Investigation of double-layer tensegrity glazing systems

Ioannis S. MITSOS[1], Simon D. GUEST[2],

Shelton NHAMOINESU[3] & Mauro OVEREND[4]

[1] Department of Engineering, University of Cambridge, Cambridge, UK, *im330@cam.ac.uk*

[2] Department of Engineering, University of Cambridge, Cambridge, UK, *sdg@eng.cam.ac.uk*

[3] Department of Engineering, University of Cambridge, Cambridge, UK, *sn393@cam.ac.uk*

[4] Department of Engineering, University of Cambridge, Cambridge, UK, *mo318@cam.ac.uk*

Summary

Tensegrity grids, with tensed cables and isolated struts, have strong aesthetic appeal, but have had limited architectural engineering applications. The present study investigates a promising application: the use of a tensegrity grid as supporting structural system for double-skin glazing systems.

The system considered consists of two layers of glass panels sandwiching a core modular tensegrity grid. The tensegrity grids consist of steel compression tubes and steel tension cables designed to pre-stress the glass supporting system. The use of structural glass is central to the design as the glass plays a double role in the structural system. Apart from their functional purpose (thermal insulation, visual transparency etc.), the glass panels also serve structural purposes acting as load bearing structural elements integrated with the tensegrity supporting system.

The paper will consider the advantages of a tensegrity system, both from a functional and structural perspective, as well as considering aspects of assembly and pre-stressing.

Keywords: inverse bidirectional; tensegrity; pre-stress; grid; structural glass; double-skin glazing.

1. Introduction

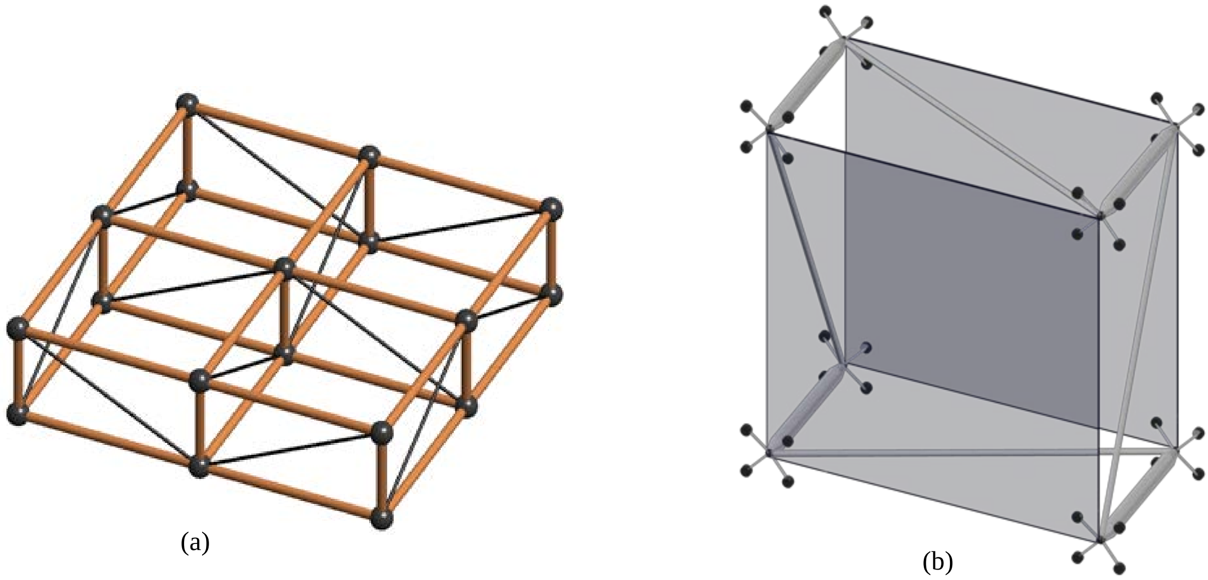
Could tensegrity structures be part of the construction industry through an interesting novel application? Although tensegrity structures are fascinating and favoured by architects and artists, their application in the engineering field is rather limited. Their singular morphology, complex geometry, constructability and limited structural redundancy have suppressed their use in any single branch of the construction industry. However, recent investigations have shown that tensegrity systems have the potential to serve numerous engineering applications such as solar collector space grids, pedestrian bridges etc. [1-2].

