Challenging Glass 7
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Façade becomes structure

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The Green Village at the TU Delft is a living lab for sustainable innovations. The Co Creation Centre will be their new meeting centre. This centre is getting a climate tower and to get the isolation standards, triple glass was necessary. Unfortunately, the original design for the centre was too expensive. The triple glass was one of the big cost items. Then the team got the ingenious idea to use the façade as the bearing and stabilising structure. This idea made the project feasible in costs. The aim was to design a façade with as few as possible modifications compared to a standard façade. In the future Triple glass will become more and more standard. The Triple glass is structurally oversized and therefore the material is not used optimally, which makes triple glass less sustainable in using raw materials. Triple glass can be made more sustainable if we utilize this overcapacity for the structure. Using glass panels for stabilising a structure has been done before. But often it becomes a complex façade in assembly. In this façade silicone joints are used to initiate all the forces and the normal way of mounting is followed. And the team even went one step further. In the original design the building had both columns for the roof load and glass fins to take the wind loads from the façade panels. The glass fins are an expensive part of the façade. Since glass is good in compression, why not use the fins as columns? Of course the buckling of the fins is an important risk since these fins are 5.2 meters high. By clamping the fins between the glass panels the buckling risk is reduced significantly. ABT made FEM calculations using the DIANA software to find the critical parameters for this structure. It was found that the spring stiffness of the horizontal support by the façade is the most critical element. To verify the DIANA calculations two glass fins were tested at the TU Delft at the end of September 2019. By utilising the materials better the use of raw materials and the costs are significantly reduced. With that a more sustainable design was achieved. The aim is to develop this into an innovative standard system.

Keywords: Stabilizing glass structure, Load bearing glass fins, Structural silicone sealant, FEM DIANA stability calculations for glass, sustainable

1. A problem becomes a solution

This paper starts with a common problem; there is not enough budget for the designed building. By innovative thinking the problem is turned into a solution: Using the façade as a structure reduced costs to an achievable budget.

1.1. The project

The project is the Co Creation Centre, a new meeting centre for The Green Village at the TU Delft. The Green Village is a living lab for sustainable innovations. The Co Creation Centre is 22,5 meter long, 13,5 meter wide and 6 meters high.

The design team consist of Mecanoo as the architect, Si-X as the contractor for the glass structures and ABT for the structural engineering.

1.2. First design

In the first design the roof was carried by glass spans with a span of 22,5 meter and demountable nodes. The stability was organised by glass stability frames. Both the demountable span and the stability frames were in an experimental stage at the university of Delft.

After calculation the costs of the project exceeded the budget. Triple glass was one of the big cost items. The team considered double glass but this would reduce the important Rc-value of the building. The consequence of that would be that the capacity of the climate tower and all the installations and installation space would have to become bigger. That option was impossible because the foundation was already realised with energy piles and End of Life concrete and could not be changed anymore.

Fig. 1 3D impression of the first design (3D impression by Mecanoo, Delft).

1.3. The solution

The design team suggested the idea to use the Triple glazing as stabilizing element. This would remove the need for the glass stability crosses. The architect was very excited about the idea because it gave a more visually quiet image. But the costs were still too high for the budget. Thereafter the design team proposed to use the wind fins as columns and skip the glass span. This was an uncertain trajectory because it was not sure that the glass fins could safely bear the load. In fact this choice made the project economically feasible but introduced an uncertainty in the technical feasibility. The solutions for that was to plan tests for the glass fins and to make a back-up plan in case the test would not succeed.

Fig. 2 3D impression of the optimized design (3D impression by Mecanoo, Delft).

1.4. The structural design

The building plan is 22.5 meter wide and 13.5 meter deep. The total building is 6 meter high. The wind fins stand every 1.5 meter in the façade. On the fins, all around, a steel edge beam is placed. The roof beams are steel beams which lay every 3.0 meter on the edge beam. The position of the steel beams is always halfway through the position of the glass fins. The façade panels are 1.5 meter wide and 5.2 meter high. They span between the wind fins.

