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Experimental Investigation on the Structural Performance of Square Hollow Glass Columns Under Axial Compression

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This paper presents an experimental study into the global behavior of glass columns with square hollow cross-section under axial compression. In the research, totally 6 specimens were tested. All specimens were of the same geometry (length 750 mm, width 150 mm and 10 mm) but had different composition. Half of them were made of monolithic glass, with the other half made of laminated glass. The adopted interlayer material is PVB which is widely used in practice. During the test, vertical displacement, lateral deflection and normal stresses at mid-span were measured. For all specimens, local failure mechanism at the top or bottom due to progressive cracking was found, without any damage occurred at the glued joint. However, there is significant difference between the specimens made of monolithic glass and those made of laminated glass. Laminated glass columns had a sufficient residual capacity, able to carry compressive load in the post-crack stage, while monolithic glass columns collapsed quickly after the appearance of the first crack. Subsequently, the influence of the initial geometrical imperfection was studied in detail. Based on the results of experiment, the current findings could be further extended to various glass columns typologies (e.g. different cross-sections) in order to build appropriate practical design rules.

Keywords: Glass columns, Square hollow cross-sections, Axial compression

1. Introduction

As we all know, glass is increasingly used in load-carrying constructions due to its intrinsic transparency. While the investigation of glass members subjected to bending (e.g. beams and panels) is frequent in practice, glass members subjected to compression are relatively scarce, despite the fact that compressive strength of glass is much higher than its tensile strength. Consequently, there is still a lack of knowledge of mechanical properties of glass columns in different conditions.

The major role of glass columns is to transfer the vertical load from the floors or beams to the ground. Due to the existence of surface microcracks, glass is extremely sensitive to initial defects. Any local irregularities or eccentricities may lead to cracking and structural failure because of the progress of cracks. In the design stage, we should not only consider the initial resistance of glass columns before cracking but also the residual capacity in the post-crack stage. Hence laminated glass (LG) which consists of two or more glass piles bonded together is widely used for safety reason.

In recent years, some literature has been available on the mechanical properties of glass columns. Analytical formulation for the buckling performance of glass columns with rectangular cross-section has been put forward based on Newmark theory (Amadio 2011). With the help of it, Euler's critical load and buckling resistance can be calculated considering the boundary conditions and initial geometrical imperfections. Based on analytical and FE research, a design buckling curve has been proposed for glass columns under axial compression (Bedon 2015). Experimental and numerical studies on laminated glass columns with rectangular cross-section have been taken (Liu 2017). Influencing factors such as the type of interlayer, slenderness ratio and loading time are taken into account.

Compared to glass columns with rectangular cross-section, glass columns composed of several glass panels may have better structural performance considering buckling resistance. Hence extended studies are required on their mechanical behaviors including failure mode and load-carrying capacity. Experimental and numerical investigations on structural performance of glass columns with composite section including X-shaped and T-shaped have been proposed (Aiello 2011; Ouwerkerk 2011; Campione 2014). The results have shown that glass columns with composite section have higher stiffness and structural resistance. However, the quality of the adhesive connection between each panel has significant influence on the structural performance, hence requiring extended investigations and appropriate design method.

In this paper, experimental investigations on square hollow glass columns assembled by four glass panels are carried-out. All specimens were of the same geometry. Half of them were made of monolithic glass, with the other half made of laminated glass. During the test, vertical displacement, lateral deflection and normal stresses at mid-span were measured. According to the result, the difference between glass columns assembled by LG and those assembled by monolithic glass is proposed. Moreover, the influence of the initial geometrical imperfection was studied in detail.

2. Test program

The experimental program comprised a total of 6 tests conducted at the College of Civil Engineering in Tongji University. A detailed description of test methods is provided in the following sections.

2.1. Specimens

There were totally 6 specimens in the investigation. Each specimen was composed of four glass panels. Half of them are made of annealed glass with the other half made of laminated glass. Every single panel was characterized by length l=750mm and width h=150mm respectively. For annealed glass columns, the thickness of glass panels is t=10mm; for laminated ones, the thickness is t=10.38mm (5mm+0.38mmPVB+5mm). For each specimen, four panels were joined along the edges by structural adhesive (SikaFast-5211NT) with Young's modulus E_{glue}=250Mpa. The cross-section of the joints was d=10mm which equals the thickness of glass panels, with the depth of 2mm.

