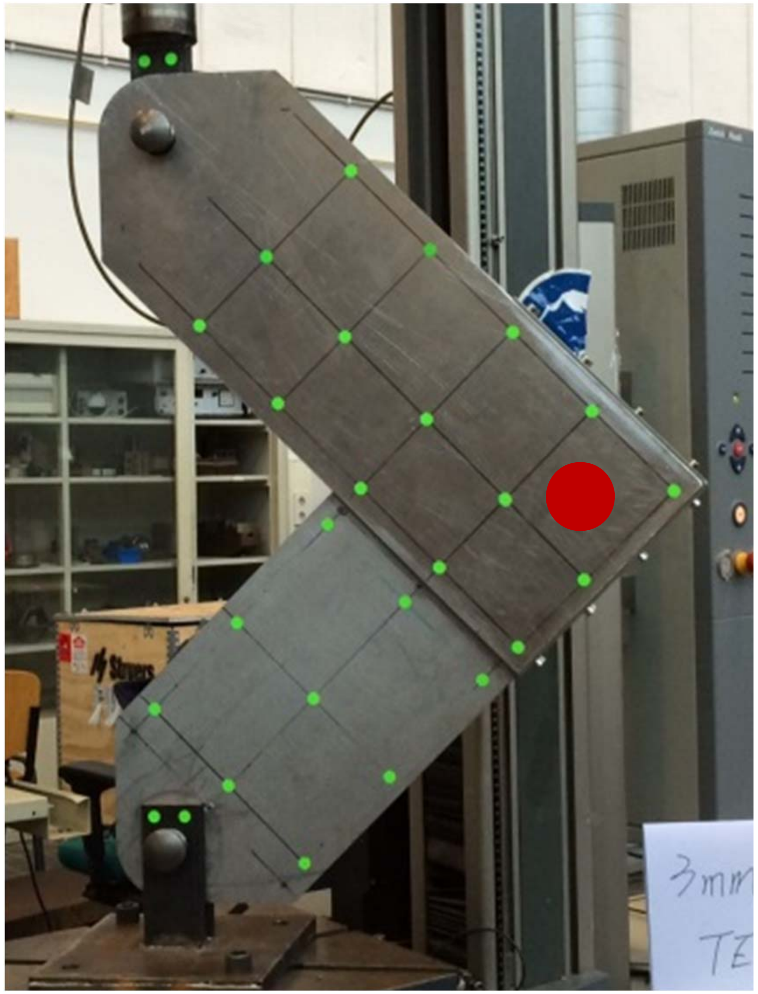
Goals : To find out the rotational stiffness k of this connection.