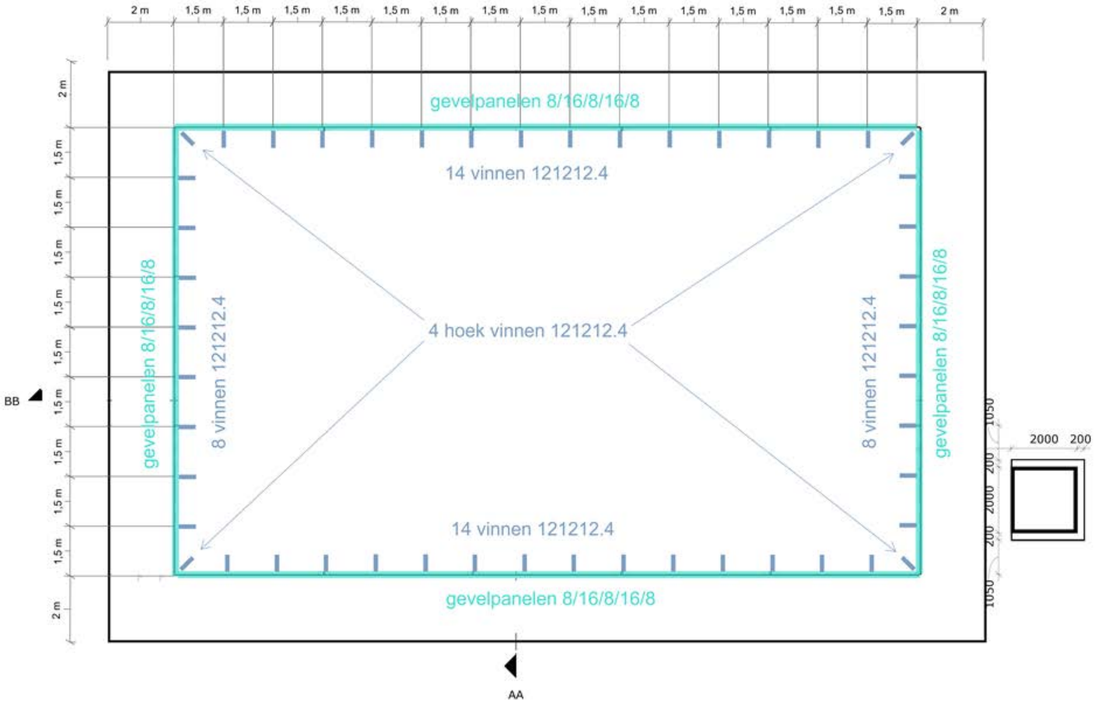

Fig. 3 stabilizing and bearing glass structure in plan.

The stabilizing glass panels of the façade are made of fully tempered glass. Because of safety reasons fully tempered glass or laminated glass was prescribed. Laminated glass would lead to two laminated glass plates and this thereafter would lead to a very heavy glass panel. Each glass pane of the Triple glass is 8 mm thick.

The glass fins are made of thermally toughened glass, three times 12 mm with Sentry glass interlayers.

In the first design the glass fins were positioned in the middle of the inside pane of the triple façade glazing.

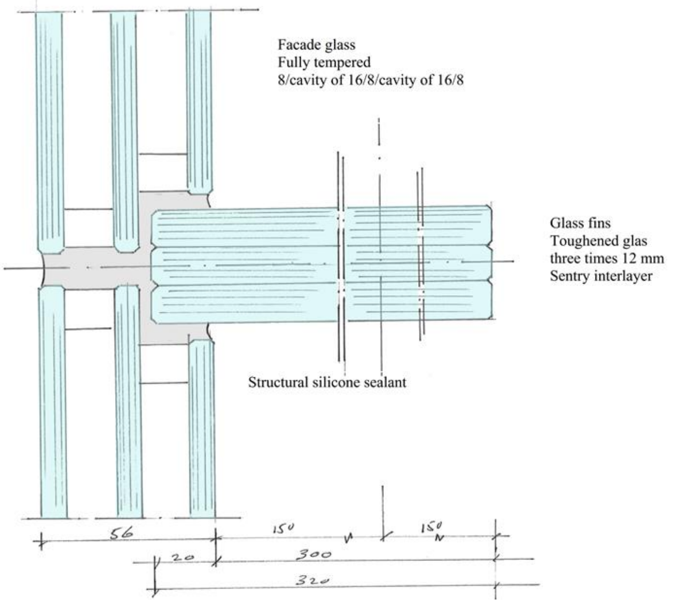

Fig. 4 horizontal section of connection fin and façade glass in the first design.

