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Transparent form-active system with structural glass.

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Abstract

Free-form transparent wide-span spatial structures which have being constructed so far, are based on the concept of three sets of components, the structural components, usually steel elements to ensure both compressive and tensional capacity; the glass cladding elements for expressing transparency; and thirdly an in between set for connecting the cladding with the primary skeleton. Even though glass technology is becoming more and more promising, glass is still considered doubtful in a load-bearing capacity, which implies to a repetitive architectural and engineering repertoire. Nevertheless, in the last two decades there has been a tendency to explore the design and realization of pure structural glass domes [1, 2, 3,4]. The outcome of these experiments, resulted in glass domes of the same conservative geometry of a sphere of small spans between 5-12.5m. Therefore, the glass still has not reached its limits in terms of architectural forms and span size. Apparently, the combination of synclastic and anticlastic geometries applied for glass structures is still an unknown field and remains as a theoretical question whether or not there are possibilities to implement glass plates in the construction of free-form spatial structures, as a main load-bearing component.

In respect to the emerging technologies of glass technology and computation, design strategies revolving around the assumption of using glass to realize a transparent form-active system, are presented through a new concept for an innovative connection method. In particular, the concept of connection relies on the composition of a transparent hybrid composite composed by thermally strengthened glass, sentry glass plus and woven fabric composite. Particularly, the composite has an extended part outwards of a reinforced glass plate, used for easy assembly and disassembly as well as the transfer of tensile forces and improving so the post breakage behavior. The complete system out of glass plates and joints is controlled by determining the appropriate stiffness during design. The ultimate target, is to apply the concept of this joining method to any free-form shell geometry constructed out of planar glass plates.

Keywords: structural glass, hybrid transparent composite, embedded joining methods, form-active structures, free-form glass structures, faceted glass structures, component design

1. Introduction

The detail of glass connections has received significant contributions in recent years due to the important technological improvements concerning the capacity of an efficient bond between glass and metal. It not only has a significant impact on the structural behavior of the solutions but also opens several new fields of design research [1, 5, 6, 7, 8, 11]. Among several solutions available for the designers, embedded connections, in which a metal part is bonded to at least two glass panes with stiff interlayers such as Sentry Glass Plus, are of particular interest. Both glass and metal elements tend to lose part of their individual identity fusing into a unified hybrid component. This concept of reinforcing glass is an effective method to increase the post breakage behavior of glass [9, 10]. Once broken, the glass carries the compressive loads while the metal bridges the tensile loads together with a suitable polymeric interlayer. This interesting structural concept may be enhanced if the reinforcement plays an active role in connecting the glass elements.
The current research, based on the concept above, suggests the use of a fiber-reinforced composite such as Phenolic/E-glass fiber-woven fabric composite-biaxial lamina, since this has potential for its implementation during glass lamination process. The advantages of the use of this material instead of metal, relies on its lightness, high yield strength and high elastic elongation limit which can allow a hypothetical form-active behavior. Interestingly, its thermal expansion coefficient is close to that of glass and much lower than those of aluminum or steel, which means less internal movement in the system, thus causing less stress concentrations into glass panes. Additionally, its stiffness can be tailored according to the load bearing requirements without increasing significantly the amount of material, by adjusting the roving weaving process or/and by the use of different fibers of different stiffness where the element needs to be stiffer. Last but not least, its thermal conductivity is very low compared to metal resulting in minimization of thermal bridges.
Even though, glass with metal bond has proven its capabilities in glass construction with build examples standing for years, new lighter and flexible materials must also be studied for broadening the architectural repertoire in transparent structures in which the reinforcement becomes active.

2. Anatomy of the hybrid transparent composite

The proposed hybrid transparent composite is composed of different layers each one of them serving a different function, either architectural or structural.
Starting from the top, as it is illustrated in Figure 1, a glass insulating unit is placed on the top to insulate between the outdoor and indoor environment. Then, a polymeric interlayer such as Sentry Glass Plus, is placed and repeated between every layer for the lamination procedure and improvement of the residual strength of glass. After that, the embedded reinforcement is placed around the boundaries of the glass pane and at the same time is extended outwards for connection purposes. Within the layer of reinforcement, an optional layer of woven-fabric covering the whole area of glass pane can be added in order to control the light permeability and privacy levels of the component. Finally, at the bottom a laminated glass panel of high tensile strength such as fully tempered or heat strengthened glass completes the hybrid transparent composite.
The preliminarily designed component approximates a total thickness of only 30mm which includes the double glazing unit. This is a promising concept for a light and transparent hybrid composite which integrates many functions. In particular, recent design tools enable free-form shapes to be designed and constructed using planar plates. Therefore, production and construction can benefit from various standard sizes of available glass plates.