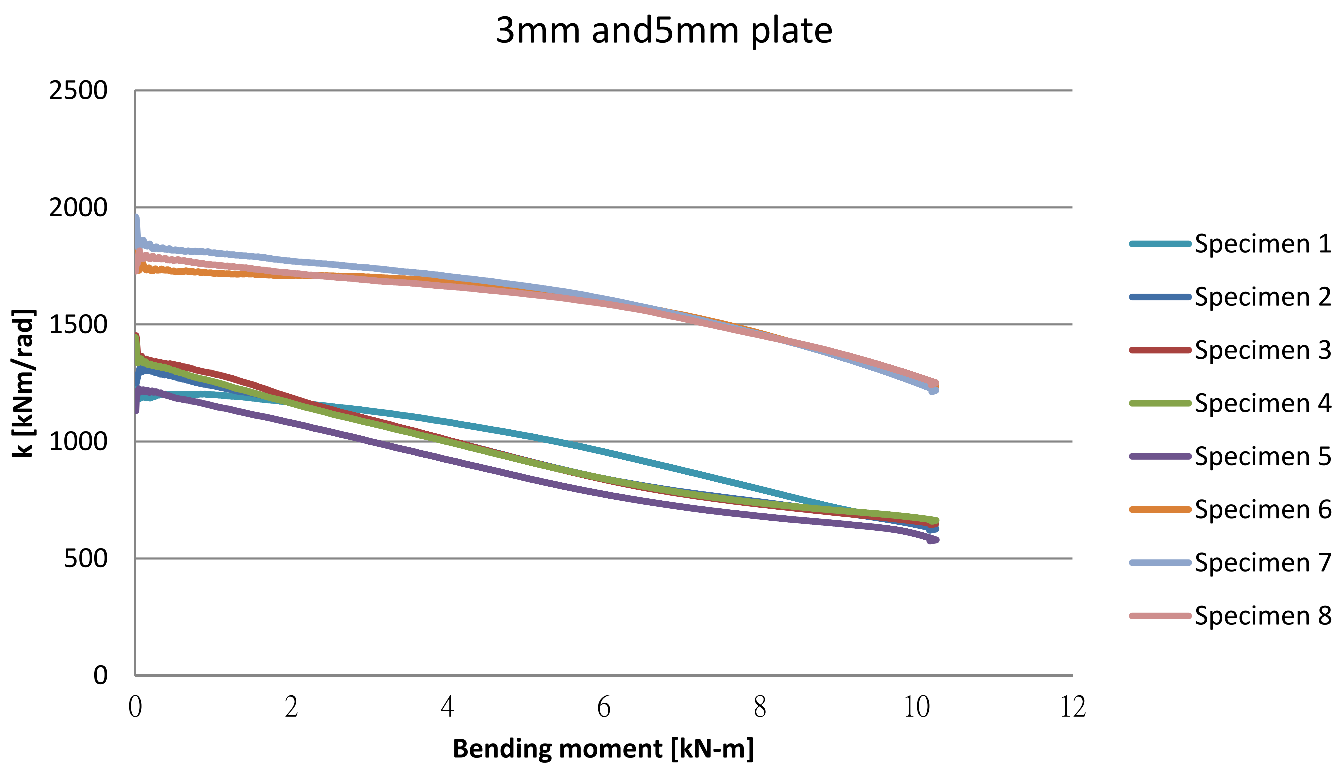
$$k = \frac{F \cdot L^2}{dW}$$

Laboratory test results

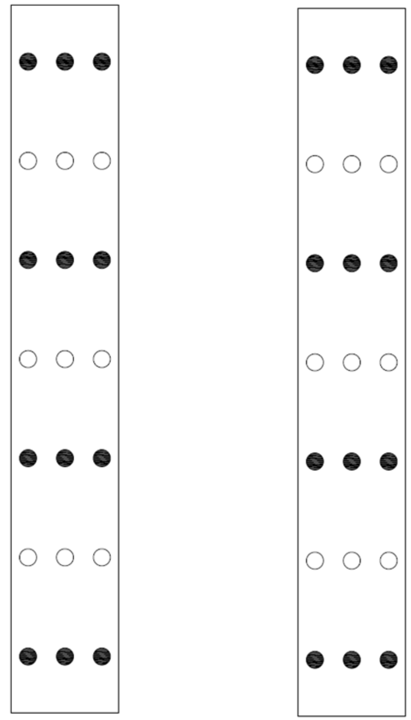
Rotation point



Laboratory test results



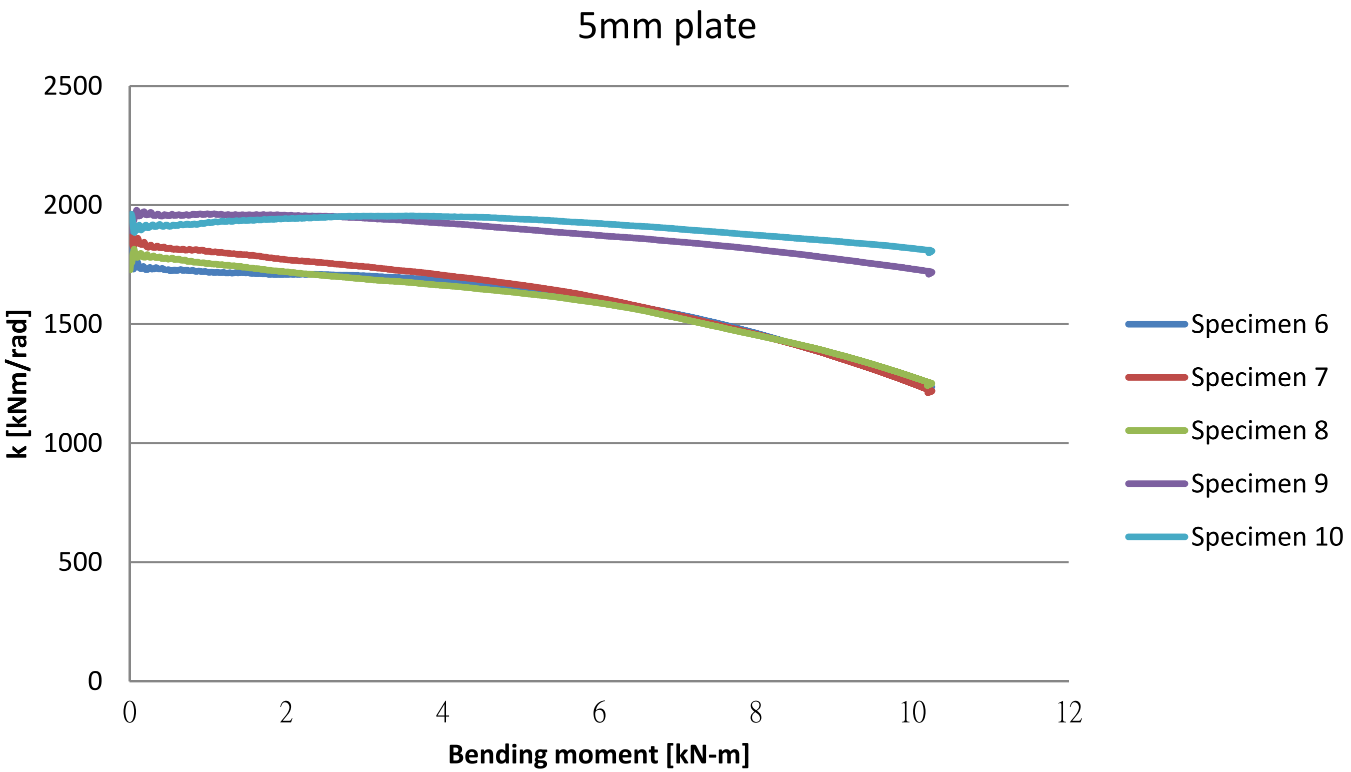