2. Stabilizing triple glass

Triple glass is more massive due to the double cavity and therefor often structurally over dimensioned. However triple glass gives better isolation the extra material make the product less sustainable in terms of raw material usage. Triple glass can be made significantly more sustainable if we utilize this overcapacity for the structure.

Using glass panels to stabilize a structure has been done before. But often the glass panels are put in between small blocks which can be seen in the structural sealant and complicate assembly. In this façade only silicone joints are used to transfer all the forces and the conventional assembly method is used. This was challenging because the allowable stress for short term loads is only 0.14 N/mm².

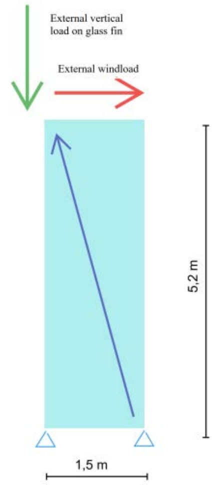

Fig. 5 mechanical scheme for stresses due to horizontal wind load.

The horizontal load on the glass panel is transferred by the horizontal structural silicone sealants from the roof structure to the Triple façade panel and from the triple façade panel to the foundation structure.

The vertical component that arises is transferred by the vertical structural silicone sealants to the glass fins. This gave stresses that exceeded the allowable stress of 0.14 N/mm² and therefore the structural depth of the silicone sealants hade to be enlarged. This gives a less optimal detail for thermal conditions of the façade and this can be optimized in further projects.

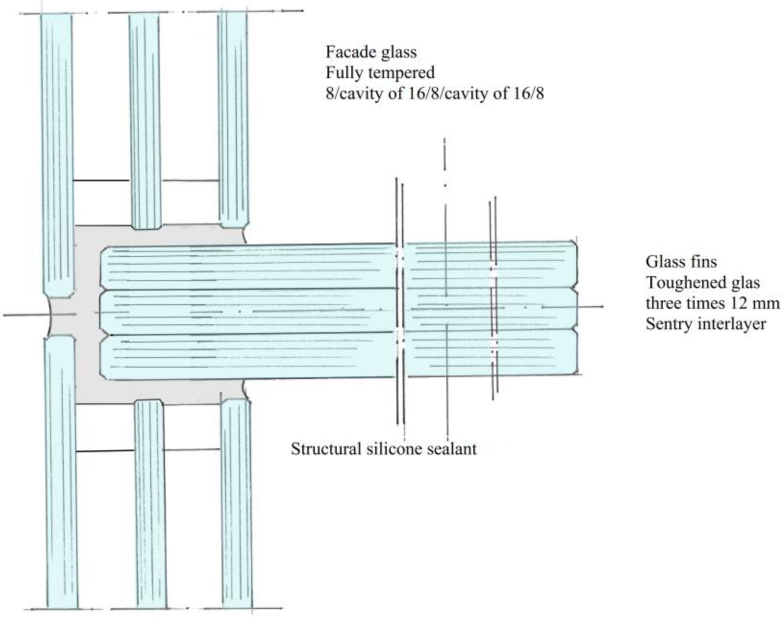

Fig. 6 mechanical scheme for stresses due to horizontal wind load.

3. Load bearing capacity glass fins

To determine the load bearing capacity of laminated glass fins, taking into account the buckling behavior and the lateral supports, no validated methods are available. Research is available (Luible & Scharer, 2016) and (Sonck & Belis, 2016) but this research is more about beams where the bending moment is more decisive. For the glass fins in this project the normal force is decisive.

Because of the progress of the project there was no time to do extensive tests. Therefor first FEM DIANA models were built to find the sensitivities of the parameters and to find a save lower limit. After that a test setup was made and two glass fins were tested at the TUDelft.

To prevent a non-feasible project when the test would not succeed a plan B was made. The plan B was to apply connecting struts at the backside of the fins. This would reduce the buckling length and would result in a appliable solution.

