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ABSTRACT: In this paper a bundled glass column is presented as a promising solution for a completely transparent, almost dematerialized structural compressive element. The aim is to obtain a glass column that can safely carry loads, achieve a high visual result and be relatively easily manufactured. Different types of adhesives, rod configurations and bonding methods are explored in search of an optimum balance between structural and visual results. The final column comprises six solid glass rods interlocking to a central glass star-shaped profile, bonded together by a clear, UV-curing adhesive. The high shear stiffness of the adhesive allows for the desired coupled behaviour of the rods whilst its similar refraction index to glass and homogeneous spread result in minimal visual distortion. To determine the strength and failure mode of the column, compression tests are conducted on 0.5 m and 1.5 m high prototypes and the results are presented and discussed.

1 INTRODUCTION

Continuous, uninterrupted spaces have long triggered the fascination of architects worldwide. However, large, column-free spaces are linked with expensive and challenging structural solutions. That said, a glass column would least disrupt the openness of a space, forming almost invisible elements capable of transferring vertical loads, revealed only by the play of light. Indeed glass' unique material properties of transparency and high compressive strength render it the sole candidate for materializing transparent structural components subject to compression. At present glass columns have been scarcely used, as their brittle nature and slender proportions have led to the general perception of them as fragile, light, unsafe and thus unsuitable for construction purposes: once a fracture occurs, glass will fail in an unpredictable, instantaneous way without giving any warning signal. The residual capacity is limited if any. Yet, glass' mechanical properties are comparable to those of conventional building materials. Glass has an inherent compressive strength exceeding that of concrete and a modulus of elasticity similar to aluminium. The engineering weakness of glass lies in its inability to carry high tensile stresses. Minute surface defects such as Griffith flaws, scratches or faults due to the polishing and grinding processes, induce localized tensile stresses in the amorphous structure of glass even when the material is loaded in compression. These result into the characteristic spontaneous failure in values much lower than the expected theoretical ones.

Nevertheless, advances in glass manufacturing technologies and structural adhesives have enabled the structural use of glass' inherent strength without jeopardizing safety. Tempering and laminating are the two most common strategies for turning glass into a safe structural material. Tempering can greatly increase the tensile resistance of glass, decreasing the probability of failure. Multiple glass layers laminated together can significantly reduce the consequences of failure through redundancy. By applying these measures, engineers have gradually started to trust

the strength of glass, introducing it in structural components such as beams, portals and building skins. In comparison, free-standing glass columns are still in an early stage of development.
R. Nijsse discusses five different types of all glass columns in (Nijsse and ten Brincke, 2014): Profile, layered tubular, stacked, cast and bundled (see Figure 1). Profile columns are at present the only type applied in construction. The first realized example is in *St-Germain-en-Laye* in France, built in 1994, where eight cruciform glass columns support a glass patio. The same typology of columns was applied in 2010 at the *Danfoss Headquarters* in Denmark. Different configurations of profile columns, e.g. square, I and H profile, and their load-bearing capacity are further explored by E. Eindrapport (Eindrapport, 2011). Research and experimental work has been also conducted regarding tubular and stacked columns by E.J. van Nieuwenhuijzen (Nieuwenhuijzen et al., 2005), J.R. Pastunink (de Jong and Van Der Voordt, 2002) and R. van Heugten respectively (Van Heugten, 2013). Cast and bundled glass columns are the least explored options. In theory, cast glass columns would be the ideal solution, forming monolithic structural glass members of the desired cross-section with maximum transparency and high strength. However, casting glass in such a large volume demands a very perplexed and excessively time-consuming cooling process. This can be well illustrated by the "*Ten Liquid incidents*" of artist Roni Horn (Horn, 2014). Each cylindrical cast glass sculpture of 45.5 cm x 91.5 cm weighs 800 kg and requires several months of controlled cooling to be successfully annealed. Such a time-consuming cooling process makes the manufacturing of cast glass columns cost- and time- inefficient.

