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STRUCTURAL PERFORMANCE OF SINGLE AND BUNDLED GLASS COLUMNS

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ABSTRACT

Architects are not fond of columns because they obscure views and interrupt space. Previous work has focus on columns made of glass as it creates an interesting visual feature because of its uniqueness i.e. its transparent characteristics. The aim of this study was to investigate the structural performance of the basic tubular single glass column (SGC) and a combination of more than one tubular single glass columns, bundled (BGC) using structural silicone sealants. A series of compression test were carried out on several different geometrical dimensions of tubular single and bundled glass columns to determine their failure mechanism, load carrying capacity and to evaluate the buckling performance. The structural performance to evaluate the column failure behaviour i.e. crushing or buckling was carried out by looking at the effect of different geometrical dimensions and shear connections in the bundled system. This study showed that the failure mechanisms depended strongly on the slenderness ratio of the columns and failure occurred either by crushing or by buckling depending on the column lengths. The scatter in the failure load for specimens that have a highr slenderness ratio was much lower than for those which have lower slenderness ratio. The variations in the strength of similar size glass columns has shown that the existence of the Griffith flaws strongly influenced the glass behaviour. In order to justify the variability of the glass strength, a Weibull statistical distribution has been used. The BGC is an alternative for use as a structural glass column because the structural silicone sealants incorporated into the structure is capable of bonding multiple tubes together. The low modulus of the structural silicone sealant suggests that its capability to achieve a full composite section in the BGC was remarkable.

Keywords: structural behaviour, tubular glass columns, compressive forces, failure mechanisms, buckling strength.

INTRODUCTION

The application of glass as a structural material has increased significantly in recent years. Structural glass has been successfully used in cable supported facades and also for shear and lift shaft walls. The present paper investigates the failure of glass columns which have already been used in building structures. However, the use of glass columns can be extended even further by architects incorporating new visual effects with the use of lasers and this structural form can also be used effectively in the future in tensegrity structures such as cable domes. The increased use of glass as a structural material has occurred primarily because of its excellent aesthetic value. Due to this advantage glass not only plays an important role as a cladding material but also has a key role acting as a load bearing element. Consequently, a significant understanding of how glass responds to loads is vital for structural engineers. At present, there is a large amount of published research concerned with the performance of glass structures (Savineau, 2001; Schober and Schneider, 2004; Overend, Vasallo and Camillieri, 2005; Jacob *et al*, 2005; Bos and Veer, 2007; Delince, 2007; Bos, 2009; Green, 2013; Lenk, O'Callaghan and Lancaster, 2013) which indicates that in the correct environment structural glass shows good stability and build-ability. Intensive research on glass structures has been undertaken at Delft University of Technology, Netherlands with the research team there undertaking the ZAPPI research programme (Bos, 2009). Their initial focus was on glass beams and plates. However research into the behaviour of glass column was initiated later, specifically on laminated tubular glass columns (Veer and Pastunink, 1999). The study on laminated tubular glass columns has focused on investigating the load carrying capacity of the column plus the effect of the interlayer (*in-situ* resin) to ensure the glass elements remain bonded together. The study was extended to investigate the safe failure behaviour of laminated glass columns after the first crack initiated during loading (Nieuwenhuijzen, Bos and Veer, 2005). Laminated cruciform glass columns of varying dimensions have also been studied (Overend, Vasallo and Camillieri, 2005). This type of cross-section shape eases the complexity of the beam-column connection. However, the inherent low torsional rigidity of cruciform columns is a disadvantage for structural glass applications when the elements are used in load-bearing structures. Thus, the tubular glass column is of interest achieving a high torsional rigidity and consequently these elements become structurally efficient for glass applications. A very interesting precedence has been set at the ABT-Office, Arnhem, Netherlands in which 7 tubular glass columns of size 30 mm diameters were bundled together with a resin to form a column. Inspired by the laminated glass arrangement to introduce redundancy into the structural

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glass, bundling the glass columns by applying resin could be an alternative to constructing glass columns while keeping the transparency characteristics in the structural system. To date, no experimental data is available in respect to the structural behaviour (failure mechanism, buckling strength etc.) of bundled glass columns.

