Numerical Analysis of Crack Propagation in Tubular Glass Column

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Abstract. The demand for transparency has increased in the construction industry and contemporary architecture over the last decade. The prior researchers focused on glass columns because their uniqueness and transparent characteristics generate an impressive visual feature. Past studies on structural glass entailed numerous experimental investigations, but FEA was applied in a few investigation exercises. This study aims to validate the experimental data and analyse the crack in the tubular glass column and determine the effectiveness of different slenderness ratios of the glass column. This study investigated the column structural behaviour under compression with different geometrical dimensions of hollow section laminated glass columns to determine their load-carrying capacity, buckling performance, and failure mechanism. Finite element analysis using the explicit method was performed by using ABAQUS. The study found that the failure mechanisms depend on the slenderness ratio classified into two failure modes, either buckling or crushing. The glass column failed due to buckling when the slenderness ratio is more than 40, while it failed due to crushing when the slenderness ratio is less than 40. The finite element analysis did not correlate perfectly with the experimental data since the FEA underestimating the glass performance.

1. Introduction

Structural glass is widely used in current structures and in a variety of significant scientific and scholarly works. There has been a growth of glass application in the construction sector, and this has a partial relationship with the glass columns application. Presently, glass columns do not have significant use in the building industry, but their progress is fascinating. For the utilization and optimally exploiting glass columns as construction materials, the columns should offer excellent structural functionality and a simple fabrication process. Still, above all, they should guarantee safety. Modern buildings often use architectural glass, and there has been an increase in the use of structural glass in recent years because it has excellent artistic characteristics. In addition, structural glass possesses high action as a compressive component in the architectural building. As a result of this advantage, glass plays a significant role and performs a substantial function of an element that bears the load. Therefore, structural engineers need to understand the response of glass to loads significantly.

Glass research in the early years mainly focused on recognizing the material characteristics of the different kinds of glass. These include annealed glass, heat-strengthened glass, and fully toughened glass. Laminated glass (LG) was introduced as a discovery to promote the efficiency and strength of structural glass. Besides, LG is two or more glass layers, joined using an interlayer that originates from...
the glasses above. Generally, two glass kinds of glasses are made; Borosilicate glass, often applied in laboratory apparatus or Float glass, is appropriate for the building sector. While safety concerns are important aspects of structural glass, the optimal advantage of glass use should be received to mitigate risks to the public. Therefore, laminated glass has a prospective preference since it has exhibited excellent building performance [1].

An intensive study of glass structures has been undertaken by Veer and Pastunink [2]. They initially focused on beams and plates of glass. Nevertheless, research on how glass column behaves began much later, particularly the laminated tubular glass column. The laminated tubular glass column concentrated on evaluating the capacity to carry loads coupled with the interlayer's impact to ensure the glass component's cohesion. There was an extension of the study to include the safe failure attribute of the glass column that is laminated after the initial fracture in the loading process [3]. Besides, according to Overend et al. [4], varying dimensions of the cruciform glass columns that are laminated have been examined. This type of cruciform cross-shaped glass column easily connects the beam-column, but it shows a low torsional rigidity as load-bearing in structures. Therefore, the tubular glass column is concerned with attaining higher torsional strength and has structural effectiveness for glass applications. The buckling performance of a single laminated tubular glass column has been investigated by Kamarudin et al. [5]. The research revealed that the laminated glass buckling performance depended on the ratio of slenderness. The failure mechanism of the glass column happens either through the buckling or a deforming crush. Nevertheless, Kamarudin et al. proposes an FEA to be utilized to investigate fracture development in the laminated tubular glass column under axial load compression.

Studies on laminated glass are vital for pursuing advanced glass technology. Specifically, more studies on building applications of adhesive bonding are needed. Even though structural silicone glazing has been used for years, there are still problems with improper processing and workmanship [6]. In addition, during the composite action of the laminated glass, when one outer glass layer is broken, the interlocking efficiency of fragments in touch enables the cracked glass to act as if it were still intact [7]. On the other hand, the residual static load carrying capacity and stiffness of laminated glass are known to be limited following glass fracture [8]. Furthermore, a significant finding shows that the bearing capacity and secant stiffness of tempered glass panels increase as the thickness of each layer of the panel increases [9,10].