3mm and 5mm plate pattern 1 results

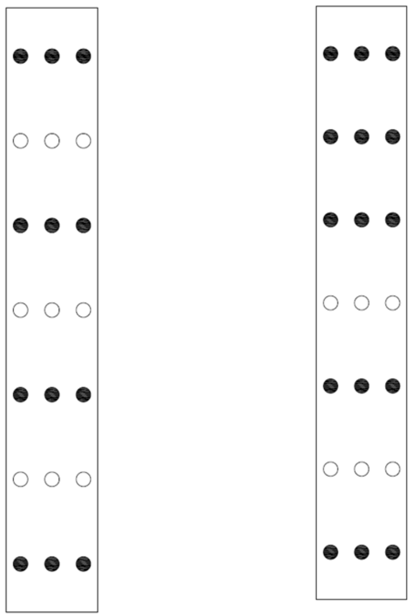


3mm Specimen1-5

5mm Specimen6-8

Laboratory test results



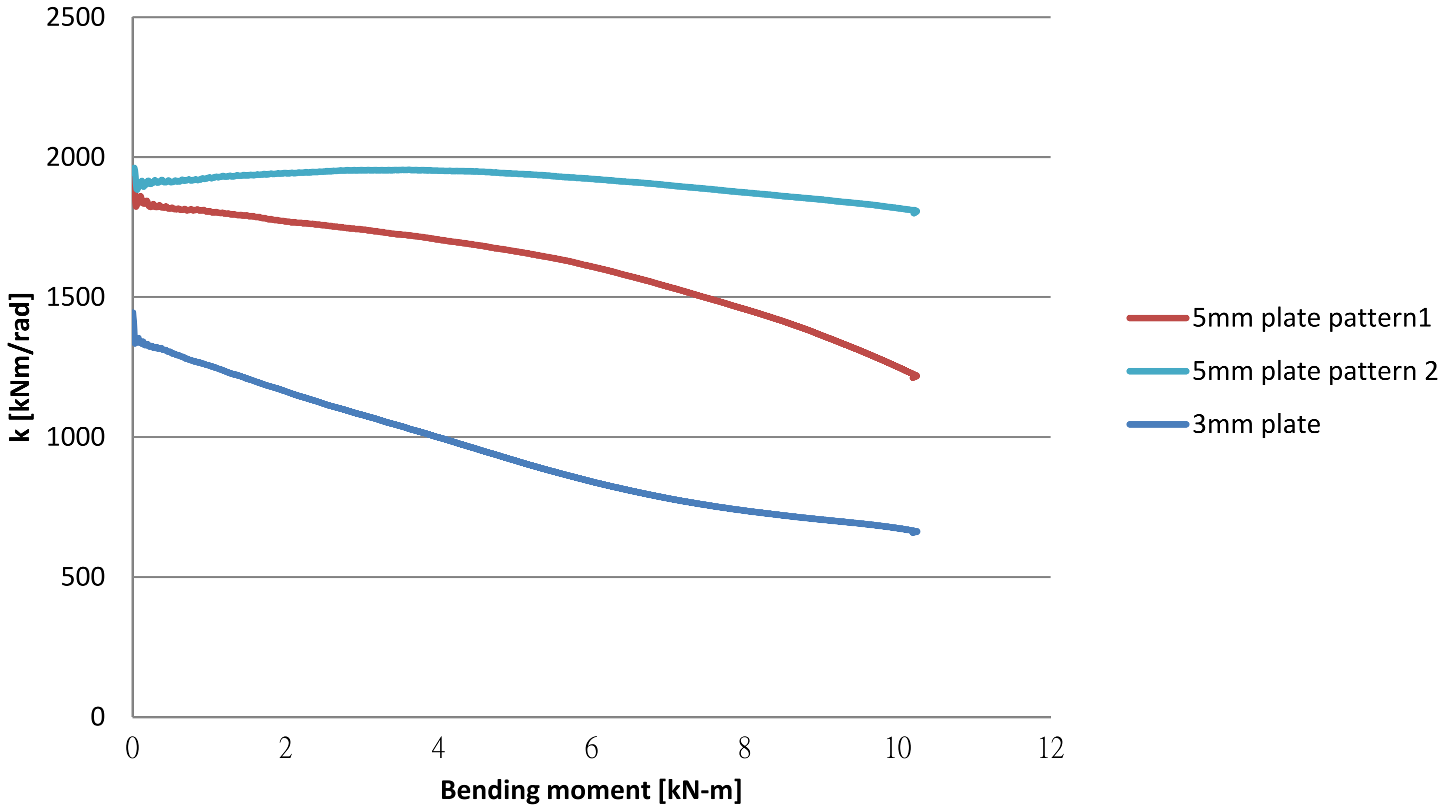


Pattern 1