The main objective of this study is to investigate the structural behaviour of single tubular glass columns (SGC) and bundled glass columns (BGC) under compression which will be achieved by pursuing the following; a literature review, physical testing programme to establish failure mechanisms, load carrying capacity and buckling performance. The investigation was carried out by performing an experimental program of compression tests based on the Veer test arrangement (Nieuwenhuijzen, Bos and Veer, 2005) since a standard test method for compression test on tubular glass columns is yet to be established.

GLASS COLUMN STRUCTURAL PERFORMANCE

This experimental program was designed to provide a better understanding of the behaviour of structural tubular glass columns under compressive load. In this study, various diameter sizes of the SGC and BGC were used in the experimental programs. The study was limited to testing annealed-borosilicate glass tubes due to their low cost and this material has been widely used by earlier researchers (Overend, Vasallo and Camillieri, 2005; Bos and Veer, 2007; Veer and Pastunink, 1999; Nieuwenhuijzen, Bos and Veer, 2005; Doenitz *et al*, 2003).

Test specimens

The SGC was a single-piece hollow section tubular glass column with a standard length of 1500 mm with the manufacturer's specification for the glass material. There were five types of SGC prepared and tested in order to invoke a spread of capacity. The BGC was formed by joining three SGCs with a standard length of 1500 mm, bundled and bonded together using a structural silicon sealant. There were two types of BGC prepared and tested. The details of the SGC and BGC are given in Table-1. The glass column was of Schott-Duran borosilicate glass with plain-cut and fused end finishing.

Structural silicone sealants used to fabricate BGC as shown in Figure-1 was manufactured from C-TEC N.I Limited who produces CT1 clear unique sealant and construction adhesive. This sealant provides adhesion on any material in most applications without the need for additional fixings. A layer of the structural silicone sealant was applied on the first piece of glass column's surface along its length and followed by installing the second piece of glass column on top of the applied sealant running parallel to the first tube. A brief pressure applied by hand was essential in making the two glass columns to attach together soundly.

Table-1. Details of specimens for SGC and BGC.

Type	**Specimen**	**L** (mm)	**d** (mm)	**t** (mm)
T1-S	1-4	1500	60	7.0
T2-S	5-9	1500	60	2.2
T3-S	10-14	1500	50	1.8
T4-S	15-19	1500	24	2.5
T5-S	20-24	1500	20	1.8
T6-B	25-29	1500	20 (per tube)	1.8 (per tube)
T7-B	30-34	1500	24 (per tube)	2.5 (per tube)

d=outer diameter, t=wall thickness, T1,T2..=type, S=single, B=bundled

Once the sealant reaches its skin curing time which was about 8 minutes (according to the material specification), another layer of sealant was applied on top of the junction in between the two attached glass tubes and the third piece of the glass column was put on top of the sealant layer and again held in place by hand pressure. The full curing time was 24 hours.

Figure-1. BGC fabricated using structural silicone sealant.

Test set-up and instrumentations

A SATEC series kN Model universal testing machine from Instron was used for the test. The machine has a capacity of 600 kN and it allows the load cell to be moved hydraulically at a constant rate of displacement. Six strain gauges of Micro Measurements 120µ strain (CEA-06-240UZ-120). Each of these strain gauges had a working range of 2.095 + 0.5% gauge factor. The strain gauges were mounted on the surface of the glass at specific locations. The quarter bridge type strain gauge arrangement were used to measure the axial strain along the length of the glass and were connected by cables to the data logger. A StrainSmart data logger made by Micro

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Measurements was used to monitor and record the strain data obtained. The load cell fed continuous signals to the data logger via the amplifier and these signals were scanned to capture data at 1000 points per second. There were two kinds of deflection measurements taken in the test. In order to obtain axial deformation of the glass column, the measurement was directly obtained by the load cell movement of the testing machine which was controlled by the integrated data logger. At the start of each test, the testing machine was carefully calibrated over its full working range by using the advance control electronics which provides automatic recognition and calibration of transducers ensuring the proper instrument is being used and that the data is reliable. The data logger was configured by Bluehill® Universal Materials Software system which was a fully integrated suite of application modules for all types of material testing. All data were formatted to be stored into Microsoft Excel program spreadsheets.