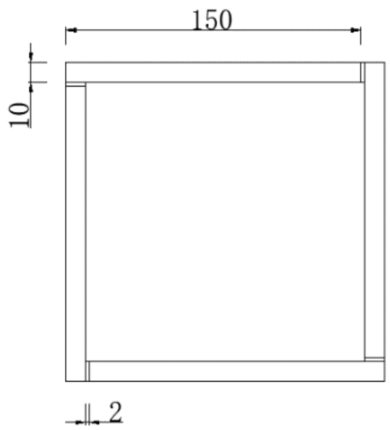


Fig. 1 The cross-section of specimens.

In order to ensure the accuracy of the test results, the dimensions of specimen have to be measured and checked before the assembling. The actual length, width, and thickness of each panel were measured. For each glass panel, the real dimensions were checked at three different sections along the glass panel span (e.g. close to the ends and at mid-span).The real dimensions of the test pieces are shown in Table 1 and Table 2, including the mean values.

Table 1: Real dimensions of monolithic glass columns.

Panel	L1			L2			L3		
	Length [mm]	Width [mm]	Thickness [mm]	Length [mm]	Width [mm]	Thickness [mm]	Length [mm]	Width [mm]	Thickness [mm]
A	749.8	149.0	10.00	750.6	150.8	9.75	749.7	150.2	9.80
B	750.1	150.1	10.00	751.0	151.0	10.00	750.0	150.2	9.75
C	750.2	150.7	10.00	751.2	151.0	9.80	749.0	150.8	9.80
D	750.7	149.7	9.90	750.8	151.2	9.80	750.0	149.6	9.75
Ave	750.2	149.9	9.98	750.9	151.0	9.84	749.7	150.2	9.78

Table 2: Actual dimensions of LG columns.

Panel	M1			M2			M3		
	Length [mm]	Width [mm]	Thickness [mm]	Length [mm]	Width [mm]	Thickness [mm]	Length [mm]	Width [mm]	Thickness [mm]
A	749.8	149.0	10.00	750.6	150.8	9.75	749.7	150.2	9.80
B	750.1	150.1	10.00	751.0	151.0	10.00	750.0	150.2	9.75
C	750.2	150.7	10.00	751.2	151.0	9.80	749.0	150.8	9.80
D	750.7	149.7	9.90	750.8	151.2	9.80	750.0	149.6	9.75
Ave	750.0	150.3	9.80	750.4	150.5	9.78	749.7	150.2	9.78

The assembly process of glass columns is important. The quality of the bonding and any initial geometric defect can directly affect the mechanical properties of the specimens. Firstly, each glass panel was cleaned to avoid impurities on the surface of glass which may influence the quality and durability of the bonding. In order to remove the dust and grease on the glass surface, acetone was used. Then a buckskin towel was used to wipe away the remaining liquid. After the cleaning, the two glass panels are placed on a V-shaped bracket prepared in advance, as shown in Figure 2, to ensure that the adjacent panels are relatively vertical during the assembling process. Since the thickness of the adhesive joint should be 2 mm, a 2 mm spacer is placed between the two glass panels. At the same time, in order to prevent the structural adhesive from leaking out before curing, the glass panels were sealed with transparent tape. After all the glass panels are bonded into a V-shaped member, two V-shaped members were finally assembled into a full hollow square specimen.