This study investigated the propagation of cracks in laminated tubular glass columns based on experimental and numerical findings, including additional simulations conducted in ABAQUS. Since previous studies from Kamarudin et al did not incorporate the fracture behaviour in the analysis modelling, hence this study adopted the explicit method in ABAQUS/Explicit to analyse the fracture behaviour. ABAQUS is a robust application to reproduce the glass fracture behaviour by using the brittle cracking material model. Furthermore, this investigation portrays the mechanism of glass failure since it determines the initiation of the first crack on the glass surface. Hence, it is paramount to investigate the structural characteristics of tubular glass columns of different dimensions by FEA. The main objectives of this study are to determine the crack propagation in tubular glass columns by using ABAQUS and to carry out a parametric study in looking at the effect of different slenderness ratios of glass columns.

2. Numerical model
In this study, ABAQUS/Explicit was used to determine the crack propagation in the glass column. Data were obtained from the experiment to achieve correlation and verify the obtained results in this study. The finite element method is one of the handiest methods to study the behaviour of a structure. It gives solutions for complicated geometry very readily. ABAQUS/Explicit is a finite element analysis-based software; It gives many solutions to structural analysis such as fracture, failure, and damage of a structure. The analysis modelled in this study to simulate the behaviour of the tubular glass column under compressive loads was used ABAQUS version 6.15.
2.1. Element type
The element type used in this study was S4R to construct a tubular glass column modelled by 3D extrusion deformable solid shell element. S4R is a double-curved linear quadrilateral with four notes, as displayed in figure 1. Thus, this element can provide a curved geometry.

![Figure 1. S4R – Shell, 4 nodes, reduced integration (ABAQUS Manual).](image)

2.2. Geometry
The structural behaviour of six types of tubular glass columns was investigated. All the specimens have the same height of 1500 mm with different outer diameters, named; 60 mm diameter with 7.0 mm thickness (TGC-60-7.0), 24 mm diameter with 2.5 mm thickness (TGC-24-2.5), 100 mm diameter with 7.0 mm thickness (TGC-100-7.0), 200 mm diameter with 7.0 mm thickness (TGC-200-7.0), 300 mm diameter with 7.0 mm thickness (TGC-300-7.0) and 400 mm diameter with 7.0 mm thickness (TGC-400-7.0). The identification of the specimens, e.g. TGC-60-7.0 is TGC means the "tubular glass column", then the following number means the outer diameter of the TGC, and the last number means the thickness of the TGC. The details of all specimens are shown in table 1.

| No. | Test | Specimen      | Height, \( L \) (mm) | Outer Diameter, \( do \) (mm) | Inner Diameter, \( di \) | Thickness, \( t \) (mm) |
|-----|------|---------------|----------------------|-----------------------------|----------------------|------------------|
| 1   | T1   | (TGC-60-7.0)  | 1500                 | 60                          | 46                   | 7                |
| 2   | T2   | (TGC-24-2.5)  | 1500                 | 24                          | 19                   | 2.5              |
| 3   | T3   | (TGC-100-7.0) | 1500                 | 100                         | 186                  | 7                |
| 4   | T4   | (TGC-200-7.0) | 1500                 | 200                         | 186                  | 7                |
| 5   | T5   | (TGC-300-7.0) | 1500                 | 300                         | 286                  | 7                |
| 6   | T6   | (TGC-400-7.0) | 1500                 | 400                         | 386                  | 7                |

2.3. Material properties
In this study, the tubular glass column was used as linear elastic. Therefore, the model was built to respond elastically. The material Young's modulus of the glass used as the experiment which is 6400 N/mm² and 0.2 Poisson's ratio. Tables 2 to 4, present the material properties of the glass column.

| Properties                     | Symbol | Unit  | Value |
|--------------------------------|--------|-------|-------|
| Glass density                  | \( \rho \) | kg/m³ | 2490  |
| Young's modulus of Glass       | \( E \) | MPa   | 64000 |
| Poisson's ratio                | \( \nu \) | -     | 0.2   |
2.4. Load and Boundary Conditions

A concentrated load has been defined at the top of the tubular glass column with 200 kN. Two different types of support for fixed-defined boundary conditions were used in this study. The boundary conditions at the top and bottom are presented in figure 2 and table 5. All three directions (U) and the rotational degrees of freedom (UR) were restrained to be zero at the bottom fixed-end. At the top movable end, all three directions (U) and the rotational degrees of freedom (UR) were restricted to be zero except that the U3 was free to move 7 mm with a tabular amplitude as shown in table 6.