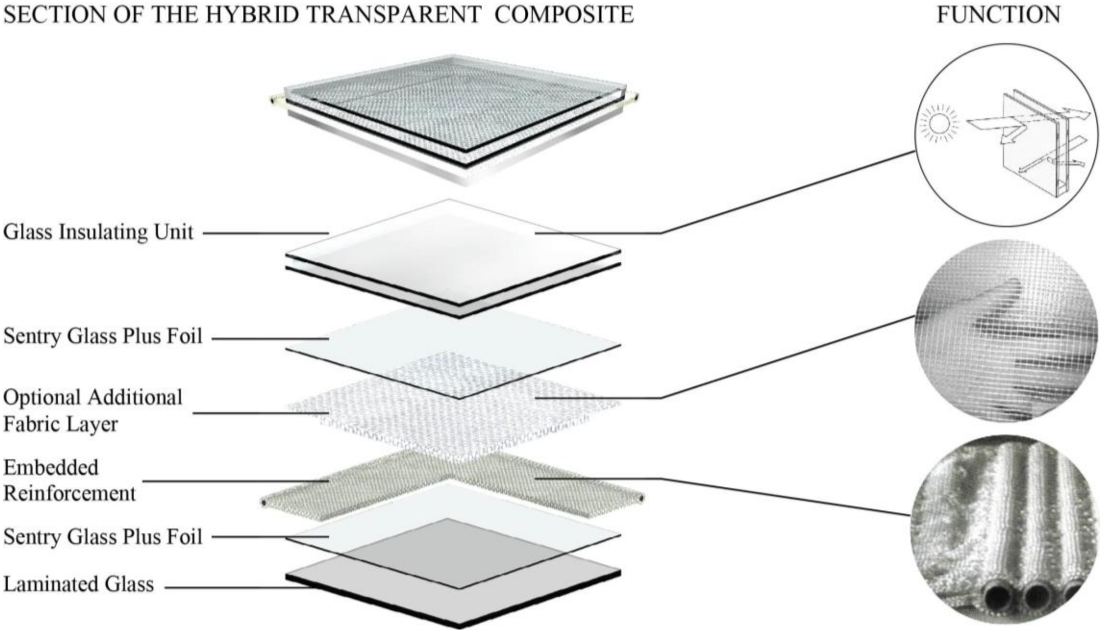

Figure 1: Anatomy of the hybrid transparent composite composed of different layers of different function.

3. Defining a form-active system

If the joints between the plates are able to allow transformability in a controllable manner either physically or mechanically by actuators, then can be beneficial for a whole glass facetted structure. A physical approach is less energy consuming but requires the determination of the joints' stiffness during design and it is closely related to the material. Generally, in a form-active situation the joints behave more like springs, accumulating energy during an asymmetrical live load and then; after loading, return back to their initial state. By this way, the plates are more likely to translate than bend, ensuring safety with less use of material.

The moment development through the facet, which explains the use of more material; depends on the degree of fixing at the boundaries. If we compare for example an arch (Figure 2) composed of segments which are fixed one to another and an arch in which the segments are free to rotate, we see that in the first case the elements develop higher bending moments. On the other hand, in the flexible system, the elements are less rigid so allowing rotation between the segments. As a result, the deflections are higher but the distribution of bending moments is smaller. Note that in a very rigid system almost no deflection occurs and then suddenly there is a total collapse especially in case of shells. Paradoxically, the less efficient the shell, in terms of rigidity, the better behaves in buckling.

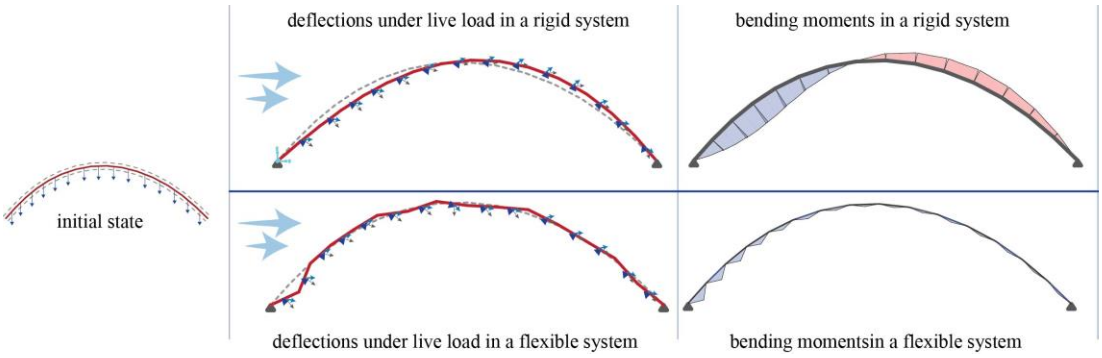

Figure 2: Comparison between a rigid and flexible system in a non-linear analysis.