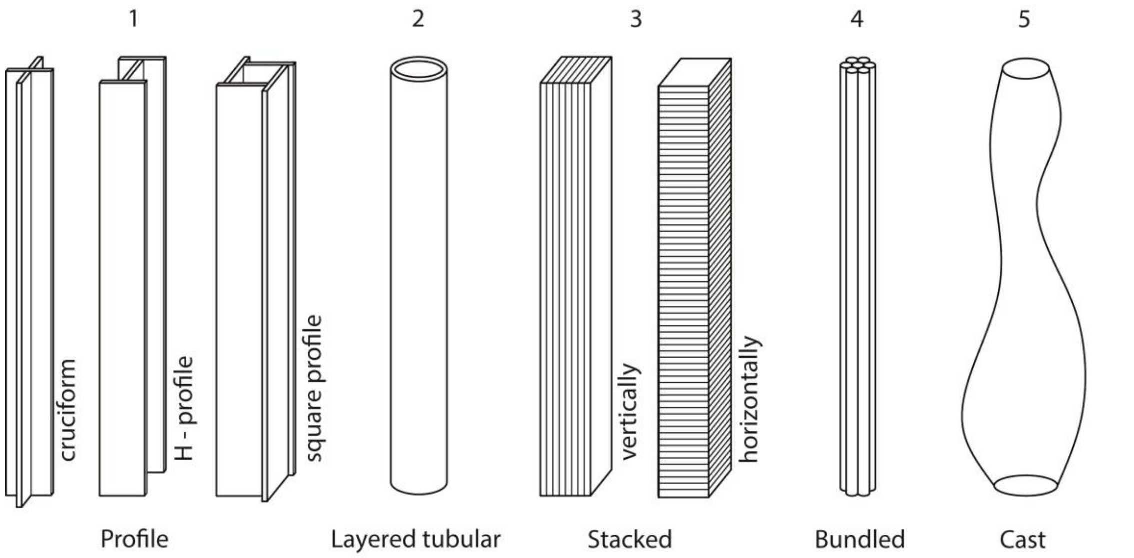

Figure 1. The five different types of all glass columns described by Nijsse.

This paper presents the research and testing of the fifth type of glass columns, the bundled and discusses its potential application. This promising concept was first introduced by R. Nijsse in (Nijsse, 2003) as a safe, all glass column made of a bundle of massive glass bars. This alternative has not been explored in depth until now, even though it presents great prospects in terms of fabrication, visual result and structural performance. The idea itself is simple. Multiple solid glass bars are bonded together via a transparent adhesive to form a composite yet integral cross-section. The degree of collaboration of the rods is highly dependent on the adhesive applied. The higher its bonding strength, the more the single elements couple, preventing individual buckling. To further improve the load carrying capacity of the column, a symmetrical cross-section of both the rods and the composite shape is crucial. Solid glass rods of circular cross-section are the optimum choice due to their inherent resistance in buckling and torsion. When clustered together, they can also form a symmetrical composite shape, preventing the creation of a weaker axis against bending. Safety is warranted by redundancy. Even if one or more rods break due to accidental impact, the remaining intact ones should be able to carry the total load for sufficient time to allow for replacement of the damaged column or to flee. Lastly, in terms of visual performance, the bundled glass column is transparent but not invisible. The curved shape of the rods results to playful distortions and light reflections, revealing subtly the existence of the column.

2 PRODUCTION TECHNIQUES OF THE BUNDLED GLASS COLUMN

Different glass rod configurations, adhesives and bonding techniques were explored in search of a combination that would:

- ensure the desired coupled behaviour of the glass rods
- achieve optimum transparency through minimum visual unevenness
- result to an easy, standardized manufacturing method.

Prototypes of bundled columns consisting of seven rods each, six for the external bundle and one central, are made to evaluate each of the bonding methods. All prototypes are made by DURAX® rods of Schott (SCHOTT, 2012). These are standardized, extruded borosilicate glass rod profiles 1500 mm long with diameters ranging between 3 to 30 mm. Aside from the standard mechanical properties of glass, owing to their borosilicate composition the rods present durability and resistance to chemical attack, high temperatures and thermal shock. The explored bonding techniques and configurations are briefly described below.

