Towards Design Rules for Structures with Glass Panels During Impact

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The safety of glass structures is regulated by safety requirements. The Dutch safety standards for structures which are placed between height differences (NEN 6702) require a dynamic impact test. Failure of the structure may not occur to pass the test. Currently, no accurate tool is available to design the structure to meet the required impact test. Therefore, failure of the structure may occur when it is actually tested. Unfortunately, several glass structures fail the test each year. Here, a Finite Element Method based approach is used to integrally test the glass structure during impact. The strength and stiffness of the glass structure can be predicted on beforehand using this approach, reducing the risk of failure and minimising over dimensioning of the construction, which reduces the building costs.

Keywords: impact modelling, glass structures, design tool, “slingerproef”

1. Introduction

Structures with glass, and glass panels, are increasingly applied in practice. The glass structures are used for vertical separations, building facades and balconies, but also in horizontal separation such as stairs, floors and roofs. Safety standards require tests to ensure sufficient strength and stiffness of the structures. The Dutch standards demand both dynamic and static loading tests. The dynamic impact test for vertical separations, with height difference, is the “slingerproef” (“swing test”) (NEN 6702 art. 9.6) [1]. A glass pearl filled sack impacts the structure in this test. The complete structure is tested with this impact test, and the test often takes place just before the delivery of the building object. This test shows if the design of the vertical separation at height differences meets the required standards.

Classically, glass panels are clamped along an edge to fasten them to the underlying construction. More recently, point connections are used to fasten the glass panel to the structure. The point connections are increasingly used, partly because of their great aesthetic advantages. One disadvantage of this connection method is stress concentrations at the connection points.

There are virtually no guidelines for the design of the structure due to the large amount of uncertainty of the impact load in the test and the complex behaviour of the structure with respect to point connections in glass. Generally, the design of the structure is determined on the basis of experience. Particularly in the field of preload in the axial connection, the magnitude and the position of the impact load in the test and thermal influences ensure uncertainties in the design. Often, extra security is built in by over-dimensioning the design in order to cover these uncertainties. Despite the over-dimensioning of the structure the “slingerproef” always remains a “thrilling” affair in which failure of the structure, glass or underlying structure, still occurs too often.

This paper describes how design rules for complex constructions with glass panels can be determined. The design process of a balcony with glass panels is outlined, based on the “slingerproef”. The design process involves the use of the Finite Element Method, in which the balcony, including glass panels and underlying structure, is modelled.

2. Design requirements for vertical separation with height difference

The safety standards for structures which vertically separate height differences are described in NEN 6702. Both static and dynamic loading tests are described in this standard. Often static calculations are performed for (parts of) the construction, but rarely dynamic calculations.

The NEN 6702, article 9.6.1, prescribes a dynamic impact test, the “slingerproef”, on the structure. A leather sack, filled with glass pearls, with a total mass of 50 kg is swung against the structure in the “slingerproef” (see figure 1). Several positions in the structure can be tested, ensuring sufficient strength and stiffness of the complete structure (glass and underlying structure).