According to the plate theory, what determines the behaviour of a connection in plates is the correlation between the spring stiffness k_m and the plates own resistance against edge rotation k_p from a uniform moment acting at the edge and it is expressed as α.

$$\alpha = \frac{k_m}{k_m + k_p} \quad \alpha \in [0;1], \quad k_m = \frac{Et^3{}_{joint}}{6w_{joint}}, \quad k_p = \frac{Et^3{}_{plate}}{6l_{plate}(1-v)}$$

When the ratio α=0, the connection corresponds to hinge behaviour, while for α≈1, the edge is fully clamped (Figure 3).

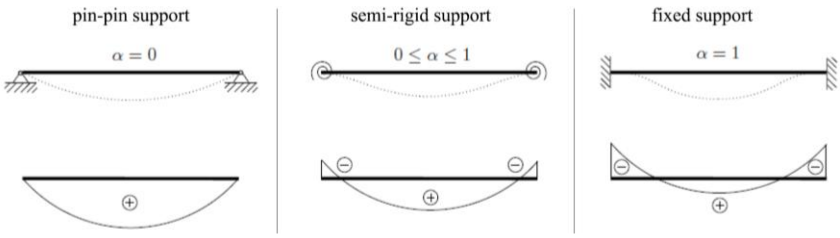

Figure 3: Bending moments in different types of boundary conditions.

In conclusion, in case plates are rigidly connected the bending moments occur high stresses in the plates. If either the glass or the connection fails the structures becomes a mechanism. In the form-active system semi-rigid connections allow for larger deformations of the structure and reduce bending moments in the plates. In case of too flexible connections the structure can snap through when deformations become too large. The appropriate stiffness for the semi-rigid connection should be determined during design in order to avoid stress concentration in glass plates and thus ensure a safe failure.

4. Structural behavior of the hybrid transparent composite

The plates were numerically tested using two different methods in the finite element programme Fx+ for iDiana. The numerical modelling consists of the following procedure:

- Construction of the model: element types, material properties, meshing of the model, boundary conditions, load introductions and solution procedure.
- Results: model deformation and stress distribution.

In the first method, three plates were modelled as flat shell elements (Figure 4), so that the results could be compared with hand calculations and to investigate the behaviour in terms of bending moments in glass plates. Thus, it would give a clue about the spectrum of the joint behaviour where the joint is rigid, semi-rigid or flexible. In all models the glass plates have the same size of 3000x3000mm with a thickness of 30mm as an approximation of the composite section of glass plate and Young's Modulus 38577 N/mm^2. Note that, the aim of the analysis is to examine the behaviour and not the magnitude of stresses. The first model does not include the extended part so it can be compared with those including the extended part. The second and third one have a strip of a width of 16mm and 50mm respectively and a thickness of 5mm.The strip represents the extended reinforcement with a Young's Modulus of 33300N/mm^2.

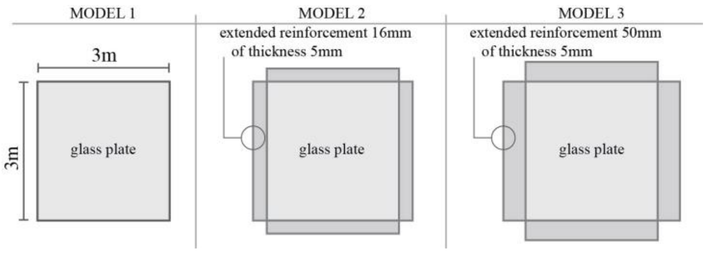

Figure 4: The construction of FEM Shell Models.

In the second method (Figure 5), the numerical models of glass plates consider all the main construction layers of the hybrid composition (glass layers, sentry glass plus and the composite reinforcement) and they are composed of solids. In the analysis with solids, we can investigate the stresses but not the bending moments. Again, three models were tested, firstly, a single solid with a representative value of thickness 28 mm and Young's modulus 55814N/mm^2. Model 2 and 3 contains 2 glass solids of thickness 10mm each and Young's modulus 70000N/mm^2 and 2 layers of SGP solids of 1.52mm thickness and stiffness 240N/mm^2. The reinforcement strip has an internal part of 200mm width and an extended part of 16mm for model 2 and 50 for model 3. The stiffness of the reinforcement is 33300 N/mm^2.