3.1 DIANA FEA calculations

In the FE program DIANA, a glass fin consisting of 3 layers each with a height of 5200 mm, a width of 300 mm and a thickness of 12 mm was modelled with shell elements. A surface interface between the three glass layers was modelled with a negligible shear stiffness to model the lower limit situation where the three layers do not work as one whole. To model the horizontal support on the front vertical edge, two boundary line interfaces were applied at each edge of the first and third layer with a horizontal stiffness normal to the glass fin.

For the first calculations linear buckling analysis was performed for different values of the horizontal stiffness. From these calculations it seemed that the stiffness of the lateral support on the front side had a big influence on the linear buckling load. An overview of the first mode shapes with linear buckling loads is given in Fig. 7 and Table 1.

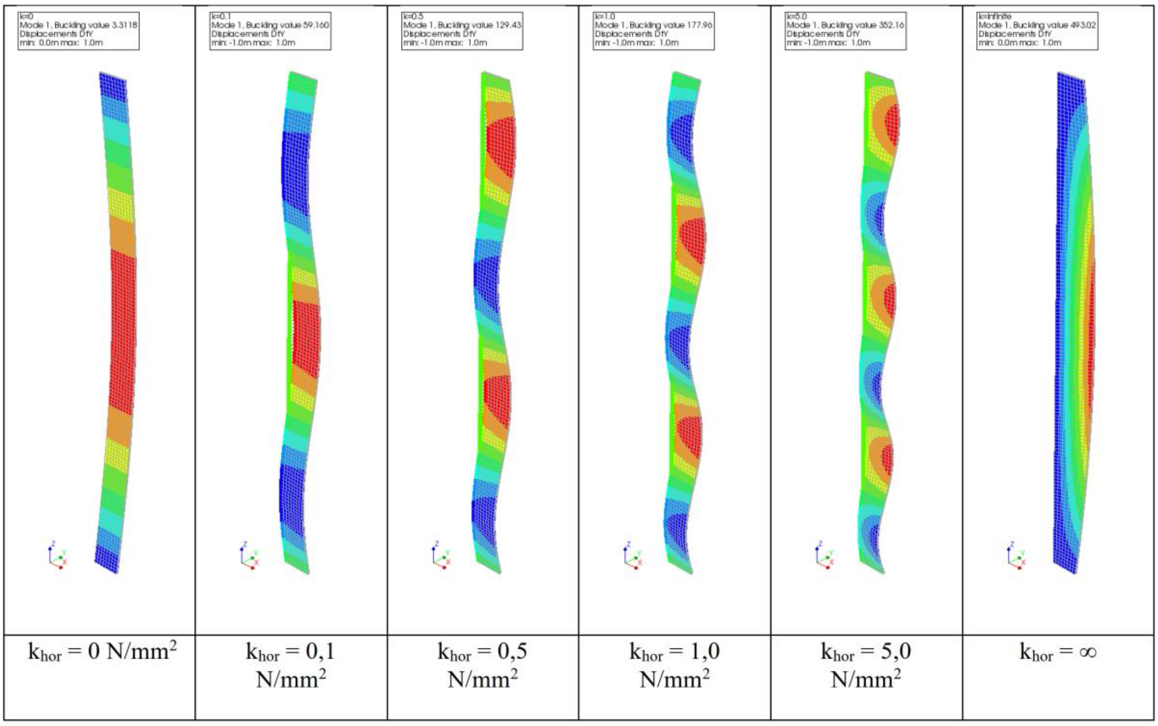

Fig. 7 First mode shapes from linear buckling analysis for different horizontal stiffness values.

Table 1: Overview of linear buckling load related to stiffness of lateral support.

Stiffness of lateral support [N/mm^2]	Linear buckling load F [kN]
No support	3.3
0,1	59.2
0,5	129.4
1,0	178.0
5,0	352.2
∞	493.0

The equivalent stiffness of the line interface based on the stiffness properties of the structural sealant is expected to be 1.0 N/mm². So according to calculations, the linear buckling load would be approximately 178 kN.