### Table 3. Brittle cracking properties.

| Direct stress after cracking | Direct cracking strain |
|-----------------------------|------------------------|
| 138                         | 0                      |
| 0                           | 1E-006                 |

### Table 4. Brittle shear and failure properties.

| Brittle Shear | Brittle Failure |
|---------------|-----------------|
| Shear retention factor | Crack opening strain | Direct cracking failure strain |
| 1              | 0               | 1E-006               |
| 0              | 1E-006          | 1E-006               |

Figure 2. Load and boundary conditions in the analysis model.

### Table 5. Boundary conditions at top and bottom of the TGC.

| Boundary Conditions | At Top | At Bottom |
|---------------------|--------|-----------|
| U1                  | 0      | 0         |
| U2                  | 0      | 0         |
| U3                  | 7      | 0         |
| UR1                 | 0      | 0         |
| UR2                 | 0      | 0         |
| UR3                 | 0      | 0         |

### Table 6. Amplitude.

| Time/Frequency | Amplitude |
|----------------|-----------|
| 0              | 0         |
| 0.001          | 0.001     |
| 1              | 1         |
2.5. Mesh Density

In the meshing step, it is necessary to get good accuracy results by using optimum mesh density. A refinement mesh element was carried out to reach the optimum mesh density. The mesh element built by using a various number of edge seed, as shown in table 7. To achieve the best mesh density, an Eigenvalue analysis for buckling performed by comparing the theory buckling load with the buckling load in the FEA test. By using the equation 1 obtained from ABAQUS guidebook, the critical buckling load calculated for TGC-60-7 and TGC-24-2.5 from the FEM analysis.

\[ P_{cr} = E \times a \times \frac{\Delta L}{L} \times A \]  

(1)

\( P_{cr} \) is the critical buckling load, \( E \) is Young's modulus, \( a \) is the eigenvalue, \( \Delta L \) is the displacement input, \( L \) is the column height and \( A \) is the cross-section area. The buckling load in theory calculated by using equation 2.

\[ P_{cr} = \frac{\pi^2 E I}{L^2 \alpha^2} \]  

(2)

The comparison between the buckling load in theory and the buckling load in FEM analysis for different mesh densities are shown in Table 7. The optimal mesh size for tubular glass column analysis was determined using 40 elements, as seen in figure 3.

| No. of elements | FE Pcr (kN) | Theoretical Pcr (kN) | % error |
|-----------------|-------------|----------------------|---------|
| 10              | 403.5       | 467.58               | 14      |
| 20              | 438.64      | "                    | 6       |
| 30              | 445.31      | "                    | 5       |
| 40              | 447.65      | "                    | 4       |
| 50              | 448.74      | "                    | 4       |
| 60              | 449.33      | "                    | 4       |
| 70              | 449.71      | "                    | 4       |
| 80              | 449.95      | "                    | 4       |
| 90              | 450.1       | "                    | 4       |
| 100             | 450.22      | "                    | 4       |

| No. of elements | FE Pcr (kN) | Theoretical Pcr (kN) | % error |
|-----------------|-------------|----------------------|---------|
| 10              | 9.82        | 11.10                | 12      |
| 20              | 10.67       | "                    | 4       |
| 30              | 10.83       | "                    | 2       |
| 40              | 10.89       | "                    | 2       |
| 50              | 10.92       | "                    | 2       |
| 60              | 10.93       | "                    | 2       |
| 70              | 10.94       | "                    | 1       |
| 80              | 10.95       | "                    | 1       |
| 90              | 10.95       | "                    | 1       |
| 100             | 10.95       | "                    | 1       |

Figure 3. An example of 40 numbers of mesh density elements on the edge of the column for TGC-60-7.
2.6. Methods
To study the crack propagation in laminated tubular glass columns, a geometrically Linear Elastic Fracture Mechanic (LEFM) analysis was carried out by using the Explicit method in Abaqus/Explicit. The brittle cracking model was used to analyse the crack in the tubular glass columns. The brittle cracking model is the perfect method to analyse the applications where the brittle behaviour subject s. This model assumes that the material is linear elastic in compression. Therefore, the brittle cracking model can be used for glass and other materials such as concrete and brittle rocks or ceramics.