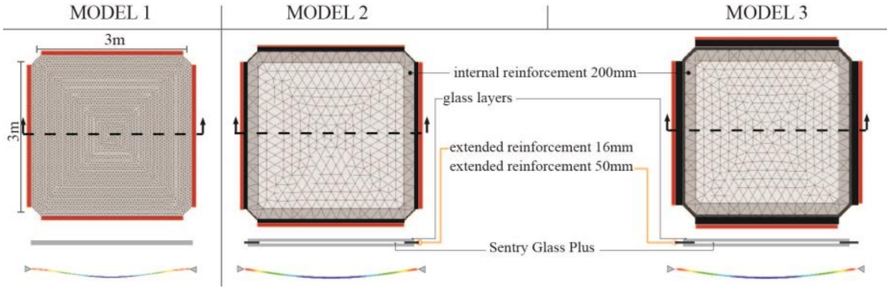

Figure 5: The construction of FEM Solid Models and the deformed shapes.

3.1. Analyzing the behavior in bending

The results from the analysis show that the plate without extended reinforcement and simply supported at all edges, does not have zero bending moment at the corners and edges but exhibits a semi-rigid to pin-pin behaviour. Interestingly, the extension added to the plate in the fixed condition immediately occurs a pin-pin support and the middle edge bending moments are reduced 10 times. More obvious is the reduction of bending moments at the corners where the moments of the second model is only the 11% of the first one, but the third model develops about the double moment corners. In the condition with fix supports it is clearer that the plates (model 2 and 3) behave between the range of semi-rigid to rigid situation, exhibiting a better performance in terms of deflection and the magnitude of bending moments. Generally, there is a difference of about 10% in bending moments between hinged model 2&3 and fixed model 2&3 respectively.

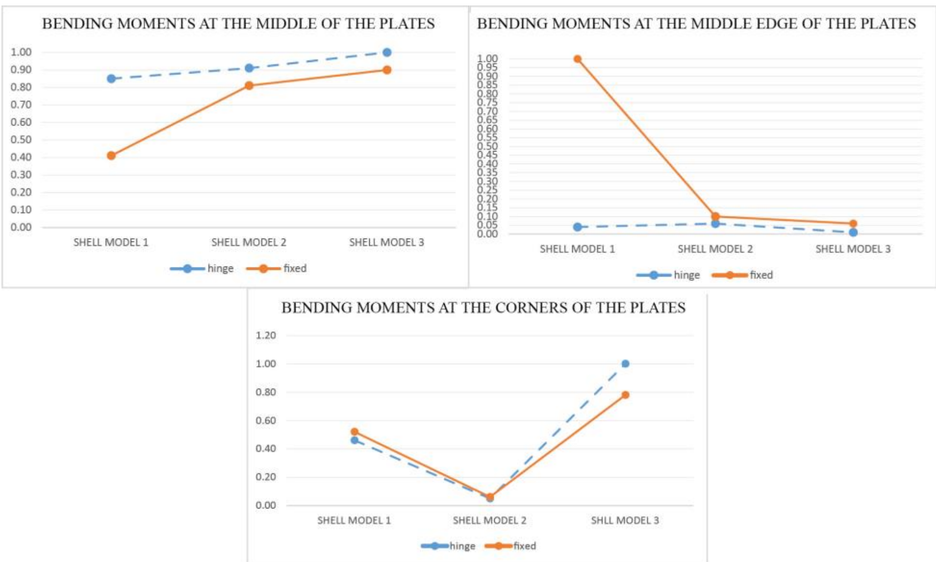

Figure 6: Bending moments at the middle edges and at the middle respectively for the three flat shell element models of the same size. The values are expressed by their division with the maximum bending moment both for the middle and corners/edges.

3.2. Stress distribution

The aim of the second analysis method was to determine if there is any effect of the boundary internal strip reinforcement to the stress distribution of plate and especially the influence of the extended part. The models are tested only for both cases, simply and fixed supported edges.

