Structural use of glass: Cruciform columns and glass portals with bolted connections subjected to bending

Rasmus Ingomar Petersen, Anne Bagger
Ramboll Denmark, Teknikerbyen 31, DK-2830 Virum, Denmark

Keywords

1=glass structures 2=columns 3=bolted connections 4=portal frame

Abstract

Even small projects can contribute significantly to the understanding of how glass can be employed in the design of load bearing structural elements. During one such project, a reception building was added in front of an existing office block. In order to achieve maximum transparency glass columns were designed to support the roof, and a small entranceway was constructed entirely from glass. Tests were carried out to gain confidence in the design and assess the robustness of the glass structures. These tests yielded important insight in the behaviour of glass when employed as a structural material.

Introduction

Confidence to use glass as a structural material is built step-by-step from tests and experience gained from design and construction of small structures.

As part of the refurbishment of an industrial company's headquarters in Nordborg, Denmark, a new reception building has been constructed with emphasis on maximum transparency. The reception building's roof is supported by cruciform glass columns, and glass fin supported glazed façades allow an unobstructed view through the building.

A small entranceway – a glazed porch – leading the visitor through to a set of revolving entranceway designed as a stand-alone glass structure to support the main architectural concept.

This paper concentrates on the design of the glass columns and the entryway, where full-scale tests on key elements formed an essential part of the design process.

Architectural concept

The architectural concept of the reception building is to create a portal structure that straddles both the reception area and a small circular auditorium/cinema. All of this is set in a reflecting pool to mirror the sky and increase daylight conditions.

To reduce the structural span and keep the depth of the roof low, two rows of columns support the

Figure 1
Front view of the new reception building

Figure 2
Side view of the new reception building with the glazed entranceway

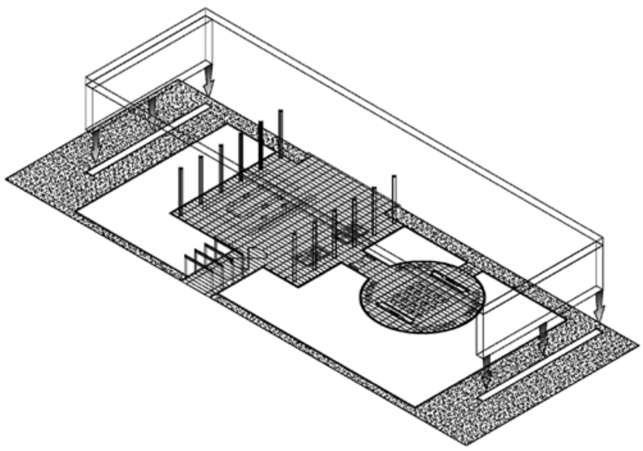


Figure 3
Layout of reception building with the entranceway in front

structure. Circular glass columns were initially considered but the design was eventually fixed on cruciform glass columns made up from multiple-layer laminated glass.

The entranceway in front of the building was designed as four sets of glass portal frames with sides and roof in laminated glass.

Design of glass columns

The glass columns are approximately 5,5 m tall with a cruciform section of 449×449 mm. Each arm of the cross is made up from 3 layers of 12 mm low iron float glass with 1,52 mm pvb laminates.

Two opposing arms were glued to each side to the one continuous glass plate with a hard adhesive, and the 5 mm gaps on each side of the non-continuous arms were filled with a clear silicone.

At both ends of the column great care was taken to ensure that no bending was transferred to the column. The column's ends were set in steel shoes inlaid with 10 mm thick neoprene strips, and the steel shoes connections to the floor and roof were detailed so that the column was unrestrained from rotation.

Structural calculations of the columns

Structural calculations were carried out involving:

A. Ultimate limit state analysis with a cross section consisting of only one layer of 12 mm float glass in both directions (assuming that the outer layers do not contribute to the load carrying capacity of the column). The ULS design load was 250 kN.

B. Accidental limit state analysis where one of the arms is removed and with only 2 layers of 12 mm float glass in the remaining 3 arms. Removal of one arm introduces bending in the column due to the off-centre loading of the column.

C. Accidental limit state analysis where one arm is subjected to a 0,7 kN concentrated load at the tip of the continuous arm.