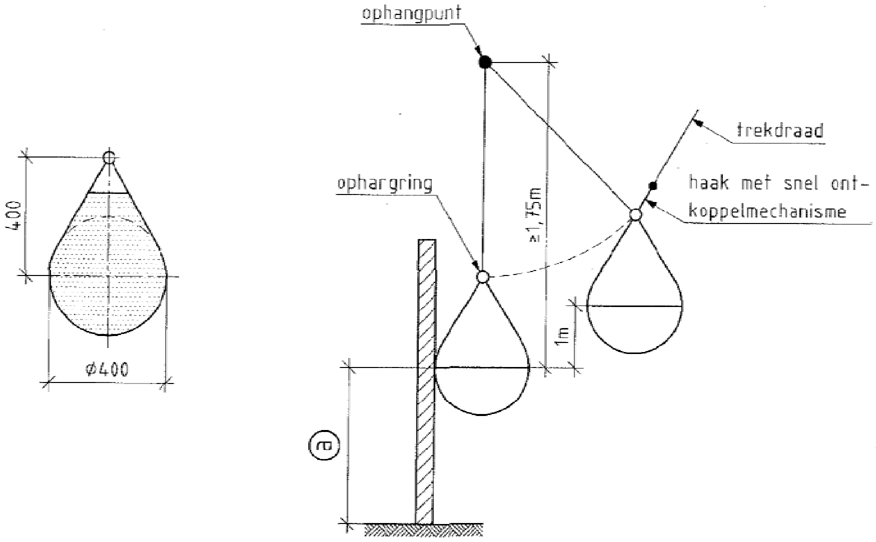


Figure 1: Schematic view at the “slingerproef”

The dynamic impact test may be replaced by very conservative static calculations as specified in NEN 6702, articles 9.6.2 and 9.6.3. Generally, these equivalent static calculations are not used since they will lead to uneconomic solutions. It is however expected that the current generation of simulation software packages can simulate dynamic impact tests.

The design and implementation of the connection between the glass and the underlying structure is crucial in structures with glass, and more critical than in structures with wood, concrete or steel. The connection itself can dominate the behaviour of the complete structure by imposing different boundary conditions to the glass.

It is therefore a challenge to simulate the complete structure with a Finite Elements Method. The loading behaviour, the connections in glass, glass panels and underlying structure must be included in the model in order to develop design rules for the test. Unpleasant surprises after testing the design in the “slingerproef” can thus be avoided.

3. ROC Twente balcony design

Balconies with glass panels are installed at the ROC Twente, Hengelo, the Netherlands (see figure 2). Obviously, the outdoor placed balconies must be safe to be used during summer and winter time. Safety regulations require a dynamic impact test to prove that the strength of the balconies is sufficient.

Figure 2: Overview, and detail photo of the ROC Twente balconies

Each balcony consists of a steel frame and three glass panels. The large front panel is fastened onto the steel structure at 6 points. The two smaller side panels are fastened at 4 points. The laminated glass panels consist of two plates of 8mm thick thermally prestressed glass, with 2 layers of PVB (1.52mm) between the plates.

The glass panels are fastened to a steel framework by point connectors. Each connector consists of a stainless steel bolt, a stainless steel nut, two stainless steel washers and two EPDM rubber washers. Each connector tightens the glass panel between the two rubber washers, which are compressed by the steel washers and nut. The pre-compression of the connector was set at 0.5 mm, which is equivalent to 2-2.5% engineering strain. A PVC bushing over the steel bolt prevents direct contact between the steel and the glass panel.

4. Integral design approach

A Finite Element Method (FEM) based approach is used to predict how the structure will behave under impact loading. This method can predict the impact behaviour of complex structures on a numerical basis. Car crash simulations are an example for this [2].

The calculations of individual parts of the construction will not suffice to determine the complex behaviour of the complete structure with glass. Therefore, a model of the total construction, including the underlying construction and the glass panels, with their connections, was built in SIMULIA [3], as is depicted in figure 3. Relevant effects such as axial preload in the connections, temperature effects and positions of the impact load can be investigated with this model.

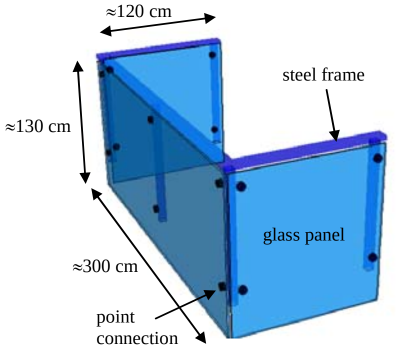


Figure 3: Finite Element Model Set-up

4.1. Modelling the PBV layer

The FEM model includes the layered construction of the glass. The two glass plates and the PVB layer are individually modelled with volume elements. The PVB layer has a significant effect on the bending behaviour of the glass panel. The deformation behaviour of a glass panel during bending is shown in figure 4. This behaviour is widely recognised and the theory behind this behaviour is taught in for instance the PAO course “Architectonische en constructieve toepassingen met glas” [4].