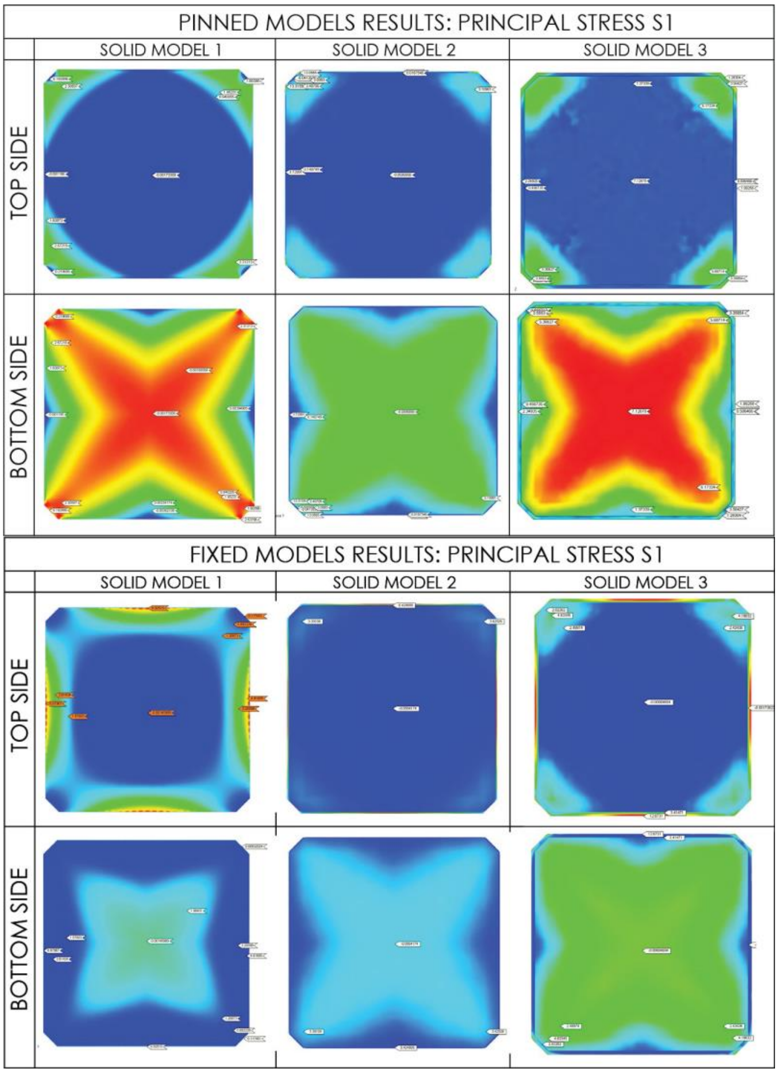

Figure 7: Principal Stress S1 diagrams for both sides

Looking at the stresses at the corners and edges (Figure 7), where it is assumed that there is an influence of the internal part of reinforcement, we see that the stresses are dropping dramatically from

the case of single solid glass to that of including all the layers and an extension of 16mm. Then, the stresses start rising again for the case of the extension of 50mm. Additionally, Figure 7 shows that the variation of stresses at the edges and corners exhibited in the case of single glass solid element do not occur in the other two models. The models 2 and 3 including all the layers of the composition, exhibit a more uniform distribution of the stresses in both sides, top and bottom. The peak stresses are concentrated in the middle area with the smoothest graduation appearing in the second model.
The conclusion of this analysis, is that the internal part is positively effective, whereas the length of the extended part, when it increases, it negatively influences the behaviour of the plate. The negative influence might be related to the increasing eccentricity from the plate to the support as well as the stiffness of the extended part which is reduced, since during the test despite the change of the length, the thickness remained constant.

4. The connection detail

The high tolerance, ability for disassembling, structural and climate performance integrated in the composition of one component is the challenge of the whole design research. The concept of study-detail of the current research refers to a double hinged system which links the glass plates. The connection concept is illustrated in Figure 8. The main structural glass component with an embedded reinforcement which is extended outwards of the plate, is placed into a linear strip-like joint. The strip-like joint is composed by a bottom and top part -for disassembly purposes- which when they come together, lock the plate components at the desired angle. By this way direct contact between the glass plates is avoided.