As an answer to above question the present paper aims to investigate and draw some interesting inferences concerning the potential of double-layer tensegrity grids as structural façade enclosures through a specific case study. The novelty of such an application is further enhanced by using a 'brittle' material such as glass to act as a structural component in to the system. The application proposed is the use of glass panels as structural components forming the top and bottom layers of a double-layer tensegrity grid in order to create a double-skin glass façade with interesting structural properties. The latter application is described through a case study were a double-skin glass façade wall spans a large area which could possibly be a face of an atrium in a tall building or a face of an airport lounge.

2. Double-skin tensegrity glass façade proposal

2.1 The glass panelling concept

Advances in glass façade technology have shown that the double-skin glass facades present improved thermal and acoustic properties compared with the conventional single skin glass facades [3]. However, the need for more efficient structural enclosures for the double-skin glass facades remains unsatisfied since the existing 'open' systems require the use of large profile anchorage structures to counterbalance the pre-stressing forces. In this context an inverse bidirectional tensegrity grid (Figure 1-a) acting as a 'closed' structural system is used to replace the conventional one. Furthermore, for the sake of structural efficiency and enhanced visual transparency, an attempt for dematerialisation is made replacing the top and bottom layers of strut elements from the tensegrity grid by glass panels which aim to act as structural components (Figure 1-b). Recent advances in structural glass have shown a great potential of using glass as a structural material with commendable structural properties [4]. Thus, the glass panels will play a double role in this study acting both as a skin and a structural component resisting mainly compressive forces resulting from the applied pre-stress in the structure.



(a) (b)

Figure 1: Representation of a 2×2 module tensegrity basic unit (a) and a tensegrity module with top and bottom glass panel layers (b).

2.2 The double-skin tensegrity façade wall

The double-layer façade wall investigated is a 16m×12m structure aiming to serve as the glazing face of an atrium in a tall building or the facade of an airport lounge. The proposed case study considers an 8×6 module double-layer grid glass façade composed of 2m×2m×1m modules accommodating 2m×2m square glass panels as shown in Figure 2. The façade structure comprise 63 compression struts, 96 tension rods and 96 square glass panels connected with rest of the structural members through four-way spider fittings as shown (Figure 1-b). The struts and the rods are made of S335 stainless steel and the glass panels from toughened glass, having similar coefficients of thermal expansion avoiding possible uneven length changes due to temperature changes.