In order to obtain the lateral deformation at the mid-height of the column, three D/10000 C linear differential transformer transducers (LVDTs) were used. These transducers were carefully positioned at three different circumference points, namely 60^o, 180^o and 300^o orientations. The transducers were connected to the StrainSmart data logger and were calibrated via the respective amplifier using accurately measure slip gauges to set the displacement to zero. The transducer displacement was scanned at each pre-set interval to capture data again at 1000 data points per second. The glass column was setup at both ends on 4 mm thick neoprene rubber pads which, in turn were resting on 10 mm poly-methyl methacrylate (PMMA usually known as 'Perspex') pads. Prior to the test, the supports (PMMA and rubber pad) at the top and bottom of the specimen were placed at the centre of the platen at both ends of the testing machine with regards to the central vertical alignment. The glass column was then placed according to the initial marks that have been created on the supports to achieve a central vertical position. The glass column was fastened by lowering the load cell. To comply with the risk assessment and important safety reasons, an acrylic custom-made tube cover was put around the test set-up to prevent flying shards of glass that could cause hazards. Three designated holes on the acrylic tube cover were specified to allow the LVDTs to be placed at points that have been marked around the mid length of the column. Pre-loading was applied about 3 times by adopting about 3% of the theoretical buckling load. The specimen was then loaded at a constant 0.5mm/min axial displacement controlled rate. Figure-2 illustrates the test set-up in the lab.

Failure mechanism

The failure mechanism is explained in terms of the physical appearance of the structure observed during and after conducting the test. The observation was made from the recorded video (a commercial video recorder with a recording speed of 25 frames per second). All specimens failed catastrophically. It was noticed from the videos that all of the SGC specimens failed due to buckling except for tubes T1 and T2 which failed due to crushing (compression). At the initial stage of the test, there was no measurable lateral deformation along the length of the column. The failure mechanism during loading of specimens T1 and T2 was such that the first crack appeared as load increased. The first crack was detected from the 'cracking' sound in the recorded video.

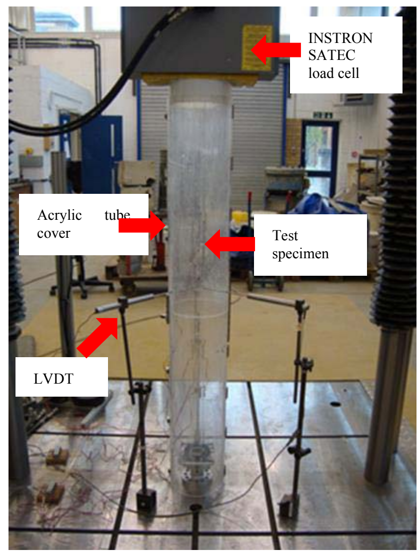

Figure-2. Test set-up in the lab.

The video captured the initial crack at the bottom end of the glass column of specimens T1 and T2. The crack propagated in a linear fashion towards the direction of the mid length of the column. The failure mechanism for T3 was driven by the buckling deformation which dominated the failure of the structural glass column. Prior to the buckling, cracks occurred. The period between the first crack and the ultimate failure in T3 was short. It shows the effect of the instantaneous failure the was triggered in the glass column due to the elements vulnerability. Transverse deflection rapidly followed until the column failed explosively. Buckling failure also dominated the failure mechanism in T4 and T5. However, there was no sign of a first crack or no cracks have been recorded in T4 and T5. The glass columns did not shatter throughout the length but interestingly broke into several large parts in the middle of the columns. In addition, there was no physical shattering at the ends of the columns. After buckling started to dominate the behaviour of the glass columns, the columns started to show considerable deflection while still carrying the maximum load. The test results are tabulated in Table-2a and 2b.