Specimen6-8

Pattern 2
Specimen9-10

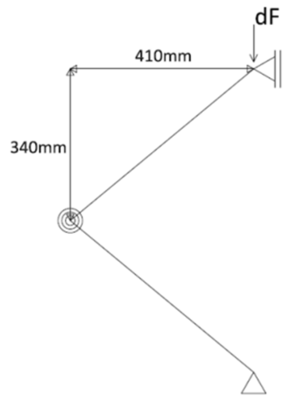
5mm plate, pattern 1&2 results

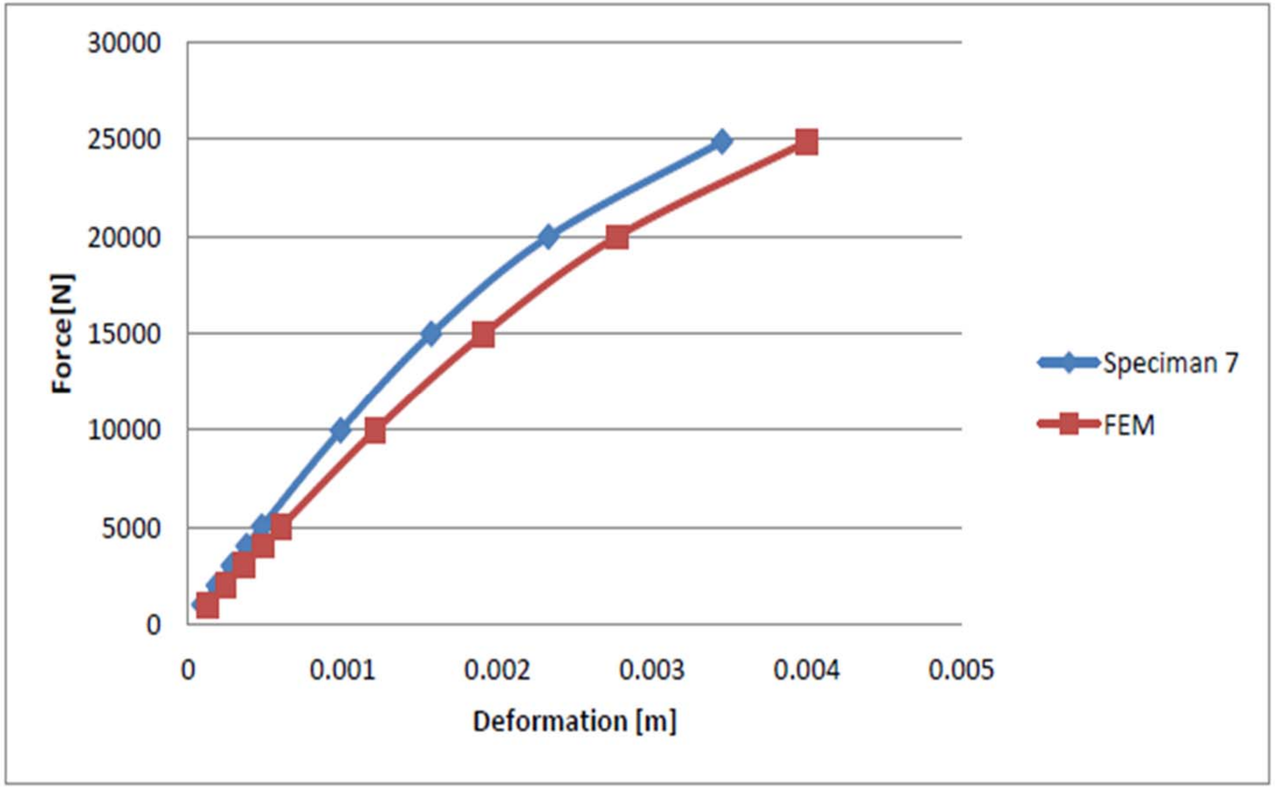
Laboratory test results



3mm and 5mm plate, pattern 1&2 results