One of the big uncertainties was the initial imperfection of the glass fin, the influence of which is not taken into account in linear buckling analysis and can lead to a significant lower load bearing capacity compared to the linear buckling load. To obtain a conservative lower limit for the load bearing capacity, a further geometric nonlinear structural analysis was performed including an initial imperfection. The initial imperfection was taken as $w_0 = (l/5)/400 = 2.6$ mm and is based on the first mode shape with 5 waves from the linear buckling analysis with a specified scaling factor of 0.0026. The geometric structural nonlinear calculation then starts off from this initial deformed shape with the vertical load being increased in steps. From this analysis, stresses and absolute displacements could be obtained. In Fig. 8 the occurring stresses in the outer fiber and displacements at a load of 150 kN are shown.

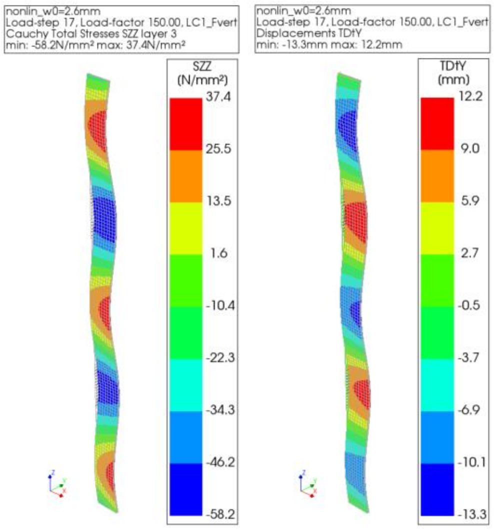

Fig. 8 Stress and displacement results from geometric nonlinear structural analysis.

To evaluate the sensitivity of the initial imperfection, calculations were also run for different values for the initial imperfection, 1 mm and 5 mm respectively. In figure 3 the vertical load is plotted against the maximum horizontal displacement for the different variants. Also a graph is shown where the vertical load is plotted against the maximum occurring stresses. It can be seen that the initial imperfection has a significant influence on the maximum occurring stresses at a certain load. If one assumes a tensile strength of 40 N/mm² , an initial imperfection of 1.0 mm would lead to a possible failure load of approximately 168 kN whereas an initial imperfection of 5 mm would lead to a possible failure load of approximately 130 kN.

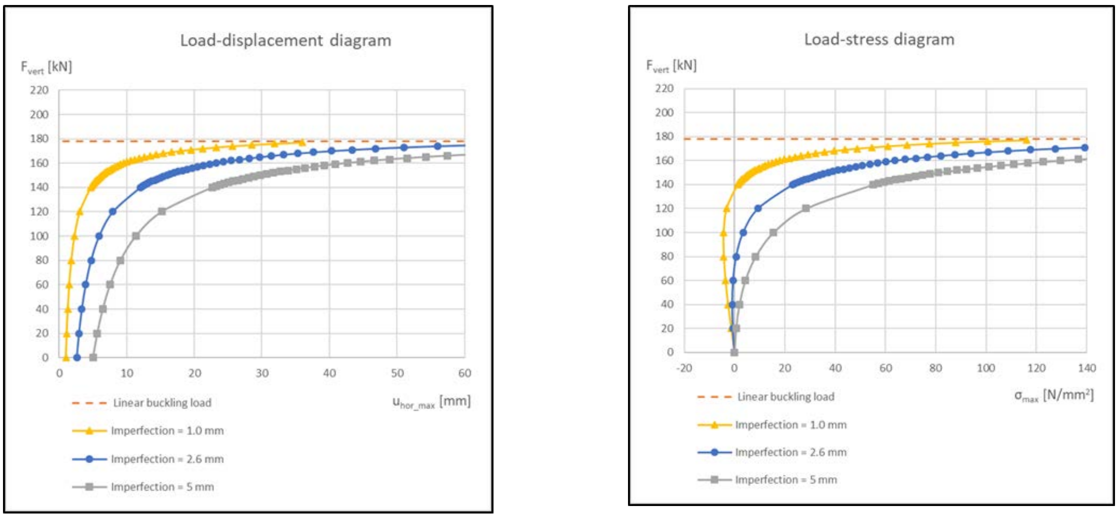

Fig. 9 load-displacement and load-stress diagrams for different values for the initial imperfection.