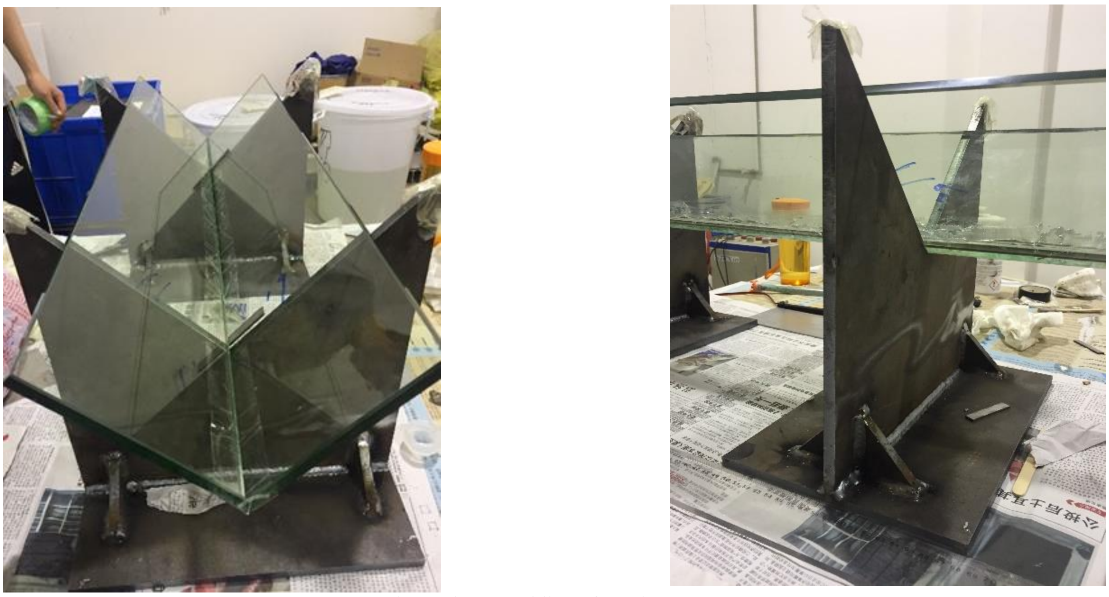


Fig. 2 The assembling of specimens.

2.2. Test method

In order to avoid direct contact between glass columns and the steel support which may lead to premature failure of glass, a plastic pad (PMMA) was used as shown in Figure3. These pads were designed as a two-stage component. Loads were transferred from the steel shoes to glass columns via PMMA pads, and this design can also limit twisting at the top and bottom of the specimen. After the glass columns and PMMA pads were relatively fixed, they were placed into a steel support.

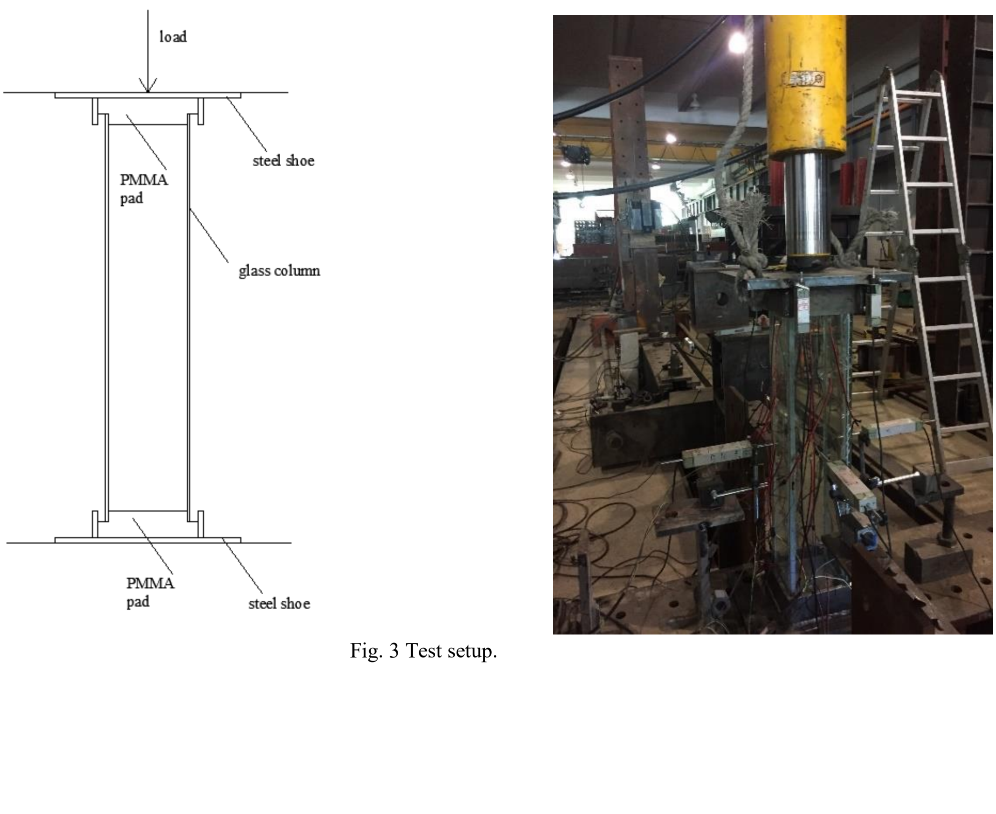


Fig. 3 Test setup.