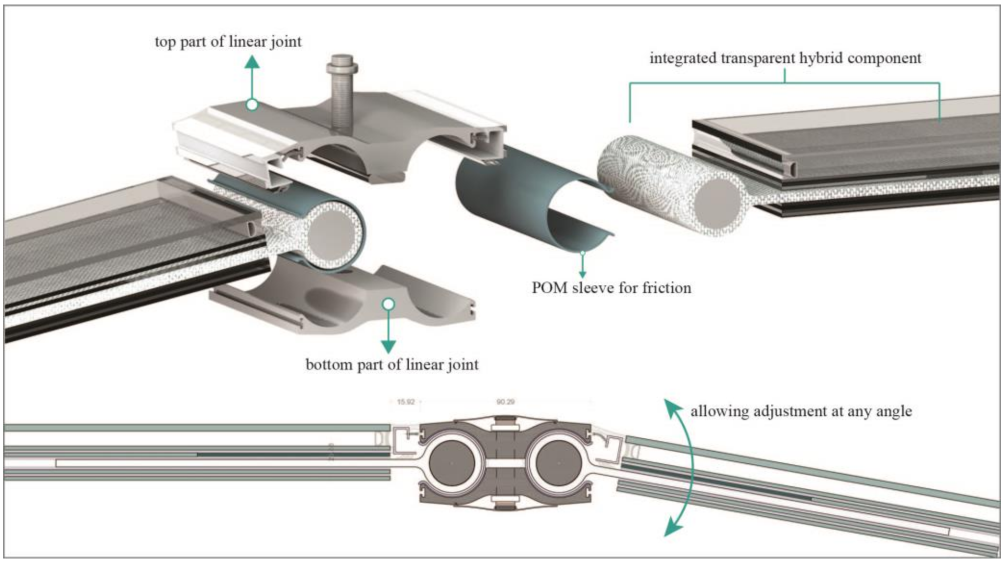

Figure 8: Section of the connection detail

The joints are intended to perform a form-active behavior allowing for inextensible modes of deformation by which the joints work as a spring deforming during an asymmetric load (e.g. wind) and returns back after loading. So the plates are more likely to translate than bend. By this way, high bending moments or sudden buckling collapse can be avoided.

4.1. Joint capacity

The joint was numerically analyzed as a plane strain element in order to identify the critical points which need to be stiffer in the section plane of a plate. The model examines a case of an axial load F=230N combined with self-weight, applied to a section of the component, simply supported at the right edge (Figure 9).