FEM & Laboratory test results comparison





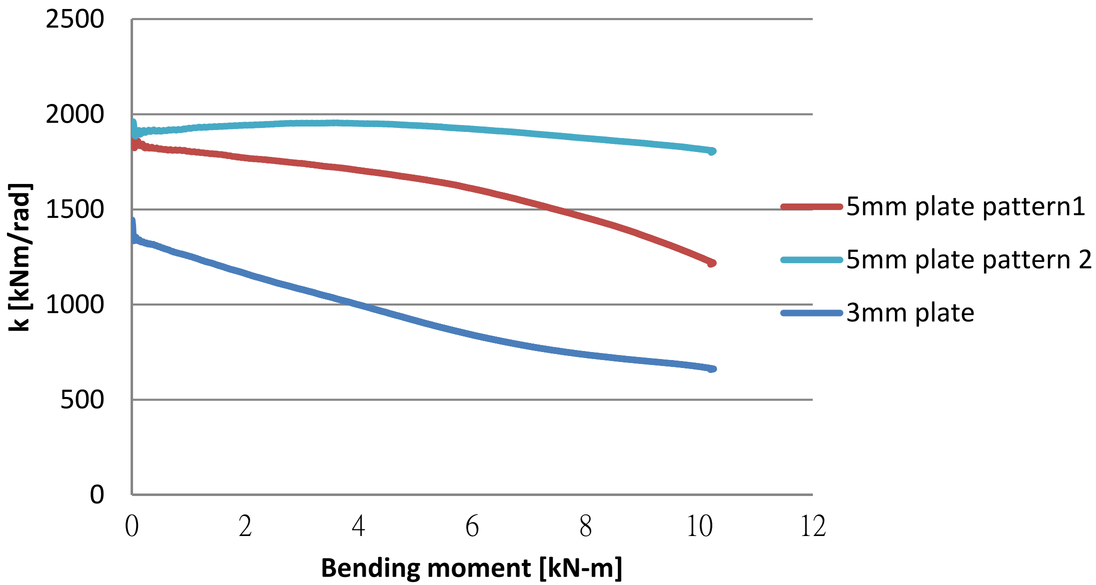
FEM and lab test comparison

Laboratory test - conclusion

- 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.