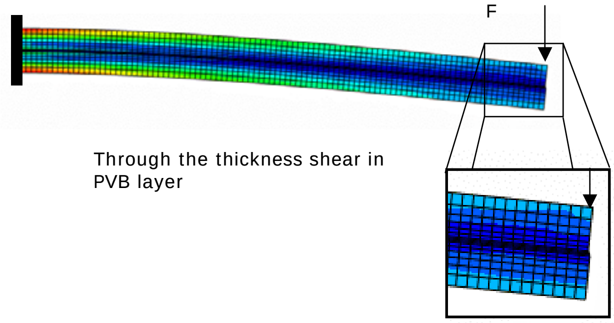


Figure 4: Through the thickness shear effects in the PVB layer

The PVB is a relatively weak thermoplastic material. It shows very temperature dependent properties in the temperature range between -25 to 50 °C. This temperature range is in the same range as specified in NEN 6702 table 12. This important behaviour of the laminated glass should be included for accurate predictions. A 50% reduction of the bending stiffness of the glass panel can be achieved easily, depending on the temperature and glass/PVB thickness. The effect of this behaviour on the performance of the system is evident.

4.2. Modelling the structural behaviour

The structural behaviour of the balcony during loading on the side panel and front panel is investigated. The front panel is loaded from the inside at a height of 70 cm from the balcony floor. The side panel is also loaded from the inside at 70 cm from the floor. The steel poles of the balcony are fixed at the bottom side, preventing any movement. The model set-up is shown in figure 5. The EPDM washers at point connections are pre-compressed with 0.5mm, mimicking the tensioning of the bolts. Contact was included in the simulations. The friction coefficient was set at 0.2.

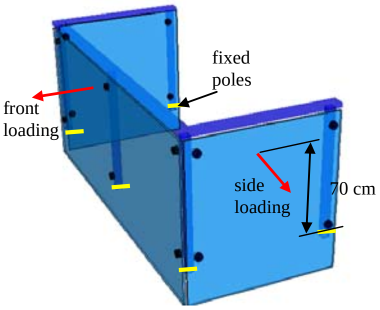


Figure 5: Positions of the front and side loading in the balcony

Mass effects are neglected during the simulation, simplifying the calculations significantly. The glass pearl filled sack is, as a first approximation, not included in the model, and replaced by a quasi static loading. An implicit solution scheme, which includes non-linear behaviour, was used to simulate the loading of the structure. The model focusses of the performance behaviour of the glass panels. An arbitrary stress of 139 MPa is assumed to be the onset of failure in the glass.

The temperature effect on the structural behaviour of the PVB layer is included in the model by changing the modulus of the material according to table 1 [4].

Table 1: Temperature dependent properties of the PVB material

Temperature (°C)	Modulus (MPa)
-10	1000
20	100
35	10

The properties of the glass (70 GPa) , steel (210 GPa) and EPDM washers (100 MPa) were not varied in the analysis.

5. Results

5.1. Model validation

The model has been validated on the basis of a static test. A load of 61 kg was horizontally positioned onto the loading position of the front panel. The measured deformed displacement was 1.2mm. This static test was reproduced in the model, resulting in a 1.25 mm displacement. The accuracy of the model is considered to be sufficient.

5.2. Loading of the front panel

The effect of loading the front panel of the structure was simulated, and the Von Mises stress results are shown in figure 6. The Von Mises stress is an equivalent stress measure to relate the stresses obtained in tensile tests to more complex stress situations.