The test setup is shown in Figure 3. Hydraulic jack was used for loading. The whole test was carried out in a load-controlled manner with hierarchical loading method. The load gap between each stage was 10kN and the loading speed is around 10kN/min up to collapse.

Data acquired from the tests consisted of applied loads, lateral displacement at the mid-span cross-section and elastic strains of the specimens. In detail, totally 40 gauges were used to monitor the vertical strain of each panel of the specimen. As shown in Figure 4, these gauges were installed at five height levels. The horizontal displacement was monitored by four LVDTs placed at the mid-span of the specimens. The accuracies of the load cell and the LVDTs were 0.1kN and 0.01mm.

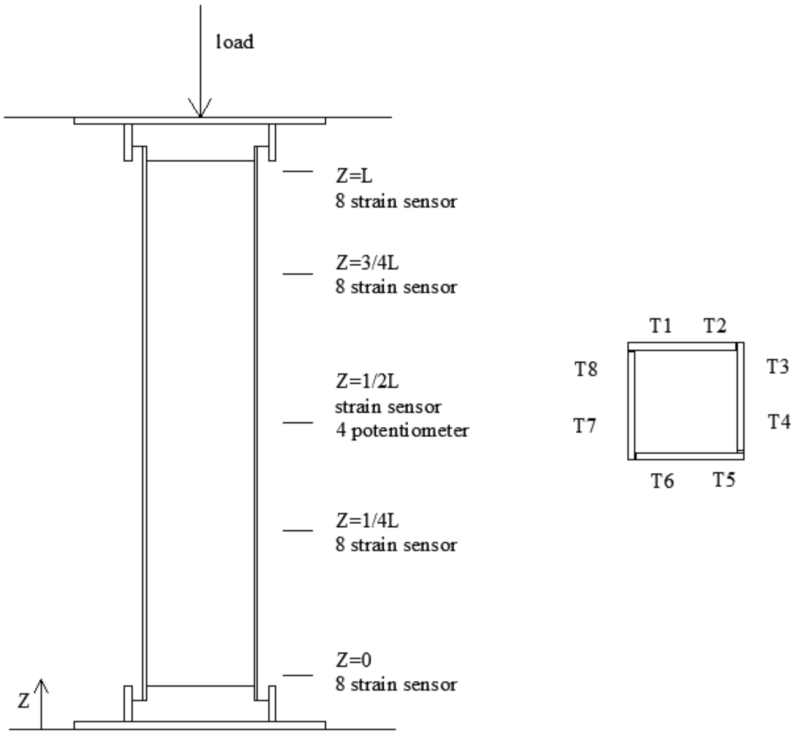


Fig. 4 Position of the strain sensors and potentiometers.

3. Test result

3.1. Overall performance

Table 3 presents the results in terms of the cracking load (N_{cr}), failure load (N_{max}), the values of N_{max}/ N_{cr}. There were totally 6 specimens among which specimen M1, M2, M3 were monolithic glass columns and specimen L1, L2, L3 were laminated glass columns. During the test, all specimens showed similar structural behaviors. They had great overall performance without any damage occurred at the glued joint. The structural failure started with a vertical crack at the top or bottom of the specimen. In post-crack stage, the compressive load could still increase to varying degrees. At last, local failure at the top or bottom happened which led to the collapse of the specimens.

Table 3: Cracking load and failure load.

	M1	M2	M3	L1	L2	L3
N_{cr}[kN]	659.1	488.4	318.6	273.3	311.2	399.6
N_{max}[kN]	688.2	489.9	380.1	376.6	462.4	517.2
N_{max}/ N_{cr}	1.04	1.00	1.19	1.38	1.48	1.29
Ave	1.07			1.38		