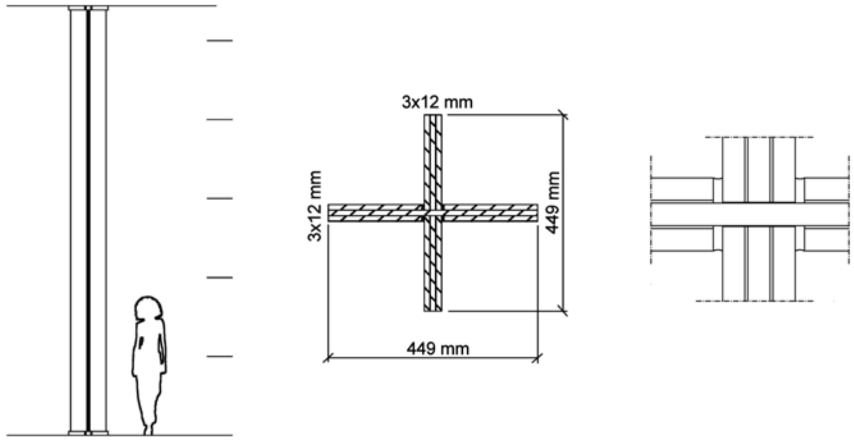


Figure 4

Dimensions and build-up of glass columns

In addition to this, the roof structure was designed with redundance so that forces could be redistributed if one column was removed.

The calculations concluded that the load bearing capacity of the cruciform columns was satisfactory. However, it was not considered possible to predict the strength of neither the glued connection nor the column's behaviour under dynamic impact (e.g. knocks from people accidentally bumping the columns etc.).

Furthermore, it was concluded that the assessment of the robustness of the column when one or more layers of glass were broken required full-scale testing.

Full-scale testing of columns

A full-scale specimen was tested at the Technical University of Denmark, Copenhagen.

The column was laid horizontally (supported at 1/5 points) and subjected to the following test regime:

Loading to full ultimate limit state axial load of 250 kN for 1 hour with subsequent unloading and checking of the neoprene strips in the steel shoes at both the column's ends.

Figure 5

Test set-up for full-scale testing of the glass column

Figure 6

Soft and hard impact testing of the glass column

Figure 7

Column after final up-loading and loss of load bearing capacity

The column was then subjected to soft and hard impact of the kind used for the testing of safety glass while the column was subjected to the serviceability limit state axial load of 190 kN.

Finally the column, with several of the arms heavily damaged from the hard impact testing, was loaded until the column lost its load bearing capacity. This was reached at an axial load of 575 kN. Loss of load bearing capacity was quite un-dramatic without harmful disintegration of the column.

The conclusion of the full-scale test was that the laminated cruciform glass column had sufficient resistance to impact loading and that the column's load bearing capacity was sufficient even when it was severely damaged.

Entranceway

The entranceway is considered to be a secondary structure for which a collapse is most unlikely to produce serious consequences. However, any structural failure is likely to yield bad publicity, and – glass being glass – any breakage will be highly visible in such a transparent structure positioned in a prominent location welcoming all visitors.

Design of the entranceway

Loads on the structure consist of horizontal loads (wind) and vertical loads (snow and dead load from the glass).

Longitudinal stability of the entranceway is provided through diaphragm action of the side walls' glass panes.

Transverse stability is provided through 4 portal frames set at 1,35 m centres made up from laminated glass beams and columns connected at the corners with stainless steel bolts. The outer dimensions of the portals are 3,84 m wide by 2,85 m tall. The glass members are made up from 8+12+8 mm toughened glass. The legs of one of the portals are wider than the others to accommodate a sliding door at this point.

Loads acting in the entranceway's longitudinal direction are quite limited due to the relative small area exposed to wind loading. The weight of the structure is sufficient to withstand overturning.

The side walls consist of 10 mm toughened glass panes. These are joined at the vertical edges through clear silicone joints.

The portals are simply supported at the footings by inserting the portal legs into steel shoes that are internally lined with EPDM to avoid direct contact between glass and steel and which will allow a small rotation to take place.

Rigid connections are necessary at the top corners to stabilise the portal since the footings are simple supports.

Glued connections have been used

Figure 8

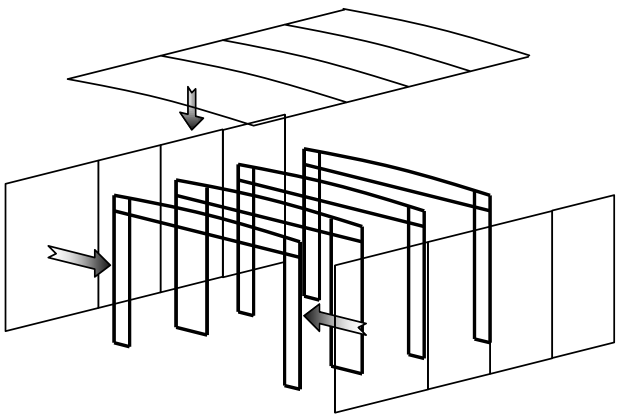
Glass columns in the finished building

Figure 9

The fully glazed entranceway leading to the reception building's revolving doors

Figure 10

Glass elements in the entranceway



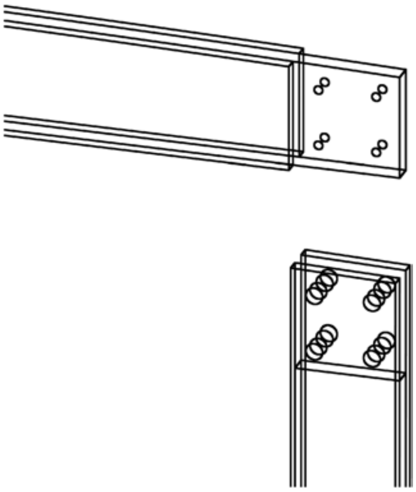


Figure 11

Bolted lap joint in the glass portals' corners.