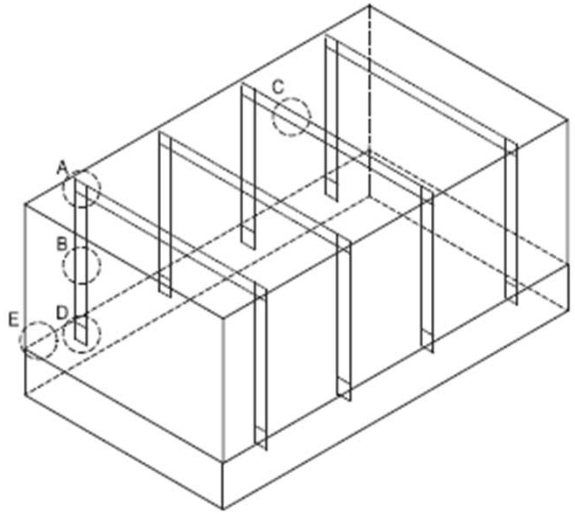
- The FEA has similar results as the lab test results

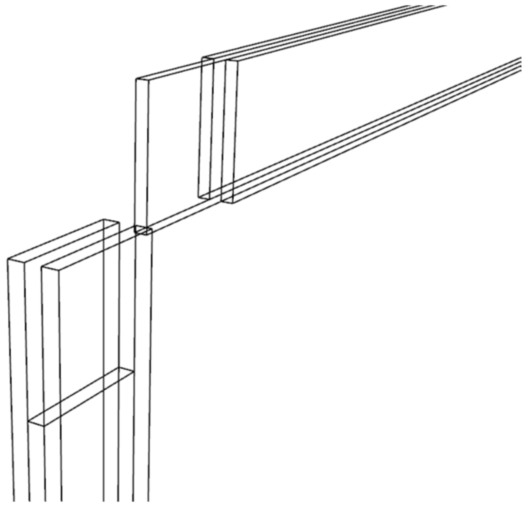


Comparison with adhesive connection

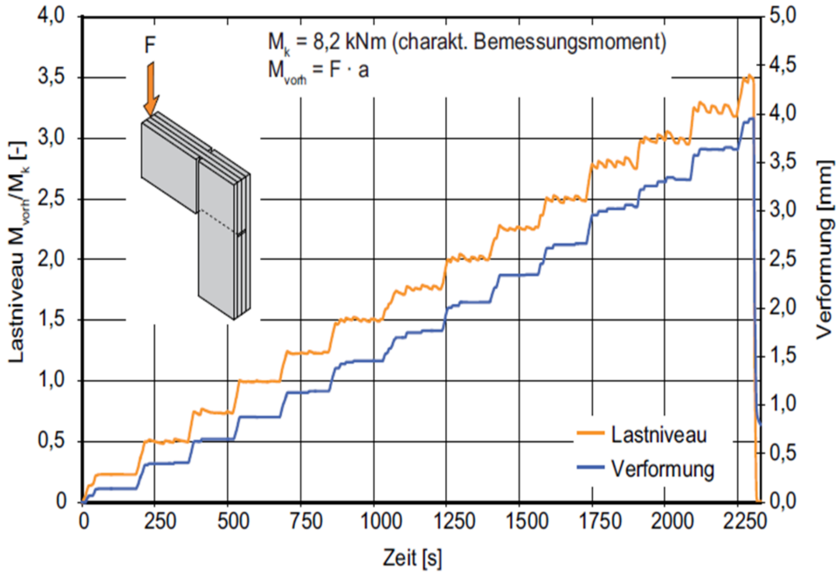
Leibniz Institute for Solid State and Materials Research,Dresden,Germany

7.7x4.4x2.5m pavilion , with 250mm wide beam and column, Bridle joint with transparent acrylic adhesive connection