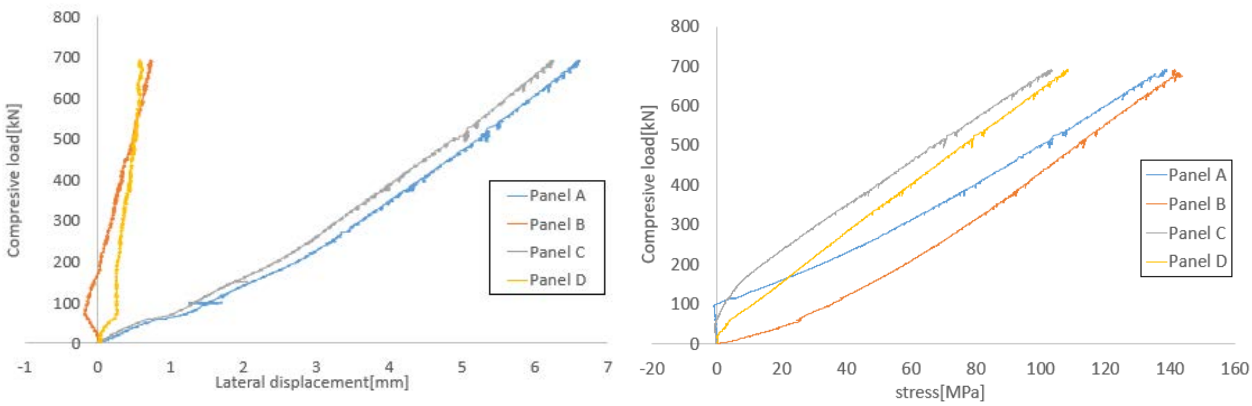
3.2. Detailed description

Since all 6 specimens had similar structural behaviors, M1 is taken as an example to be shown in detail.

As shown in Figure 5, the first crack, located at the top of the column (panel B), occurred at the attainment of a compressive load almost equal to $N_{cr,1}$=659.1kN. The further increase of the compressive load N led to a propagation of cracks up to the collapse of the specimen. The failure load was $N_{max,1}$=688.5kN which showed a little residual strength.

Fig. 5 Location of the first crack of M1.

Figure 6 a) shows the increase of mid-span lateral displacement of four panels, as a function of the load N. Apparently panels A and C had approximative lateral deflections in the same direction, while negligible displacements were obtained for panels B and D, which showed a trend of global bending of the specimen.



a) b)

Fig. 6 a) Lateral displacement of mid-span cross-section b) compressive stress of mid-span cross-section of M1.

Figure 6 b) proposes the increase of compressive stresses σ of the glass panels, as a function of the applied compressive load N. As shown, the straightness is not stable at the beginning of the test. The reason of this phenomenon was that four glass panels were different in height. When the compressive load was not high enough, there was still some space between the specimen and support. Hence the stress distribution in the cross-section was uneven which was also the reason why the compressive stress of every panel differed from each other's during the whole test.

4. Discussions

4.1. Comparison between monolithic glass columns and LG columns

As shown in Table 2, for monolithic glass columns, the average value of the ratio of failure load (N_{max}) to cracking load (N_{cr}) is 1.07, while it is 1.38 for LG columns. It indicated that monolithic glass columns collapsed quickly after the occurrence of the first crack. However, for LG columns, the applied load could still increase in the post-crack stage which confirmed that they had relatively sufficient residual capacity. Hence in practical applications, LG columns are recommended for safety design.

4.2. Failure mode

According to the phenomenon recorded during the test, structural failure started with a vertical crack at the top or bottom of one of the panels for all specimens. There was one possible reason. During the loading process, there was tensile stress in the horizontal direction (X direction in Figure7) for glass panels. When the tensile stress exceeded the tensile strength of glass, cracking occurred, and then progress of cracks led to structural failure.

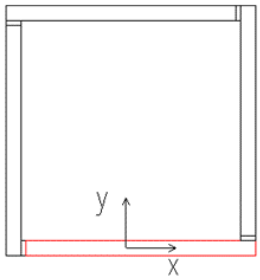


Fig. 7 X direction in the cross-section.

In the X direction, the limitation of the adhesive on the deformation of the glass panel was ignorable due to its relatively low Youngs modules (E_{glue}=250Mpa). Assuming the panel was in a unidirectional stress state, tensile stress σ_t in the X direction could be calculated by compressive stress σ_c in the vertical direction.

$$\sigma_c = E \cdot \varepsilon_c \tag{1}$$

$$\varepsilon_t = \upsilon \cdot \varepsilon_c \tag{2}$$

$$\sigma_t = E \cdot \varepsilon_t \tag{3}$$

Where v is Poisson's ratio with the value of 0.2 and E is the Youngs modules of annealed glass (E=72000Mpa) (Ministry of Housing and Urban-Rural Development of the People's Republic of China,2003). Table 4 presents the data in terms of the compressive stress σ_c recorded when the first crack occurred and calculated tensile stress σ_t. As shown, the average value of σ_t is very close to the tensile strength of annealed glass f_t (Ministry of Housing and Urban-Rural Development of the People's Republic of China,2003). Hence it is reasonable to believe that the vertical crack occurred because the tensile stress in the horizontal direction exceeded the tensile strength of annealed glass.