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Table-2(a). Summarized results of the compression test for SGC and BGC.

Type	Specimen	Maximum Failure Load, P (kN)				
		1	2	3	4	5
T1-S	1-4	86.01	125.19	163.19	47.48	-
T2-S	5-9	64.69	60.11	60.98	76.70	56.74
T3-S	10-14	57.04	41.19	53.31	46.78	51.99
T4-S	15-19	2.11	1.95	4.39	3.83	0.89
T5-S	20-24	0.95	1.10	1.07	0.97	1.02
T6-B	25-29	14.15	11.19	13.59	12.56	15.34
T7-B	30-34	8.01	5.77	6.54	7.03	7.42

Table-2(b). Mean failure and standard deviation.

Type	Specimen	P_{mean} (kN)	σ
T1-S	1-4	105.47	43.19
T2-S	5-9	63.84	6.91
T3-S	10-14	50.06	5.52
T4-S	15-19	2.63	1.29
T5-S	20-24	1.02	0.05
T6-B	25-29	13.37	1.41
T7-B	30-34	6.95	0.76

Load *vs.* end axial shortening

A graph has been plotted to portray the relationship between the maximum failure load and end axial shortening for a series of glass columns tested loaded in compression as shown in Figure-3. Based on Figure-3, the slenderness ratio has influenced the behaviour of the glass column where the glass columns with a lower slenderness ratio being stiffer than those columns of a higher slenderness ratio. It is obvious to see that BGC columns resisted a higher load than that obtained from the SGC of a similar diameter. The scatter for specimens that have a higher slenderness ratio was much lower than for those which have lower slenderness ratio. This is caused by the fact that failure was governed by stability rather than by local peak stresses. It also shows that the glass column with a larger diameter is likely to have suffered more surface defects due to the increase in surface area.

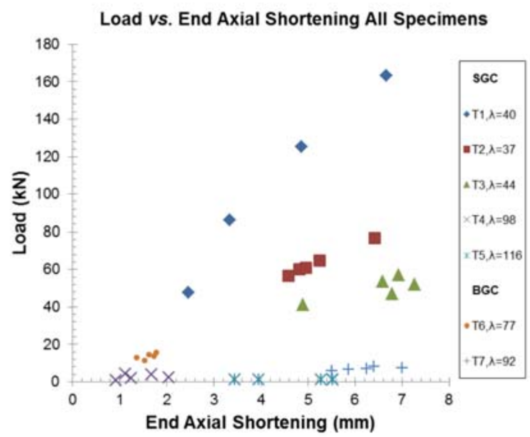

Figure-3. Comparison of maximum failure load *versus* end axial shortening of the specimens tested.

Effect of different slenderness ratio

The slenderness ratio is a non-dimensional value used to classify columns which is then used for design considerations. It is a ratio of the effective length, L_e of a column to the least radius of gyration of its cross section, r. In perfect steel compression members for example there are three typical characteristics to classify a column. Columns with a slenderness ratio (L_e/r) less than 40 are known as a short (stubby) column which will deform elastically until the material yield stress has been reached throughout the column cross section initiating plastic deformation without buckling. A slenderness ratio $L_e/r < 40$ is also considered to be a low slenderness ratio. For $L_e/r > 100$ or high slenderness ratio, a steel column is categorized as a long (slender) column in which the elastic buckling dominates the column failure mechanism. With an intermediate slenderness ratio $40 < L_e/r < 100$, the column will approach plastic buckling failure. When considering columns made from glass, the intermediate slenderness ratio would be insignificant because glass is a brittle material where stress redistribution would not take the form of plastic deformation. Thus, for short and

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slender columns a similar behaviour to steel could be justified for glass columns with the provision that a short column would fail by cracking at the ends rather than yielding. From the experimental results, the slenderness ratio for each type of glass column tested was calculated and their failure mechanisms were summarized as shown in Table-3. Previous researchers' results on the failure load of glass columns are also included to show the effect of different slenderness ratios on structural behaviour of glass columns. It can be concluded that the slenderness ratio, $L_e/r < 40$ can be classified as short SGC which are subjected to progressive crushing at the ends of the glass columns. While, $L_e/r > 40$ can be classified as slender SGC which are subjected to flexural buckling of the glass columns.