The influence of wind-pressure and wind-suction in combination with a normal force was calculated with a lateral support of 1.0 N/mm². The conclusion was that the wind load had a negligible influence on the results.

3.2 Pressure testing

To validate the lower limit buckling load of the glass fins in December 2019 two glass fins were tested in the lab of TUDelft. The glass fins were connected with structural silicone to a steel profile representing the lateral support of the facade panels. The first glass fin was loaded until 125 kN (125% of maximum design load). The load was held for 10 minutes. No damage was observed to the specimen. After this the right ply was severely damaged and the fin was loaded until 125 kN. No increase in damage was observed to the specimen. Then the left ply was also damaged and the fin was loaded until 125 kN. No increase in damage was observed.

The second column was loaded to 200 kN and no damage was observed. After this the column was unloaded and all three plies severely damaged. This column was loaded to 200 kN. No buckling or increased damage was observed.

Possible explanations for why this higher load is observed compared to the initial FE analysis are:

- Smaller / negligible imperfection
- Positive effect of the Sentry interlayers causing the glass layers to work together
- Higher stiffness of the horizontal support along the vertical edge than assumed

Based on this result it was concluded that the design was safe and that plan B was not necessary.

Fig. 10 column in test machine.

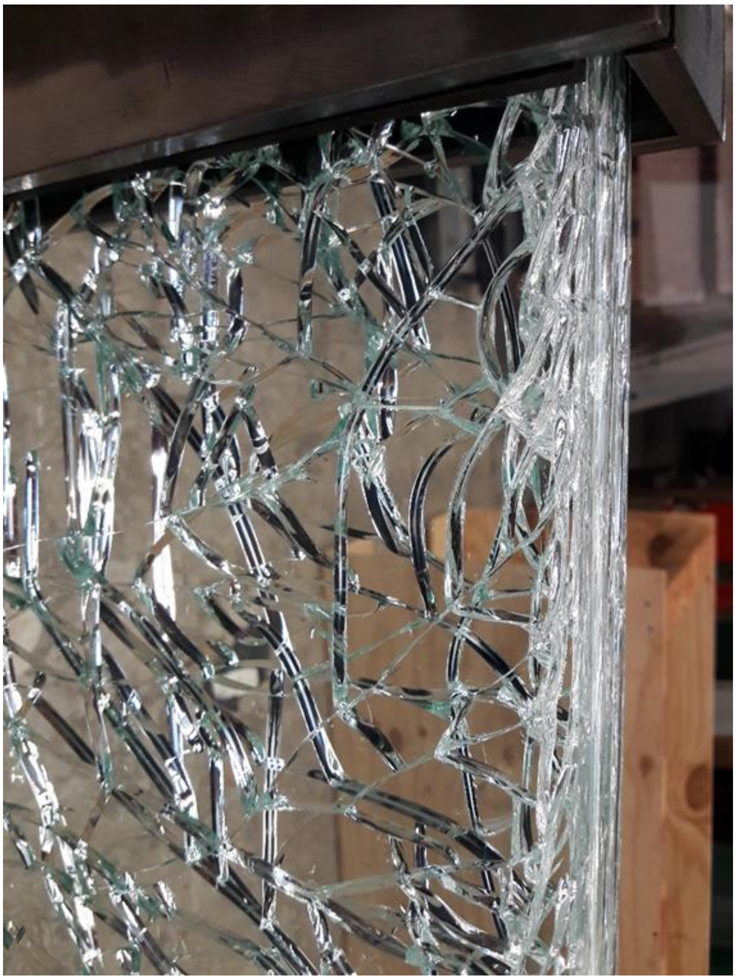

Fig. 11 column after damage on purpose.

4. End result

The installation of the façade glass panels and glass fins is finished. The roof and the inside floor will be installed.

Fig. 12 Co Creation Centre during installation in January 2020.

Using the façade as part of the main load bearing structure resulted in a significant cost reduction but also in less building material being required. So, after the successful conclusion of this project the question arises: .”How sustainable is a structural façade?”.

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