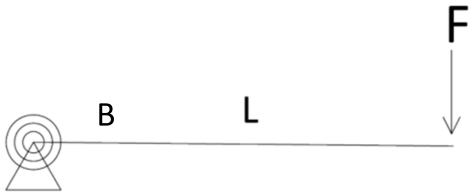


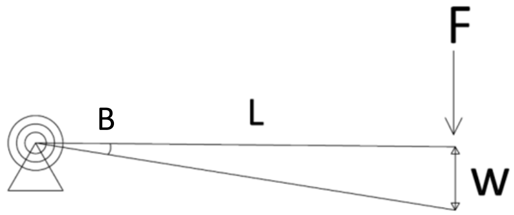


Comparison with adhesive connection

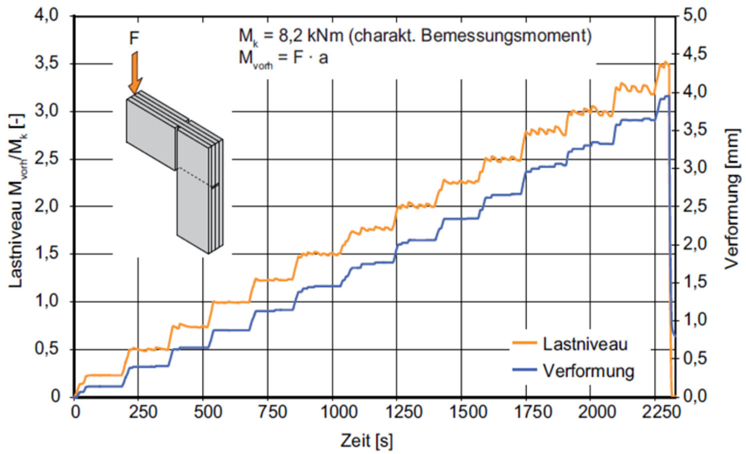


Comparison with adhesive connection





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

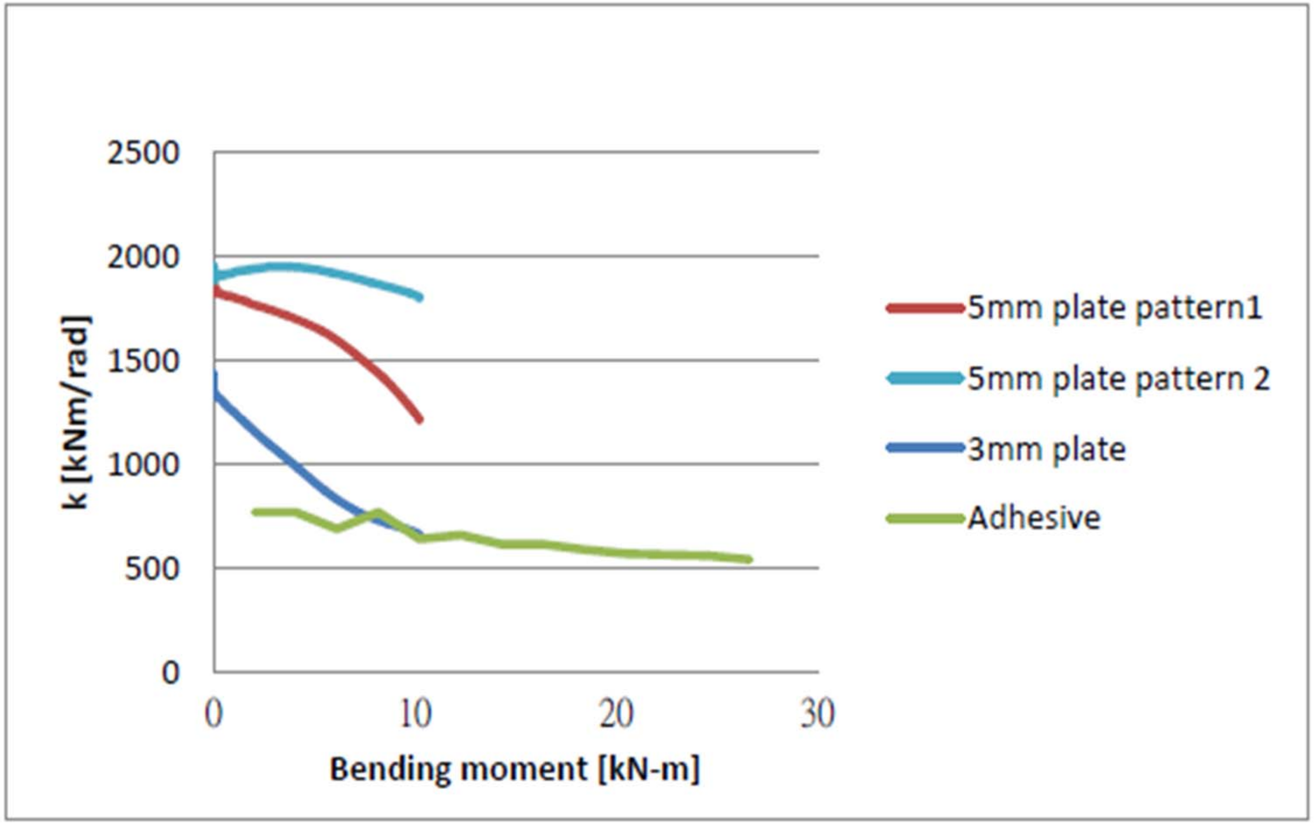


mvorh/m	F	Displacemer	k	Moment
	[kN]	[m]	[kNm/rad]	[kNm]
0.25	2.733333	0.002	768.75	2.05
0.5	5.466667	0.004	768.75	4.1
0.75	8.2	0.0067	688.432836	6.15
1	10.93333	0.008	768.75	8.2
1.25	13.66667	0.012	640.625	10.25
1.5	16.4	0.014	658.928571	12.3
1.75	19.13333	0.0175	615	14.35
2	21.86667	0.02	615	16.4
2.25	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

Comparison with adhesive connection

Conclusion

- Adhesive connection is more constant
- L-shaped connection has higher rotational stiffness



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

Design process

Original design process

Basic design
Decide the dimension of the portal frame, the height and the span.

↓

Rule of thumb
The height of the beam is 1/15-1/20 span and given it a estimated thickness.

↓

Theoretical calculation
Calculate moment and deformation. and check if the maximum deformation is within the SLS, 1/200 span.

↓

FEM Analysis
Check stress and deformation regarding ULS and SLS in FEM. For example, deformation should be less than 1/200 span. and check lateral bucking

↓ ↑

Adjustment
For deformation, it is more efficient to adjust height of the beam, due to I= bh3/12.Adjust the thickness due to stress and lateral buckling and choose the glass type:
annealed glass
heat-strengthened glass

↓

Final design

New design process

Basic design
Decide the dimension of the portal frame, the height and the span.

↓

Rule of thumb
The height of the beam is 1/15-1/20 span and given it a estimated thickness.

↓