Statistical analysis due to *Griffith* flaws

The factor which affects the strength of glass is the presence of Griffith flaws in the glass surface. In order to predict glass strength by quantifying the number of Griffith flaws on the glass surface is almost impossible due to its random population. In addition, the existence of a large numbers of Griffith flaws of variable depth on the glass surface leads to a complex interpretation of glass failure strength. However, an assumption needs to be made so an appropriate design consideration for structural glass can be applied. The variation of glass strength for identical pieces of glass is attributable to the existence of a random distribution of Griffith flaws on the glass surface. However, most of the research on glass has found that the glass failure does not follow a normal statistical distribution (main parameters: mean and standard deviation) due to the variability of the glass strength. In order to justify the variability of the glass strength, Weibull's statistical theory of failure is commonly being used. Weibull analysis is a method useful for fitting and analysing data from brittle materials to determine the probability of failure of glass. The method is appropriate even for the engineering analysis of an extremely small number of samples. The Weibull plot is inspected to determine how well the failure data fits a straight line. The two parameters (m and σ_0) are determined experimentally by stressing a sample of the material until fracture occurs.

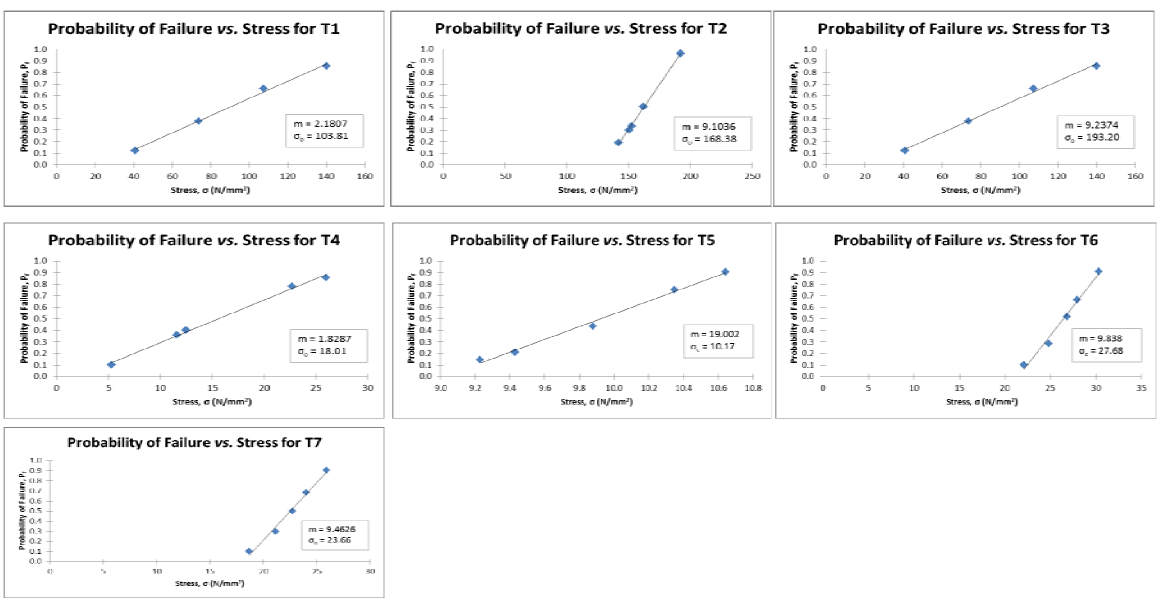

Figure-4. Weibull plot for SGC and BGC test.

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Table-3. Data of slenderness ratio of several tested glass columns.