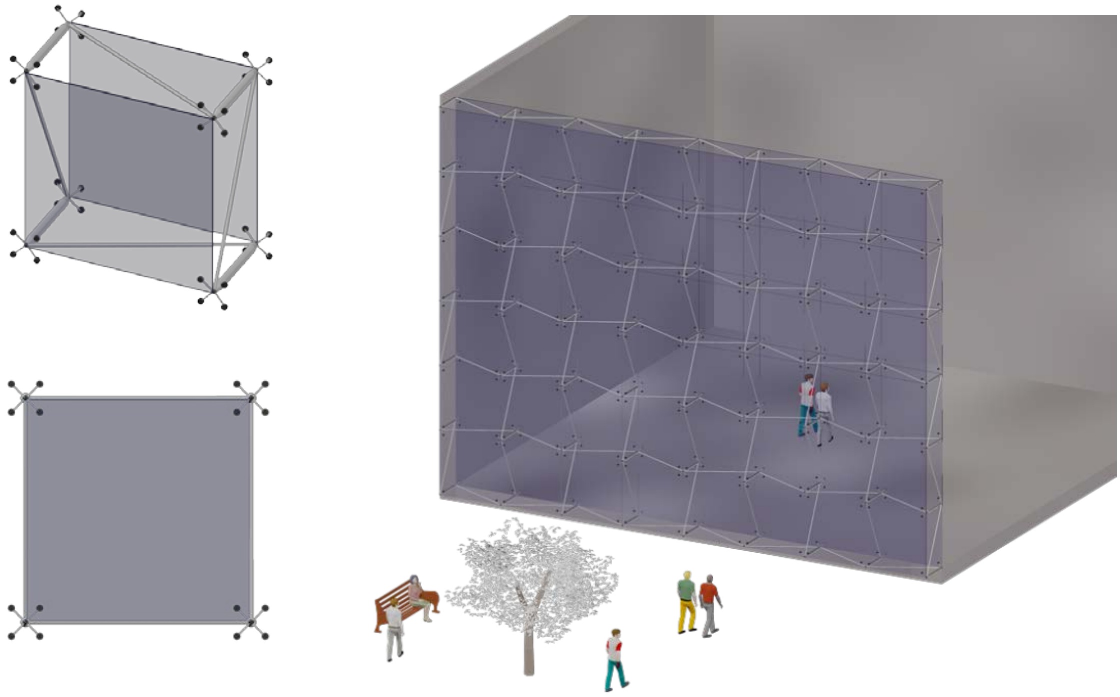


Figure 2: Architectural rendering of the glass façade modules in side and isometric view (left, top and bottom) and the 192m^2 glass façade wall (right) in isometric view.

3. Analysis of the double-skin tensegrity glass façade

Analysis of façade wall was carried out in two steps. The first part includes the analysis of the inverse bidirectional tensegrity grids in order to determine some of their structural properties. The second part is the static analysis and preliminary design of the façade wall according to the load cases retrieved from the Eurocode.

3.1 Analysis of tensegrity grids

For the present study, analysis of tensegrity structures is carried out using a computational model for pin jointed frameworks, as formulated by Pellegrino (1993), using the singular value decomposition (SDV) of the equilibrium matrix to determine the states of selfstress **s** and the internal mechanisms **m** of the tensegrity model.

3.1.1 Analysis of the 2×2 module basic tensegrity grid

The tensegrity system considered for the analysis is an inverse bidirectional grid (Figure 1-a) augmented by planar diagonal struts which aim to replace the glass panels accommodated on the top and bottom layers of the grid. The augmented basic grid is a 2×2 module grid used to form a large multi-modular tensegrity grid comprising 18 nodes and 53 elements. The augmented basic unit is composed of 12 tension rods (black lines) and 41 compression struts as shown in Figure 3.

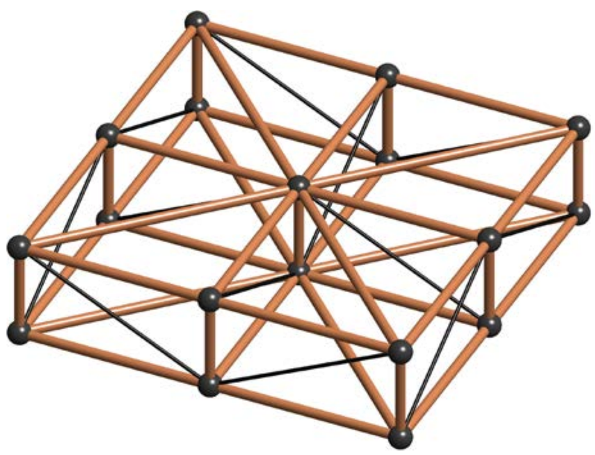


Figure 3: Representation of the augmented basic tensegrity unit.

From the analysis carried out on the basic unit it is eminent that this structure is stabilised by five state of self-stress **s=5** and the number of infinitesimal mechanisms **m=0**. The latter information implies that the basic unit shows a stiff behaviour having been augmented with the glass panels and that may be capable resisting external loads with minimum deflections. The existense of the 5 state of self-stress clearly shows that it is possible to stabilise the system through a symmetric pre-stressing pattern which will induce stress in the structural elements. In this case a stabilising self-stress state can be achieved through a pre-stressing pattern where all the vertical struts are lengthened. The induced state of self-stress achieved by the latter pre-stressing patern is shown in Figure 4 where the elements undergoing tension and compression are coloured by yellow and red fills. A rather interesting information from Figure 4 is that all the tension elements are in tension and the bars aiming to replace the panels are in compression. The latter is obviously positive since the glass panels are capable resisting large compressive forces [4].