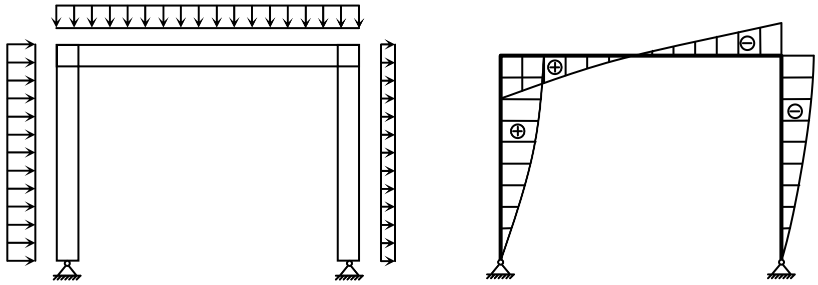


Figure 12

Loads on the portal and the resulting bending moment diagram

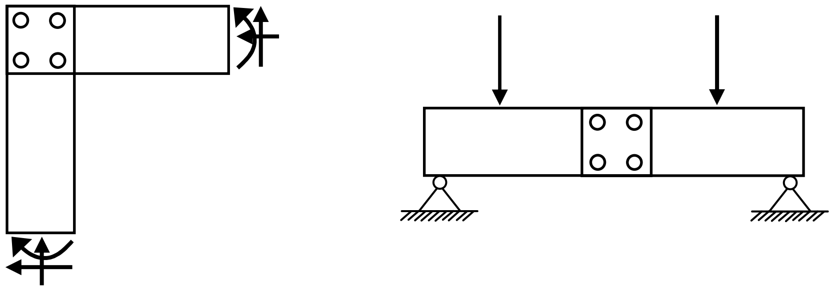


Figure 13

Bolted connection and 4-point bending test simulating the forces acting on the portals' corner connections

Figure 14

Test rig with test a specimen before and after breakage.

Figure 15

The reception building with glass columns

in other projects, but the long term effect of temperature, moisture and UV-radiation on hard adhesives is uncertain under Scandinavian weather conditions. A bolted connection was therefore chosen, and the central glass sheet in each portal's transom and legs was staggered to lap joint the members.

The critical ultimate limit state load combination for the jointing at the corners was found to be horizontal wind load combined with vertical dead load from the structure and snow on the roof. This load combination produced a maximum short term bending moment of 3 kNm.

Disks of clear polycarbonate were inserted into pre-drilled holes in the toughened glass sheets. The purpose of the disks was dual: To provide a soft interlayer between the glass and the steel bolt and to take up the small misalignment of the holes (in the order of ± 1 mm) which the laminating process can produce.

The disks were thus inserted into the glass holes and the hole for the steel bolt was drilled trough all three layers. This produced a tight fit between bolt, polycarbonate and glass. The forces acting in the bolted connection was calculated assuming linear-elastic stress distribution and a maximum force of 11,4 kN was found as a result of the bending moment, shear and normal forces acting on the connection.

Based on experience from other projects, the resistance of the glass was considered to be sufficient. However, in order to confirm this, two standard 4-point bending tests were carried out. The bending moment in the connection was chosen so that the maximum bolt force in the portal corner was reproduced.

In the first test, a 8+15+8 mm laminated toughened glass test specimen was used, and in the second a 8+12+8 mm laminated toughened glass test specimen was tested.

The test results confirmed the confidence in the design even though 2 tests are insufficient as a basis for a statistical evaluation of the strength of the connection.

Conclusions

The reception building was opened in 2006. Both the columns and the entranceway have withstood wear and tear during the time that has elapsed. Only problem seems to be that insects tend to get stuck in the small space between the glass plates in the entranceway's lap joints.

Summary

Much engineering work can seem repetitive and routine so everyone's senses are heightened when a gem like this reception building comes along. To design glass columns and glass portal frames forces the engineer to return to first principles and focus on careful detailing. Full-scale testing yielded valuable information and proved essential in order for the design team to gain confidence in the design.

Figure 16

Flies caught in the gaps in the lap joints

Acknowledgements

The author wishes to thank the façade contractor H.S. Hansen for giving Ramboll the opportunity to carry out the detailed design of one of the few truly structural glazing projects in Denmark. Furthermore, we would like to thank the client Danfoss and the architect Schmidt, Hammer & Lassen for their insistence on good architecture that extends the technical and esthetical limits.

Photo credits

Figures 1, 2, 8, 9 and 15: Adam Mork. All other figures by Ramboll.