3. Failure mechanism in different slenderness ratio
Six specimens of tubular glass column constituted of various geometrical dimensions (diameters and thickness) were analysed under a displacement rate of 7 mm, to investigate the effect of different slenderness ratios in the tubular glass column.

Based on table 8, the study found that the failure mechanisms of the specimens analysed were failed catastrophically due to crushing, except TGC-24-2.5 specimen failed due to buckling deformation. The type of failure can be divided depend on the slenderness ratio into two rates, either low or high. The column with a low slenderness ratio fails due to crushing, and the column with a high slenderness ratio fail due to buckling. Figure 4 shows the deformed shape of tubular glass columns that failed by crushing at TGC-100-7, TGC-200-7, TGC-300-7, and TGC-400-7.

Figure 5 shows the buckling mode shape of the tubular glass column TGC-24-2.5. Figure 4(a) and 4(b) shows the crack propagation and the final crack during the experimental tests, the crack was highlighted in red colour, and it failed due to buckling. The fracture that occurred through the whole height interestingly ended up by breaking the glass column into many large parts in the middle, as shown in figures 4(c) and 4(d). Furthermore, there was no fracture at the top and bottom end of the column.

| No. | Specimen     | Column slenderness ratio, λ | Maximum failure load (kN) | Axial displacement failure (mm) | Type of failure mechanism |
|-----|--------------|----------------------------|---------------------------|---------------------------------|--------------------------|
| 1   | (TGC-60-7.0) | 40                         | 40                        | 1.5                             | Crushing                 |
| 2   | (TGC-100-7.0)| 23                        | 94.7                     | 3.9                             | Crushing                 |
| 3   | (TGC-200-7.0)| 11                        | 92.7                     | 3.8                             | Crushing                 |
| 4   | (TGC-300-7.0)| 7                         | 92.3                     | 3.8                             | Crushing                 |
| 5   | (TGC-400-7.0)| 5                         | 92.2                     | 3.8                             | Crushing                 |
| 6   | (TGC-24-2.5) | 98                        | 25                       | 0.9                             | Buckling                 |

Figure 4. Deformed shape of tubular glass columns failed by crushing.
Figure 5. The deformed shape of tubular glass columns failed by buckling with compared between this study and an experimental done by Kamarudin et al. [5] in TGC-24-2.5; a) First crack initiate from the experimental. b) First crack from this study, c) Final crack from the experimental. d) Final FEA results, large glass fracture parts in the middle in this study.

3.1. Comparison and validation of the results:

A comparison of the FEA results in this study and experimental results from previous researchers is presented in table 9. It was noticed that all the specimens with a slenderness ratio less or equal to 40 mm failed due to crushing. In contrast, all specimens with a slenderness ratio of more than 40 mm failed due to buckling.

Table 9. Comparison between this study and the previous study tests with different slenderness ratio on glass columns.