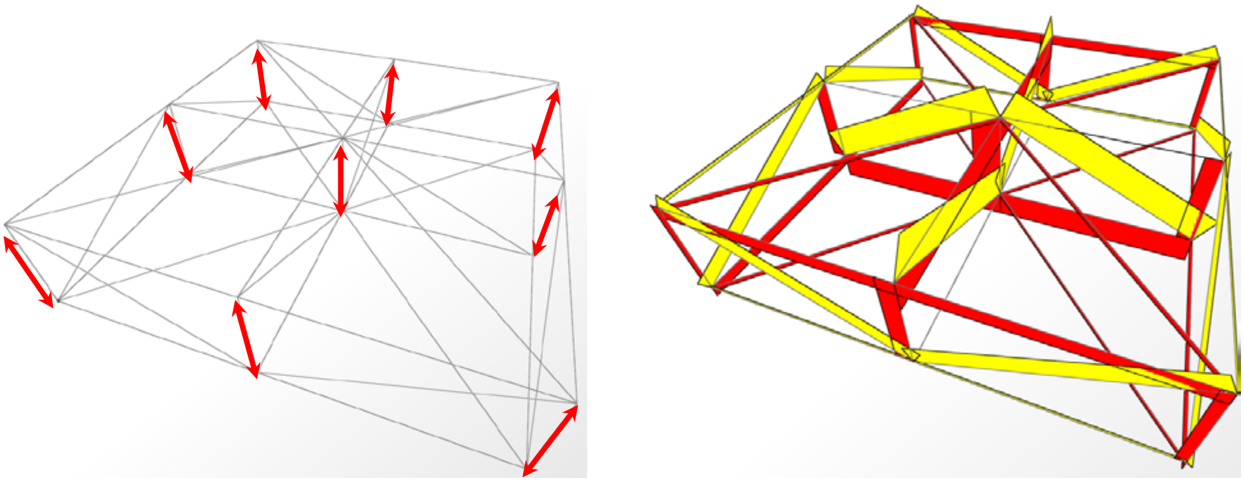


Figure 4: A stabilising state of self-stress induced by the lengthening of the vertical compression struts.

3.1.2 Analysis of the 8×6 module tensegrity grid

The 8×6 module grid is composed of twelve 2×2 module basic tensegrity grids, packed as shown in Figure 5. The aforementioned structure is composed of 126 nodes and 489 elements of which 96 are tension elements. From the analysis it was observed that the structure possess **s=117** and **m=0**. The latter results imply that the structure is rigid with a high degree of redundancy. In practice, a possible state of self-stress stabilising the system could be achieved by a pre-stressing pattern which includes the lengthening of all the vertical struts. Such a pre-stressing pattern would provide stability by inducing tension in the tension rods, compression in the vertical and planar diagonal struts meaning that glass panels will undergo in-plane compressive forces.

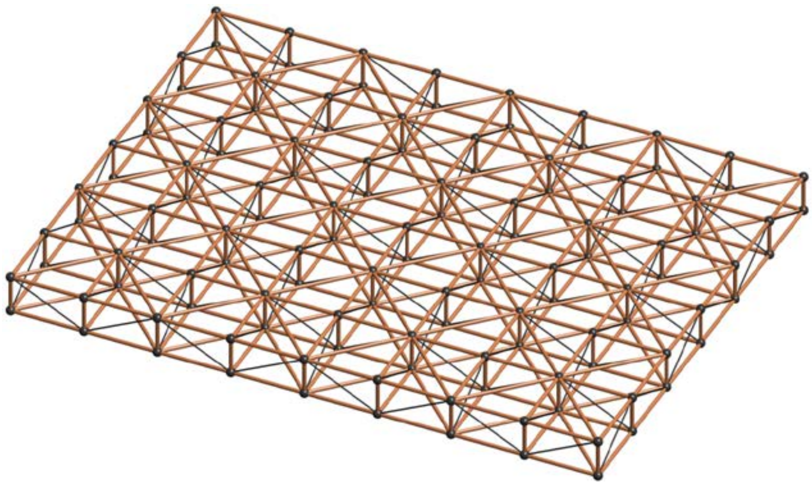


Figure 5: The 8×6 module tensegrity grid spanning the

3.2 Static analysis of the tensegrity glass façade wall

For the static analysis of the tensegrity glass façade, a computational model based on the principles of linear elasticity was used accounting the pre-stress of the system and the external design loads. Compression steel struts and steel tension rods were assigned in the model as well as thin shells as glass panel sections. Additional FE analysis was performed on the glass panels due to their central role for the integrity and stability of the structure since they are designed to act as structural elements resisting large in-plane compressive forces.