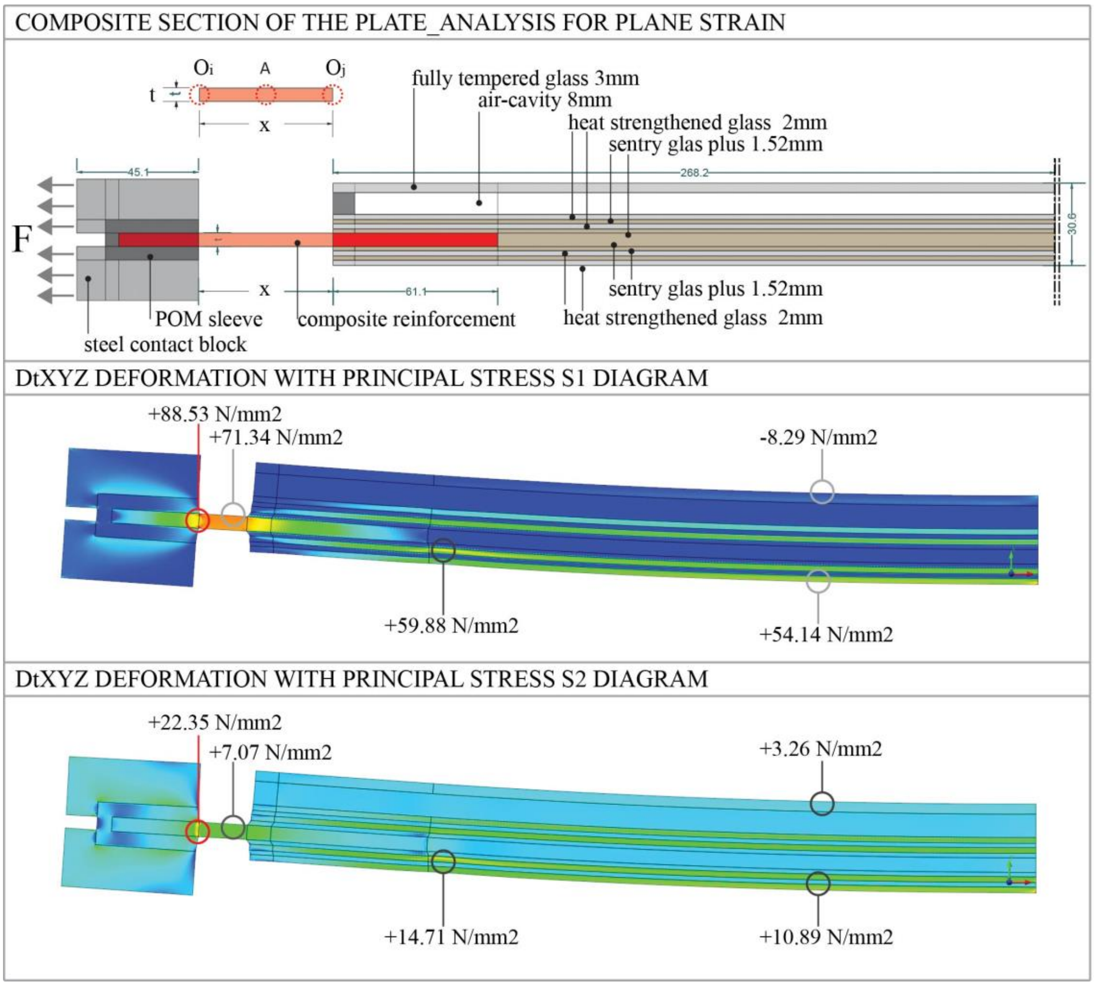

Figure 9: Numerical stress analysis in the section plane

First of all, the deformation under self-weight combined with an axial force, gains the characteristic shape of a convex curve as it is illustrated in Figure 9 due to its asymmetrical section. After several numerical tests on different lengths for x and different thickness for t, the conclusion was that the bottom layers of the hybrid component are more structurally active than the top ones. The shear capacity of the bond between the reinforcement and the interlayer Sentry Glass Plus is very critical for its capacity since attracts peak stresses around location O_j. In addition, the stresses in the connecting part, show peaks at the locations O_i and O_j. Apparently, locations O_i and O_j require more stiffness. Therefore, additional modelling for different geometries and material stiffness of the extended part at the peak locations must supplement the analysis.

4.1.1. Contact block requirements

Particularly, the contact block (linear strip-like joint) is responsible for preventing the plates from sliding away from the joint as well as preventing the plates for excessive rotation. These influencing parameters can be calculated by simple analytical method which can be adjusted for any load case and any geometrical configuration.

Required resistance of the joint:

$$\Sigma M_o = 0 \rightarrow R * \mu_{static} * r = M_q$$

$$R = \frac{q\,l^2}{12\;\mu_{static}\;r)}$$

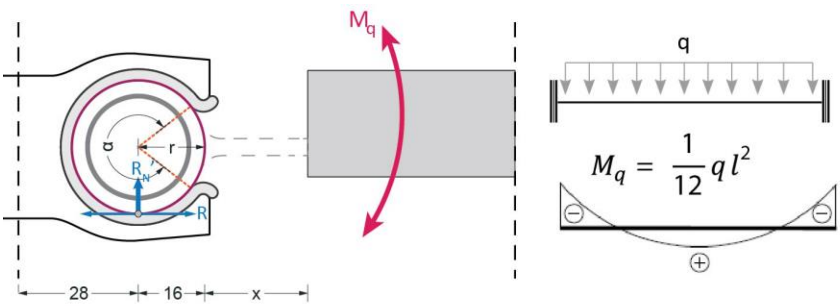

Figure 10: Rotation resistance calculations. Calculations for maximum bending moment.

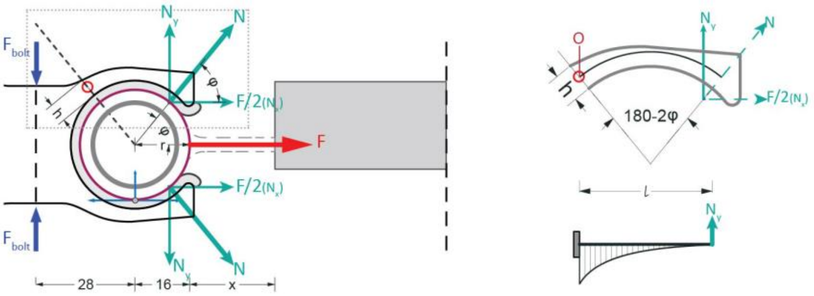

Figure 11: Pull-out action by axial force F.

Pull out resistance/ applied force by the bolt:

$$N_x = \frac{F}{2} \ , \ \cos\varphi = \frac{F}{2N} \rightarrow N = \frac{F}{2\cos\varphi} \quad , \ N^2 = {N_x}^2 + {N_y}^2$$

$$F_{bolt/top} = F_{bolt/bottom} = \sqrt{\frac{F^2 * (1-(\cos\varphi)^2)}{4\,(\cos\varphi)^2}}$$

Stress at the point of rotation inside the section of linear joint:

$$M = N_y * l \ , \quad l = 2\pi r * \frac{180-2\varphi}{360} \quad , \quad W = \frac{h^3 * 100}{6}$$

$$\sigma_{at\ point\ o\ for\ a\ width\ of\ 100mm} = \frac{M}{W} = \frac{6 * \sqrt{\frac{F^2 * (1-(\cos\varphi)^2)}{4\,(\cos\varphi)^2}} * 2\pi r * \frac{180-2\varphi}{360}}{100 * h^3} \leq \sigma_{allowable}$$

5. Application of the concept on a case study discrete shell

The concept of the hybrid composite with the proposed indirect connection method was applied on shell similar to that of British Museum Courtyard roof in order to evaluate the behavior on a larger scale. The shell’s dimensions are 73x97m and is composed out of quadrilateral planar plates (Figure 12).

By comparing a model with the plates directly connected to each other with a model model which considers the indirect connection method and the properties of joints and plates it clear that the contribution of an indirect joining method is very positive when designing for discrete shells (Figure 12). The stress variation on the plates which characterizes the shell with direct connections does not occur in the case of indirect one (Figure 12). The indirect connection method allows for a uniform distribution into the glass plates –and apparently a good shell behavior- and as a result, a safe control of plates’ design can be achieved by the use of a brittle material such as glass. Consequently, special focus on the joints is required during design.