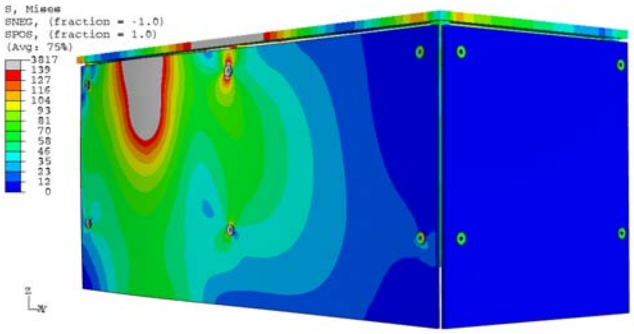
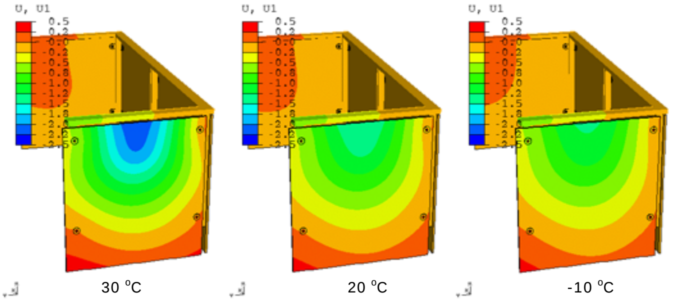


Figure 6: Von Mises stresses (MPa) in the front panel at 35kN loading

The highest Von Mises stresses occur at the position of the load. This stress is dominated by bending behaviour of the glass panel at this position. The CPU time used to simulate the loading on the structure was approximately 9 hours on a 64bits 2*Core2Duo@2.7GHz, 16GB memory machine using a single CPU.

5.3. Effect of temperature on side panel behaviour

The effect of loading the side of the structure was simulated, and the results are shown in Figure 7. The loading is simulated at various temperatures, showing the effect of decreasing stiffness of the glass panel by increasing temperature.

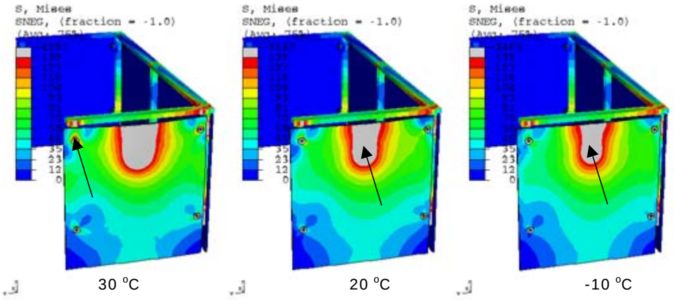


30 °C 20 °C -10 °C

Figure 7: deformations (mm) of the side panel at 1kN loading

Both the steel structure and the glass panels distorts significant, as shown in the results. Neglecting or overestimating the deformations in the steel structure can therefore lead to inaccurate results. It is obvious that the deformation at higher temperatures increases.

The Von Mises stresses as a result of the loading are shown in Figure 8. The magnitude of the stress is affected by temperature changes (stiffness). Consequently, the structure fails at a lower load if the temperature increases. The predicted position of failure remarkable changes from the center of the plate towards the point connection by increasing temperature (indicated by arrows). The effect of the point connection is significant.



30 °C 20 °C -10 °C

Figure 8: Von Mises stresses (MPa) in the side panel at 30kN loading

The testing of the structure at different temperatures is often not possible in practice since the structure is usually tested when installed on the building object. Creating a temperature controlled environment is quite difficult in such a case. A (numerically supported) design approach which accounts for all relevant loading, including temperature loading, is therefore of great importance.

6. Summary

This paper considers an approach to create a design tool for impact loading of glass panels. The Finite Element Method based approach can include effects such as temperature dependent material properties, effects of pre-tensioning on the connections, the stiffness behaviour of the complete structure and different impact positions.

Here, the complete “slingerproef” is not simulated. Instead, a static loading analysis is used to predict the structures behaviour. More work has to be done to include the glass pearl filled sack into the model. It is expected that the simulations including the sack will still give an acceptable simulation duration.

Also, this method can potentially predict invisible breakage, for instance behind the connection and predict the residual strength of a structure after for example a failed connection.

7. References

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