3.2.1 Pre-stressing

For the present computational model the pre-stress is applied through the lengthening of adjustable length compression struts. The amount of length extension applied was e=5mm considering three parameters: the amount of load applied on the structure, the allowable deflection and the fact that the tension bars should be prevented undergoing any compressive loads (avoid slack tension bars or de-tensioning).

3.2.2 External loading & load cases

The loads considered for the tensegrity façade wall apart from the pre-stress are the wind loads (WL), the self-weight of the structure (SW) and temperature changes (T). The magnitudes of the values and the allowable deflection criterion set for the present structure are listed in Table 1. The two load cases considered for the analysis were in accordance with the European code for loading of structures, Eurocode 1 and they are listed in Table 2.

Table 1: Applied loads.

WL	1.0 MPa
DL	1.0×10^{-3} MPa
T	±15°C
L/D	span/250
e	0.005 m

Table 2: Load cases.

1.4•DL + 1.4•WL + Pre-stress	(1)
1.2•DL + 1.2•WL + 1.2•T + Pre-stress	(2)

3.3 Computational analysis and results

The computational model was analysed for the load cases shown in Table 2. From the analysis it was deduced that load case (1) was the most critical load case in terms of magnitude of loads applied on the members, whereas, load case (2) was the most critical for the analysis of the glass panels. Although the amount of external loads applied on the structure was extreme, the 5mm length extension applied on the compression strut was enough to maintain the amount of de-tensioning and span deflection of the structure to minimum. Thus, all the tension rods and compression struts were successfully remained in tension and compression respectively as shown in Figure 6.

3.3.1 Worst case scenario for struts and rods

In addition to the normal load cases, an extreme load case scenario was considered where during the extreme load case (1) a glass panel is removed from the most critical area of the structure (Figure 6). In this case the loads carried by the members increased slightly comparing to the ones found when the glass panel was not removed. From the latter analysis results obtained for this case it can be deduced that the tensegrity glass façade has a degree of structural redundancy which prevents the exertion of high internal forces and significant deflections due to the loss of a glass panel validating the results of the analysis of the tensegrity model (*see section 3.1.2,* **s=117**).
In this case the maximum force carried by a tension rod and a compression strut was approximately 298 kN and 167 kN tension and compression respectively as shown in Figure 6. The windward force applied on the structure caused a maximum deflection of 4.7mm (Figure 7, U2) which is well below the allowable deflection criterion shown in Table 1.