| Year | Researcher name | Column height (mm) | Outer diameter (mm) | Thickness (mm) | Support condition | Column slenderness ratio, λ | Maximum failure load (kN) | Type of failure mechanism |
|------|------------------|--------------------|---------------------|----------------|-------------------|----------------------------|---------------------------|-------------------------|
| 2021 | This study       | 1500               | 400                 | 7              | Fixed             | 5                         | 75                        | Crushing                |
| 2021 | This study       | 1500               | 300                 | 7              | Fixed             | 7                         | 75                        | Crushing                |
| 2021 | This study       | 1500               | 200                 | 7              | Fixed             | 11                        | 79                        | Crushing                |
| 1999 | Veer             | 550                | 40                  | 4              | Fixed             | 22                        | 35                        | Crushing                |
| 2021 | This study       | 1500               | 100                 | 7              | Fixed             | 23                        | 68                        | Crushing                |
| 2018 | Kamarudin        | 1500               | 60                  | 2              | Fixed             | 37                        | *64                       | Crushing                |
| 2018 | Kamarudin        | 1500               | 60                  | 7              | Fixed             | 40                        | *105                      | Crushing                |
| 2021 | This study       | 1500               | 60                  | 7              | Fixed             | 40                        | 40                        | Crushing                |
| 1999 | Veer             | 550                | 40                  | 4              | Pinned            | 43                        | 110                       | Buckling                |
| 2018 | Kamarudin        | 1500               | 50                  | 1.8            | Fixed             | 44                        | *50                       | Buckling                |
| 2005 | Overend          | 1080               | 50                  | 7              | Pinned            | 70                        | 50                        | Buckling                |
| 2018 | Kamarudin        | 1500               | 24                  | 2.5            | Fixed             | 98                        | *3                        | Buckling                |
| 2021 | This study       | 1500               | 24                  | 2.5            | Fixed             | 98                        | 25                        | Buckling                |
| 2018 | Kamarudin        | 1500               | 20                  | 1.8            | Fixed             | 116                       | *1                        | Buckling                |
| 2007 | Veer & Bos       | 555                | 12                  | 3.5            | Pinned            | 170                       | 2                         | Buckling                |

*a*average value from the experimental work [5]
3.2. Load versus Axial Displacement Behavior

Figure 6 shows the axial load versus the displacement of TGC-60-7 in comparison between the experimental work and FE work (by Risk Method) carried out by Kamarudin et al. [5] and result from Brittle Cracking analysis. FEA by Riks Method tends to overestimate the glass tube performance but still showing an acceptable load-axial displacement behaviour and the load-lateral displacement behavior. FEA by Brittle Cracking Method has shown a consistent gradient line for the specimen’s stiffness, however the strength prediction is showing an underestimate value compared to the experimental results.

![Figure 6. Load vs Displacement behavior of all glass column types.](image)

4. Conclusions

The purpose of this study is to analyse the crack behavior of the tubular glass column under the compressive load. The structural performance of the tubular glass column was evaluated and investigated the effect of different geometrical dimensions. The explicit method in ABAQUS/Explicit was used to analyse the structural behaviour of tubular glass columns. The main conclusions of this study are as follows:

(i) The outcome of this study validates the previous researchers' theory that the strength of the tubular glass column depends on the slenderness ratio. The failure mechanisms depend on the slenderness ratio that has been classified into two failure modes, either buckling or crushing. If the glass column has a slenderness ratio of more than 40mm can be classified as a slender column that is subjected to buckling failure mode. While if it is less than 40mm can be classified as a short column that is subjected to crushing failure mode.

(ii) The relationships between the load and the axial displacements indicate a linear behaviour of the glass with an instantaneous failure without plastic deformation.

(iii) The Brittle Cracking method managed to analyse the linear behaviour of the glass. However, it tends to underestimate the glass strength. Nevertheless, when the analysis is run based on the Riks method, the linear behaviour is scarcely simulated compared to the experimental work. Therefore, the best way to analyse the glass strength is by using the Brittle Cracking method compared to the Riks method.

(iv) Glass strength cannot be justified by mean strength as compared to concrete and steel since glass inherits unique flaws though it came from a similar batch of geometrical dimensions. The same dimension of the tubular glass column will not give a similar ultimate load and displacement.
(v) Most FE results did not correlate perfectly between experimental data and FEA since the FEA leads to underestimating the glass performance. Nevertheless, the FEA gave acceptable behaviour at the lateral load-displacement and axial load-displacement.

(vi) The crack propagation related to the failure mode can be classified into two considerations either by buckling or crushing. The glass column will probably fail due to buckling in the slender column, and it will fail due to crushing in the short column.

In conclusion, based on the results of the finding, all the objectives of this study were achieved. The crack propagated in the tubular glass column has been found by using ABAQUS and shows the effect of different slenderness ratios on the tubular glass column. Consequently, the results have been validated with the previous researchers.

5. References

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