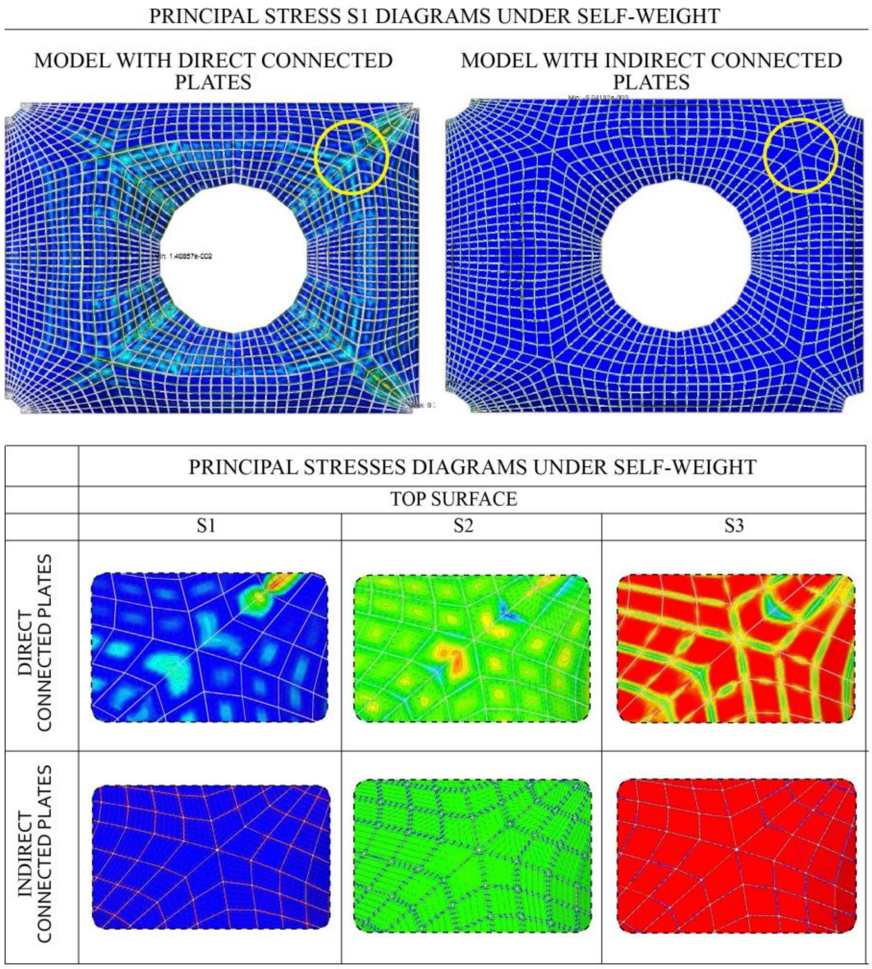

Figure 12: Comparison between a discrete shell with direct connection between plates and a discrete shell with indirect connection between plates under self-weight load.

6. Conclusion

The structural analysis at the scale of plate and joint was an important step to identify problems and solutions before applying the concept to the large scale of any architectural shape. The results from the analysis seem very promising for the use of structural glass in the construction of free-form facetted shells. The connection system can mainly allow the transfer of membrane forces through the glass plates while the semi-rigid behavior reduces the bending in plates.

Interestingly, in terms of architectural engineering, the proposed approach entails the following advantages which allow flexibility in design. First, the chosen material for reinforcement –woven

fabric composite- is very light, flexible and the same time controllably stiff. It can be either opaque or translucent according to the used fibers and also has excellent thermal properties. Second, the connection allows the assembly of various geometrical configurations and the scenario of disassembly is possible. And thirdly, this is an effective method to increase the post breakage behavior of glass. Once broken, the glass carries the compressive loads while the woven fabric bridges the tensile loads.
In terms of structural behavior, the conclusion obtained from the numerical analysis, is that in case of a too flexible connection, the structure can snap through when deformations become too large. Thus, achieving a physically form-active structure is a matter of appropriate design stiffness of the joints for each location on the structure. As a result, material saving and ductile safe failure are possible.
Currently the system is being applied to a case study of a large glass shell roof spanning 97m and 73m in the longitudinal and transverse direction respectively, in order to verify the capacity of the system and estimate the maximum possible span obtainable by using the proposed system. Application in a variety of shapes with a combination of synclastic and anticlastic geometries is also important to the validation of the system. Finally, future work requires tests with real specimens to prove the concept under real conditions.

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