Theoretical calculation

- Calculate the k when stress is at its ULS depends on the type of glass is decided to use.
- Calculate the k when deformation is at its SLS , which is 1/200 span
- Calculate the moment diagram and find rotational stiffness k when $M_M/M_B=1$

↓

Comapre three k and choose the k which meet both criteria of ULS and SLS, and withint the find the closest k to the k when $M_M/M_B=1$.

↓

FEM Analysis
Check stress regarding ULS , deforamtion regarding SLS in FEM. and check lateral bucking

↑↓ ↘

Adjustment

Glass beam
Adjust the thickness due to stress and lateral buckling
choose the glass type:

annealed glass
heat-strengthened glass
tempered glass

L-shaped connection
By changing
-the thickness of the plate
-the number of bolts
-the material
of the L-shaped connection to achieve the wanted /desired rotational stiffness k

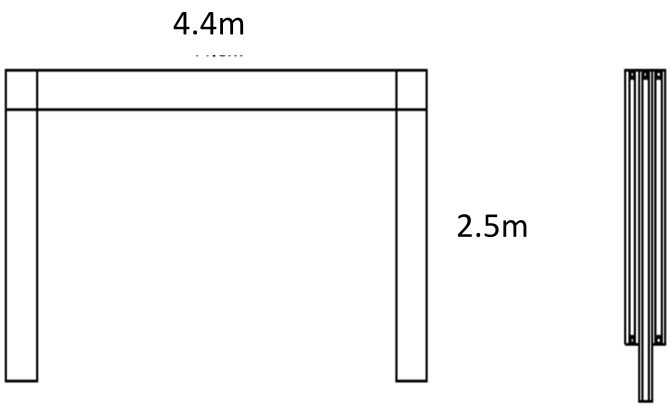
↘ ↙

Final design

Design process- Conclusion

New design process applies to the Dresden glass pavilion

The new design procedure
- can efficiently find the smallest beam height
- desired rotational stiffness k for the portal frame design



Comparison of beam-column connection in glass building

- Structural & Safety
- Construction
- Maintenance
- Aesthetic
- Transportation
- Benefits

Comparison of beam-column connection in glass building

	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

Comparison of beam-column connection in glass building

	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

Conclusion

- The L-shaped connection has many advantages;
  - High transparency
  - Easy for construction
  - Easy maintenance
  - Safer structure

- 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.

Recommendation

- 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.

Thank you for your time!