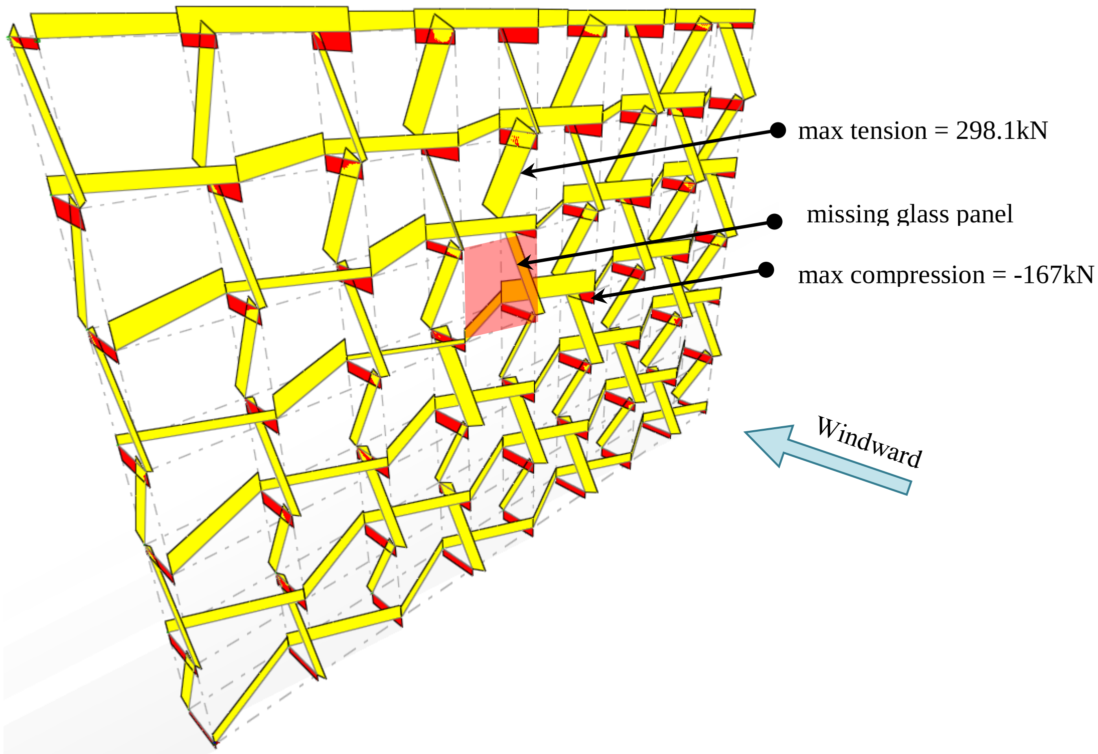


Figure 6: Axial force diagram indicating the members in tension (yellow), the members in compression (red) and the maximum tension and compression values for the extreme load case.

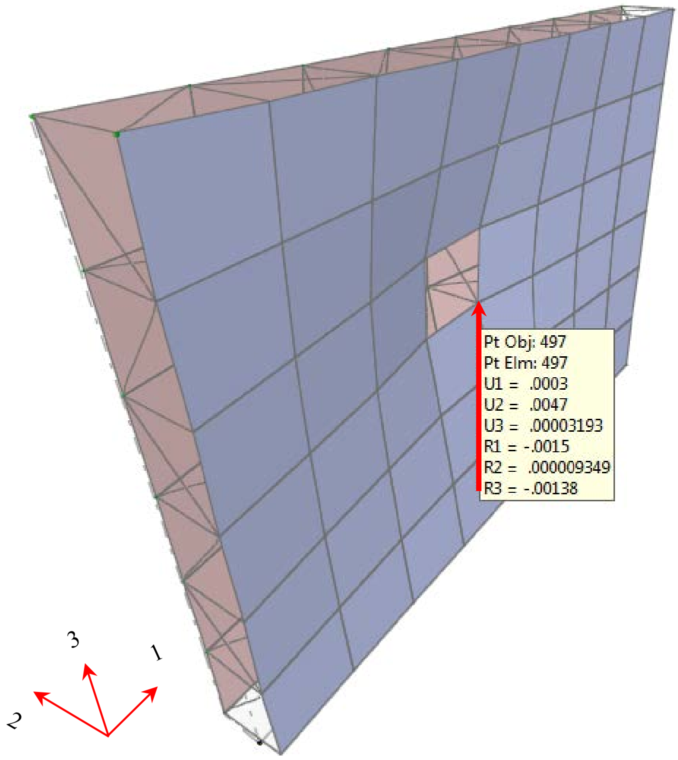


Figure 7: Deformed shape indicating the maximum lateral deflection U2=0.0047m and the most loaded panels on the façade wall.

3.3.2 Worst case scenario for glass panels

From the analysis of the façade wall it was observed that the maximum load applied on the glass panels was during an extreme load scenario where the structure was loaded with load case (2) and the most loaded glass panel was removed. The glass panel undergoing the maximum load was the panel shown in Figure 8 which was subjected in excessive in-plane compressive forces in the Z and X directions and it is located next to the missing panel. The latter has a high slenderness and when