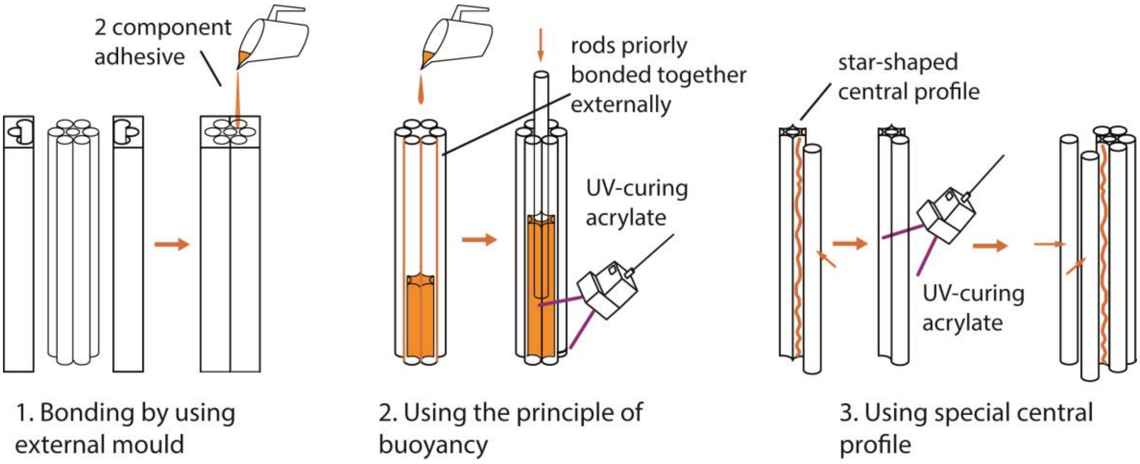

Figure 2. Illustration of the explored bonding techniques. Left: Bonding via the use of an external mould. Centre: Production technique using the principle of buoyancy. Right: Bundle with special central profile

2.1 *Bonding the bundle using an external mould*

Composition: Seven Ø 20 mm rods bonded with a two-component adhesive

This method employs a mould in order to bond the rods together in the desired configuration. Due to the inevitable intolerances in the diameter of each individual rod (SCHOTT, 2012) a custom-made mould is essential for each column made. A disposable mould from a low-cost soft material (e.g. silicone) is suggested in order to take the negative shape of the rod-configuration in-situ. Then, a two-component clear resin is applied in the gaps between the rods, bonding them together (see Figure 2). This solution results to an even spread of the adhesive between the rods and can achieve a visual result of high quality. Nevertheless, this method has proven to have some considerable disadvantages: the viscosity of the adhesive requires a minimum space of 1 mm between the central and the surrounding rods to allow for its homogeneous flow along the complete length of the column. This increased gap results in a lower bonding strength, as illustrated in Figure 3 (Den Ouden, 2009, Riewoldt, 2014), which in turn considerably decreases the load carrying capacity of the bundle. Moreover, the inevitable shrinkage of the adhesive requires a meticulously controlled curing process in order to avoid the formation of air gaps that compromise the visual quality. For all these reasons alternative bonding techniques were sought.

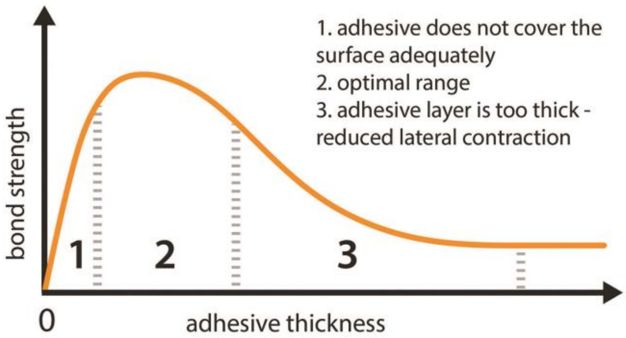

Figure 3. Illustration of the relation between the optimum strength and the thickness of adhesive

2.2 *Production technique using the principle of buoyancy*

Composition: Seven Ø 22mm rods bonded with UV-curing acrylate

This bonding technique was used to fabricate a 250 mm long bundle prototype, as follows. Six external rods placed on an aluminium base form the external bundle. The rods are sealed and bonded together externally by a high-strength UV-curing acrylate. The bundle is further stiffened by removable plastic tighteners and bonded to the aluminium base by a two-component resin. In this way, a water-tight hollow bundled glass tube is created. The total required amount of a low-viscus, UV-curing acrylate of high stiffness is poured into the tube. Then the last rod is pushed into the centre, causing the ascent of the adhesive due to buoyancy, filling completely the gaps between the rods (see Figure 2). The adhesive is then cured by UV-light in steps starting from the base of the column and proceeding towards the top. Although this solution seems to be optimum in terms of both visual and structural results, this production method proved to have practical complications. When the central part is pushed into place, it causes an increased hydrostatic pressure at the base of the column which in turn causes the failure of the sealed and stiffened joins, leading to uncontrolled leakage. Moreover, due to the standard diameter deviations of the rods, in a building-scale prototype the insertion of the central slender rod would require a very accurate and controlled procedure or a considerably increased gap between the rods that would, as explained before, reduce the total strength of the column.
Both bonding procedures mentioned above are not ideal solutions since they cannot account for the standard diameter deviations of the rods, resulting to the custom fabrication of each column unit or to columns with decreased strength. This remark highlighted the necessity of a standardized, universal production method which led to the third and final bonding technique.