Researcher	L (mm)	Outer diameter (mm)	Thickness (mm)	Support condition	Slenderness ratio, λ	Maximum failure load (kN)	Failure mechanism
Veer & Pastunink (1999)	550	40	4.0	Fixed	22	35	Progressive crushing from the base
This paper	1500	60	2.2	Fixed	37	64	Progressive crushing from the base
This paper	1500	60	7.0	Fixed	40	105	Progressive crushing from the base
Veer & Pastunink (1999)	550	40	4.0	Pinned	43	110	Flexural buckling of the column
This paper	1500	50	1.8	Fixed	44	50	Flexural buckling of the column
Overend (2005)	1080	50	7.0	Pinned	70	50	Flexural buckling of the column
This paper	1500	24	2.5	Fixed	98	3	Flexural buckling of the column
This paper	1500	20	1.8	Fixed	116	1	Flexural buckling of the column

The stress value σ_0 is the experimentally determined stress such that fracture occurs with a probability of 0.63. Theparameter m is known as the Weibull modulus, and provides a measure of the statistical spread of the distribution around σ_0. A good fit relates to the quality of the data obtained from the test. The plot gives the probability of failure of glass at a certain stress level. It was found that all data for SGC and BGC fit well with the Weibull failure line as shown in Figure-4. The relationship between the probability of failure and the stress is linear. The plots shows the benefit of knowing the probability of failure at a stress level applied to each of the glass types.

Effect of adhesive connections

The bundled glass columns (BGC) were formed from three single glass columns (SGC) of similar size, bonded together using a structural silicone sealant. Structural silicone sealant is a type of adhesive connection used to carry short term tension between glass tubes and their supporting structures. It plays a role in the distribution of loads into and out of the glass over large areas. The use of such a structural adhesive is very beneficial for glass and because glass panes are flat and easy to clean they can be used with a structural adhesive to provide efficient cladding usually for building structures. Structural adhesives with a low modulus are suitable for holding glass in place as has been utilised in this research. A high modulus sealant is more suitable for carrying shear forces. Theoretically, the strength of BGC should be greater than the sum of its constituent SGC. However, in this case, the effectiveness of the structural silicone sealant incorporated into the structure to distribute loads is investigated. The investigation was carried out based on the results of the maximum failure load and the composite action of BGC compared to the SGC as shown in Table 4. Based on Table 4, it can be concluded that BGC have achieved full composite action since for BGC-24 mm, 5.08 > 4.92 and for BGC-20mm, 6.81 > 4.78. Overall, it shows the adhesive with a low modulus was effective in connecting the tubes and achieving the composite stiffness of the multiple 1500 mm long glass columns. The chosen structural silicone sealant has proved that it can be successfully applied in structural glass applications fulfilling the design requirements.

Table-4. Effectiveness measurement of adhesive connections.

Dia.	Type	A	I	P_{exp}	P_{cr}
mm		mm^2	mm^4	kN	kN
24	SGC	168.86	9888.90	2.63	11.10
	BGC	506.58	48650.70	13.37	54.63
	BGC/SGC	-	4.92	5.08	4.92
20	SGC	102.92	4303.03	1.02	4.83
	BGC	308.76	20583.10	6.95	23.11
	BGC/SGC	-	4.78	6.81	4.78

A=area, I=second moment of area, P_{exp}=experimental load, P_{cr}=Euler load

CONCLUSIONS

In conclusion, the compression tests on single glass (SGC) and bundled glass (BGC) columns have successfully illustrated the structural performance of the glass columns compared with failure predictions. The failure mechanisms depend strongly on the slenderness ratio and the glass columns failed by either crushing for low slenderness ratios or by elastic flexural buckling for high slenderness ratios. The variations in the strength of similar size glass columns have shown that the existence

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of the Griffith flaws strongly influenced the glass failure behaviour. In order to justify the variability of the glass strength, a Weibull statistical distribution is used. The use of a low modulus structural silicone sealant suggests that it is possible to achieve full composite section in for bundled glass columns.

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