subjected to high in-plane compression loads – such as the load case represented in Figure 8, the glass elements tend to fail because of instability i.e buckling. The load case for the panel under investigation, figure 8 has been numerically modelled as a single layered 19mm thick glass with four standard-sized bolt holes. A planar countersunk stainless steel bolted connection has been proposed since it allows direct load transfer through bearing of the glass on the bolt with a nylon 66 boss used as a liner material to avoid direct steel to glass contact. The bolt assembly is fixed onto a spider support system which connects four bolts from corners of four adjacent panels. A two layer sandwich laminated safety glass panel would be most ideal but in this analysis, a single layered glass has been considered for simplicity. The panel has been numerically modelled as a thin shell QSL8 element which is suitable for analysis of arbitrarily curved shell geometries with the element formulation taking account of both membrane and flexural deformations, the analysis was run with a total Lagrangian geometric nonlinearity option which is applicable for arbitrarily large deformations. Due to the excessive in-plane compression loads transmitted through the bolts especially on the left-hand side where an adjacent panel has failed, the results of the analysis show very high stresses in the glass with peak stresses of up to XXXMPa located at the YYY of the panel. This extreme loading case results in stresses higher than the characteristic strength of thermally toughened glass which is 120MPa [6]. It is worth noting however that this is the bending strength while the glass in this case is primarily subjected to compressive loading.
A simplified buckling analysis of the single layered glass based on [7] reveal that for an applied axial compression, a solution for the elastic critical buckling load is exceeded and the maximum surface stress for the applied maximum load, also exceeds the characteristic strength of thermally toughened safety glass.

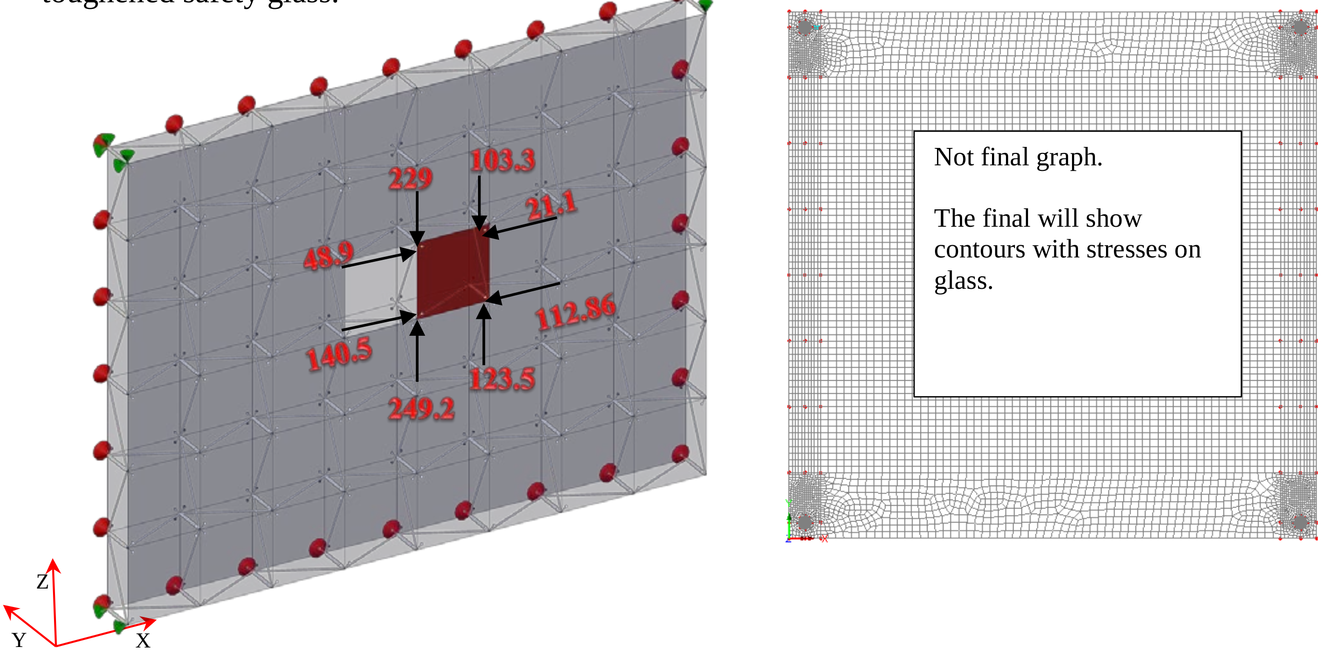


Figure 8: Graphical representation of the compressive loads (in kN) and the exact location of the highest loaded panel highlighted with red colour (left) and a contour plot indicating the levels of stress on that panel (right).