2.3 *Bundle with special central profile*

Composition: Six Ø 22mm rods bonded by a UV-curing acrylate in a star-shaped extruded central profile (CONTURAX® series)

In this bonding method an elaborated, star-shaped cross-section from the CONTURAX® series of SCHOTT forms the central element of the bundled column. The six external rods, with a diameter matching the external convex cavities of the central star profile, are successively bonded by a clear UV-curing, one-component adhesive of high stiffness along the length line, as illustrated in Figure 2. In this way the adhesive is homogeneously spread in a layer of optimum thickness. Aside from achieving a fast and easy fabrication, this bonding method can be used to manufacture standardized bundled glass columns as it compensates for intolerances in the diameter of the rods; due to the curved shapes of the elements more than one bonding lines are possible for a good contact. Moreover, the construction of several prototypes proved that the controllable application of the bonding media in the convex of the central profile achieves consistent, high visual and structural results (see Figure 4). The adhesive has a similar refraction index to glass and can be easily applied in a uniform layer along the complete length of the rods, resulting to an entirely transparent column. At the same time the most desirable loading scheme is attained, with glass loaded in compression and adhesive in shear. The application of the adhesive in the optimum thickness layer ensures the highest load carrying capacity. At the same time, the high stiffness of the selected adhesive prevents the individual buckling of the rods and allows the bundle to function as one monolithic unit under loading. This bonding method provided the most promising results in terms of visual and structural performance and therefore was selected for the fabrication of the bundled column experimental prototypes.

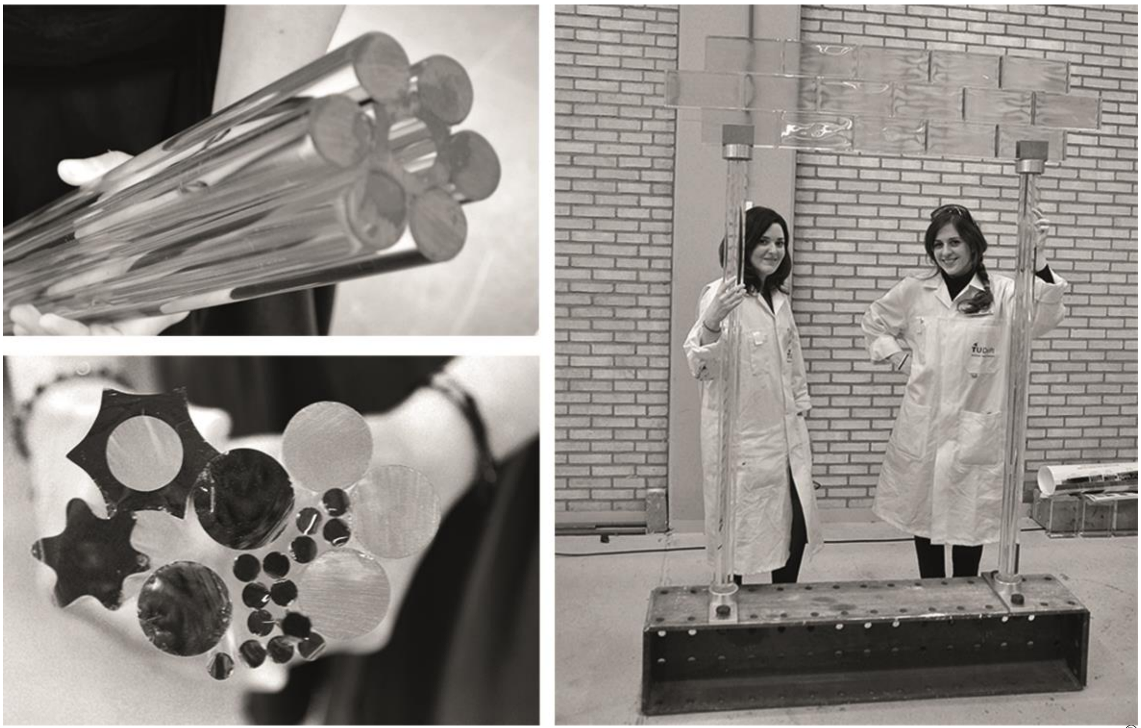

Figure 4. Top Left: Concluded configuration of the bundled glass column. Bottom Left: CONTURAX® and DURAX® profiles. Right: Realized 1.5 m high prototypes.