Table 4: Compressive stress σ_c and calculated tensile stress σ_t.

	M1	M2	M3	L1	L2	L3
σ_c[Mpa]	138.1	131.5	118.4	118.6	136.1	130.0
σ_t[Mpa]	30.4	28.9	26.5	26.1	29.9	28.6
f_t[Mpa]				28		

4.3. The influence of height difference between glass panels

As described in 3.2, in each specimen, four glass panels were different in vertical position due to their height difference. Consequently, the distribution of compressive stress was uneven in the cross-section. Table 5 presents the results in terms of the highest compressive stress σ_{max}, the lowest compressive stress σ_{min} in the mid-span cross-section and failure load N_{max} when the specimen collapsed.

Table 5: Compressive stress σ_{max},σ_{min} and failure load N_{max}.

	M1	M2	M3	L1	L2	L3
σ_{max} [Mpa]	144.6	131.6	130.1	131.0	138.2	138.6
σ_{min} [Mpa]	103.1	51.6	38.7	40.6	56.9	61.6
$\sigma_{max}/\sigma_{min}$	1.402	2.549	3.362	3.227	2.429	2.250
N_{max}[kN]	688.2	489.9	380.1	376.6	462.4	517.2

The value $\sigma_{max}/\sigma_{min}$ can reveal the degree of the uneven stress distribution in the cross-section. The higher it is, the lower the failure load N_{max} is. Hence it is necessary to control height difference between glass panels in manufacturing to make the stress distribution as uniform as possible, thus increasing the structural resistance of columns.

5. Conclusions

This paper presents an experimental study into the global behavior of glass columns with square hollow cross-section under axial compression. Totally 6 specimens were tested. The typical specimen was composed of four glass panels interacting with each other by glued joints along the edge. Among the specimens, half of them are made of annealed glass with the other half made of laminated glass. Test results obtained were discussed and compared in order to highlight their compressive behavior, failure mechanism and possible criticalities. The following conclusions can be drawn from the study:

- For all specimens, local failure mechanism at the top or bottom due to progressive cracking is found, without any damage occurred at the glued joint.
- Compared to monolithic glass columns, LG columns have relatively sufficient residual capacity which is important for safety design.
- In terms of failure mode, it is reasonable to believe that the vertical crack occurs because the tensile stress in the horizontal direction exceeds the tensile strength of annealed glass.
- The height difference between glass panels can lead to uneven distribution of compressive stress in the cross-section. Hence it is necessary to control it in manufacturing to make the stress distribution as uniform as possible, thus increasing the structural resistance of glass columns.

6. References

Aiello, S., Campione, G., Minafò, G., Scibilia, N.: Compressive behaviour of laminated structural glass members. Eng. Struct. 33(12), 3402-3408 (2011).

Amadio, C., Bedon, C.: Buckling of laminated glass elements in compression. J. Struct. Eng. 137(8) (2011).

Bedon, C., Amadio, C..: Design buckling curves for glass columns and beams. Proc Inst Civil Eng – Struct. Build. 168(7):514–26 (2015).

Campione, G., Rondello, V.: Effects of shape of transverse cross-section on the load carrying capacity of laminated glass columns. Constr. Build. Mater. 61:349–59 (2014).

Liu, Q., Huang, X., Liu, G., Zhou, Z., & Li, G.: Investigation on flexural buckling of laminated glass columns under axial compression. Eng. Struct. 133, 14-23 (2017).

Ministry of Housing and Urban-Rural Development of the People's Republic of China: Technical code for glass curtain wall engineering.JGJ 102-2003

Ouwerkerk, E.: Glass columns. M.Sc. Thesis. Delft University of Technology (2011).

Sika. SikaFast-5211 NT Fast-Curing, Two-Part Structural Adhesive, Product Data Sheet; (2013). www.sika.com.

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