Whilst it is clear that under this extreme load case, toughened glass will fail to support the loads, it is also noted that resolving several issues in the design of the tensegrity grid would make it possible to use glass structurally. Some of these issues include, (i) possibly replacing bolted connections with linear adhesive connections on the panels to reduce stress peaks that otherwise arise in the vicinity of bolt-holes, (ii) laminating the glass and increasing the panel thickness to minimise the effect of slenderness and reduce the possibility of buckling and (iii) to reduce the panel size.

3.3.3 Sizing of structural elements

Tension and compression element sections were provided according to the results obtained from the worst case scenario. According to the member sections provided shown in Table 3, the weight of the actual structure was determined to be 107kg/m^2 and the weight of the structural façade enclosure approximately 12kg/m^2.

Table 3: Sections provided for the tensegrity glass façade.

	Max load (kN)	Section assigned		Section capacity (kN)
Compression strut	165.8	M36 CHS (mm)		186
		od: 88.9	t: 5	
Tension bar	271.1	M36 Bar (mm)		376
		dia: 34		
Glass panel	(see section 3.3.2)	Glass panel (mm)		(see section 3.3.2)
		l×d: 2000×2000	t = 19	

4 Conclusions

The results obtained from the investigation carried out on an 8×6 module inverse bidirectional glass panelled tensegrity grid showed that there is a potential using the latter as a double-skin façade. The analysis of the proposed system showed that the tensegrity system is capable to resist the design forces with lightweight sections undergoing negligible deflections. The pre-stressing pattern used was able to provide the amount of pre-stress required avoiding possible de-tensioning and significant deflections even in the extreme load cases. Although the glass failed to resist the severe compressive forces in an extreme load case scenario, there are options to follow in order to avoid the glass failure. To summarise, the tensegrity glass façade from an engineering point of view showed:

- Minimum deflections for a long span using light sections and avoiding any mid-span supports or anchorage structure;
- High degree of redundancy through a large number of self-stress states;
- That glass panels failed to resist high compressive forces; however, there are options to increase the capacity of glass in the façade system.

Whereas from an architectural and environmental point of view the observations are:

- Improved transparency using large size panels supported through a lightweight structural enclosure;
- Dematerialisation using glass as a structural component;
- Advanced thermal and acoustics properties due to the double-skin nature.

5 Acknowledgements

The authors acknowledge funding support by a grand (code#06 R&D B03) from the Cutting edge Urban Development Program funded by the Ministry of Land, Transport and Maritime Affairs of the Korean Government. The first author is sponsored by Alexander S. Onassis Foundation and the Cambridge European Trust (George and Marie Vergottis Fund) for his PhD studies.

6 References

[1]. Mitsos, I., Guest, S. D., Winslow, P., & Martin, B. (2011). Experimental Investigation of a double layer tensegrity space frame. *6th International Conference on Space Structures.* London: IABSE-IASS.

[2]. Barbarigos, L. R., Ali, N. B., Motro, R., & Smith, F. C. (2010). Designing tensegrity modules for pedestrian bridges. *Engineering Structures, 32*(4), 1158-1167.

[3]. Patterson, M. (2011). *Structural glass facades and enclosures.* New Jersey, USA: Wiley, Inc.

[4]. Mocicob, D. (2008). *Glass panel under shear loading – use of glass envelopes for building stabilization.* Lausane: PhD thesis, (EPFL), Lausanne, Switzerland.

[5]. Pellegrino, S. (1993). Structural Computations with the Singular Value Decomposition of the Equilibrium Matrix. *International Journal of Solids and Structures, 30*(21), 3025-3035.

[6]. prEN13474:3:2007 . Glass in buildings – Determination of the strength of glass panes – Part 3: General method of calculation and determination of strength of glass by testing. *CEN/TC129/WG8*,2007.

[7]. Luible, A., Crisinel, M. (2004). *Buckling design of glass elements under compression.* In: Proceedings of the International Symposium of the Application of Architectural Glass, Munich, Germany, 2004.