3 COMPRESSION TESTS

To examine the load bearing capacity and failure behavior of the bundled glass column concept, compression tests were carried out on a series of small (0.5 m high) and relevant to building scale (1.5 m high) prototypes. The prototypes consist of a central hollow star-shaped CONTURAX® profile with 17 mm inner and 30 mm external diameter adhesively bonded to six DURAX® rods of Ø 22mm, forming the external bundle. All the glass profiles are annealed and have been carefully cut in size with their ends grounded and polished manually. Two engraved cups made out of aluminium, due to its comparable to glass modulus of elasticity, are used for the top and bottom bases. A soft lead sheet interlayer is placed between the cups and the glass rods to prevent their direct contact and avoid peak stress concentrations. The remaining gaps between the bases and the glass bundle are filled with a two-component clear adhesive. For safety reasons, prior to testing all specimens are wrapped in several layers of clear PET plastic foil and put in a wooden safety cage with a polycarbonate window.

3.1 Compression tests on 0.5 m high prototypes

A series of three 0.5 m long prototypes was tested under compression until failure in a force controlled electromechanical universal testing machine as shown in Figure 5. All specimens comprise a central star-shaped CONTURAX® profile and 6 DURAX® rods of Ø 20mm (specimen 1) or Ø 22 mm (specimens 2 and 3). Table 1 summarizes the dimensions, failure load and compressive strengths of each prototype. All three specimens failed in compression in a consistent failure strength of approximately 500 MPa. All specimens failed in a sudden and complete way, shuttering into thousands of pieces, without providing any warning mechanism. No cracks or deformation were observed before the failure load was reached. The high failure stress indicates that, owing to the lead connection, edge flaws and unevenness on the length of the glass rods have minor influence if any to the total load-bearing capacity. Moreover, the results prove that the high stiffness of the selected adhesive allows for the bundle to behave as one monolithic unit under loading until failure..

Figure 5. Left: Experimental set-up of the 0.5 m high specimens. Centre and right: Experimental set-up of the 1.5 m high specimens.

Table 1. Dimensions and strength values of 0.5 m high prototypes

Specimen	Length	Composition of the bundle	Surface area	Failure Load	Nominal compressive strength
	mm		mm^2	kN	MPa
1	500	6x Ø 20 rods 1x star-shape	2156	1009.9	468
2	500	6x Ø 22 rods 1x star-shape	2552	1320.2	517
3	500	6x Ø 22 rods 1x star-shape	2552	1320.0	517

3.2 Compression tests on 1.5 m high prototypes

Compression tests until complete failure were carried out on a series of three 1.5 m high specimens on a force controlled hydraulic compression machine (see Figure 5). The displacement in this experimental set-up is measured as the shortening of the column at its middle. Table 2 summarizes the dimensions and failure load of each specimen and Figure 6 shows the load versus displacement curves of the prototypes. The orange dots indicate the load where the first crack was observed. The prototypes presented initial cracks in loads significantly lower than their maximum strength, which ranged between 130-199 MPa. In specific, specimen 2 cracked at 260 kN and reached a maximum load of 389 kN; a load almost 1.5 times higher than the one of the initial failure. Specimen 3 initially cracked at 120 kN and failed under a load more than 4 times as high (508 kN). The three specimens presented visible buckling before failure, thus providing an early warning mechanism before collapse. When reaching their maximum load all prototypes broke in small pieces without maintaining any post-breakage carrying capacity. Nevertheless, the specimens can be considered to have a relatively safe failure behavior, as the first cracks initiate in considerably lower loads than the maximum one and visible buckling is observed before failure. These warning mechanisms provide enough time for the replacement of a damaged element or for fleeing the site.

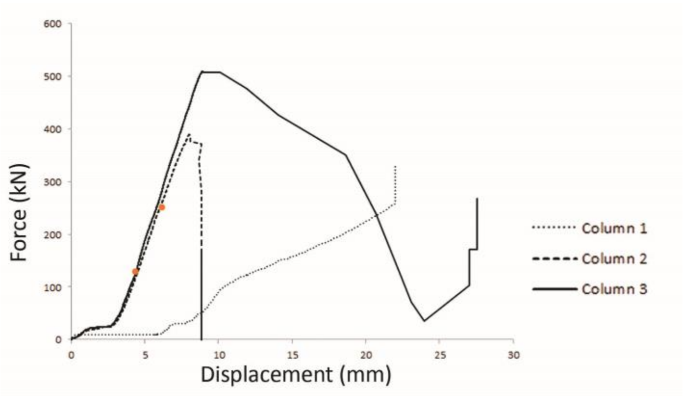

Figure 6. Load displacement data for the 1.5 m high prototypes. The orange dots indicate the recorded initial cracks in specimens 2 and 3.

Table 2. Dimensions and strength values of 1.5 m high prototypes

Specimen	Length	Composition of the bundle	Surface Area	Load where first crack was observed	Failure Load	Nominal compressive strength
	mm		mm^2	kN	kN	MPa
1	1515	6x Ø 22 rods 1x star-shape	2552	not recorded	331	129.7
2	1515	6x Ø 22 rods 1x star-shape	2552	260	389.38	152.57
3	1515	6x Ø 22 rods 1x star-shape	2552	120	508.78	199.36

4 DISCUSSION AND CONCLUSIONS

In this paper, a completely transparent, bundled glass column has been explored. The final composition and production process of the column provides consistent optimum results both in terms of visual and structural performance. The chosen bonding method allows for a controllable and even distribution of the adhesive, resulting to an adhesively bonded glass bundle without any visual defects. Moreover, the high shear stiffness of the adhesive leads to the desired coupling of the rods and their behavior as one monolithic unit under loading.

The results of the 0.5 m and 1.5 m high columns are summarized in Table 3. The small (0.5 m high) specimens present a consistent compressive strength equal to approximately 500 MPa. The consistent high strength value together with the complete absence of buckling and prior cracking suggests that the small prototypes failed due to compression. More precisely, the specimens fail when the stresses due to expansion in the perpendicular to the load direction exceed the tensile strength of glass or of the applied adhesive. Until failure, the high stiffness of the chosen adhesive enables the bundle to behave as one monolithic unit under loading. The high failure strength of the small specimens indicates that the effect of induced imperfections, such as surface defects and irregularities, has a minimum influence on the results. This can be attributed to the soft lead interlayer which absorbs by deforming small, unavoidable tolerances in the length of the rods, eliminating local peak stresses due to an uneven contact surface.

The 1.5 m high columns fail in comparably much lower stresses, ranging between 130 – 199 MPa. Their high slenderness ratio causes their visible buckling before they collapse. In addition, due to bending caused by the buckling, cracks in the specimens initiate in considerably lower stress values than their total load bearing capacity. Although the failure load is significantly lower than the one recorded in the 0.5 m high series, the visible initiation of failure before collapse functions as a warning mechanism, providing sufficient time to flee or to replace the damaged component. Owing to these warning mechanisms, the 1.5 m high columns are considered to have a relatively safe failure behavior and are promising as structural compressive elements.

Overall, the research and experimental work conducted proves that the bundled glass column can be a trustworthy and elegant solution in the search of a transparent, load-bearing component. It has sufficient compressive strength and also presents a safe failure behavior by providing warning mechanisms.
Further work will include experiments in series of 1.5 m high columns in order for statistical data to be derived, as well as in columns 2.5 – 3 m long to explore the potential of the column in given structures. Columns with one to two rods missing will also be manufactured and tested to evaluate the load bearing capacity and failure mode of an accidentally damaged column.
Future research will focus on increasing the buckling resistance of the bundle, on exploring potential measures that can further increase the safety of the glass column and on developing the top and bottom connections.

Table 3. Summary of compression test results

Prototype		Stress where first crack was observed	Nominal compressive strength	Failure mode
		MPa	MPa	
0.5 m long	1	-	468	Compression
	2	-	517	Compression
	3	-	517	Compression
1.5 m long	1	not recorded	129.7	Buckling
	2	101.9	152.57	Buckling
	3	47.0	199.36	Buckling

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