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An Experimental and Numerical Study for the Glass Floors of the Acropolis Museum**

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Design and Experimental Testing of All Glass Sandwich Panels: An Experimental and Numerical Study for the Glass Floors of the Acropolis Museum

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This paper describes the engineering steps taken in order to investigate the potential of glass sandwich elements, made of 2 glass skins separated by a glass core in the form of spacers, as a way to create planar elements with a high stiffness to weight ratio, reducing material consumption in structural glazing applications. The aim is to explore and evaluate the optical quality and the structural performance of those elements. In this research, 7 core topologies are explored in order to define which parameters influence the behaviour of a sandwich structure made completely with glass. From those topologies, one is chosen to be explored further. The said topology is optimised to make the panels more efficient in terms of stiffness and weight reduction. In order to determine the structural behaviour (strength, stiffness, failure modes) of the elements, 4-point bending tests are conducted on 9 specimens in total. Finally, in order to define the aesthetical and structural requirements of such a project, the replacement of the glass floors of the Acropolis Museum in Athens in Greece is used as a case study. The knowledge acquired through this process is used to optimise the panels of the new glass floors taking also into account other parameters related to transparent flooring e.g. optical quality, psychological factors, anti-slip resistance etc

Keywords: Glass, sandwich structures, stiffness, weight reduction, core topologies

1. Introduction: The concept of an all glass sandwich panel:

Transparency is embraced more and more in contemporary architecture, rendering glass one of the central materials in the building industry. In structural glass applications the elements are dimensioned based on stiffness and strength requirements and therefore, structural glass elements tend to be thick and heavy, often requiring a substantial supporting substructure. This has an impact not only on material consumption and transparency but also on transportation costs. In current applications, glass fins or steel beams are usually introduced. In facades, aluminium mullions are usually supposed to transfer the wind load to the slab. Sandwich structures constitute a very efficient way to increase stiffness of planar elements without increasing their weight and could potentially be the solution to the aforementioned problem. This paper describes the engineering steps taken in order to investigate the potential of glass sandwich elements, made of 2 glass skins separated by a glass core in the form of spacers, as a way to create planar elements with a high stiffness to weight ratio, reducing material consumption in structural glazing applications. In order to define the aesthetical and structural requirements of such a project, the replacement of the glass floors of the Acropolis Museum in Athens in Greece is used as a case study. Initially, after having classified the sandwich core topologies according to the way they provide support to the skins, 7 different panels of 1000x300mm are designed, constructed and tested by means of a 4-point bending test in a way to assess the optical quality of such structures, showcase their potential and finally assess which configuration is the most efficient. The most promising sandwich topology consists of uniformly distributed glass vessels within the core. This design is furtherly investigated with the aim of optimizing its structural behaviour. To explore the structural influence of the spacers' distribution within the core, more panels of 2000x400mm are made and tested in 4-point bending. The knowledge acquired through this process is used to optimise structurally and aesthetically the panels of the new glass floors of the Acropolis Museum, taking also into account other parameters related to transparent flooring e.g. optical quality, psychological factors, anti-slip resistance etc. The results demonstrate that the designed sandwich panels have sufficient load-carrying capacity and enough redundancy to be used in such a structural glazing application. On the basis of this example, this research demonstrates the advantage of glass sandwich structures over laminated glass in stiffness-dominated designs but also highlights the engineering benefits of glass sandwich panels in terms of sustainability, strength and manufacturing cost.

2. The principle of sandwich panels

Sandwich structures are very efficient type of structures usually used in planar elements in applications where high stiffness to weight ratio is a main requirement. This type of structure becomes essential in horizontal elements where the dead load acts perpendicular to the element and adds to the general load applied to the structure. The sandwich panels consist of two skins separated by a core which provides the shear interaction between them (Fig. 1). The load

bearing material is held at maximum distance from the neutral axis and thus increases the shape factor of the element. When the panel is loaded in bending the top skin is in compression, the bottom skin is in tension while the core is loaded in shear. Glass is a material with high compressive strength but due to inevitable imperfections and flaws, known as Griffith flaws, its tensile strength is relatively low. Hence, a sandwich panel would be expected to fail at the tension-stressed skin. In Fig. 2 we can see the difference between a solid section and a sandwich section of the same weight but of different thickness.

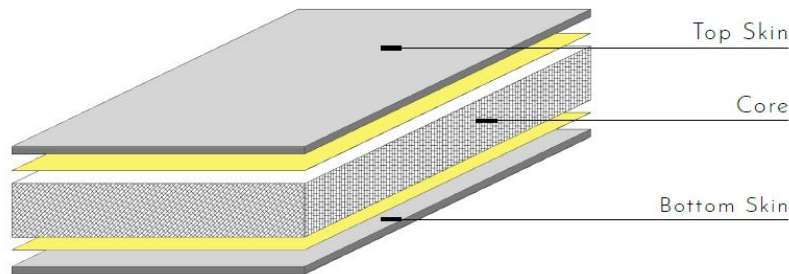


Fig. 1: Elements that comprise a sandwich panel

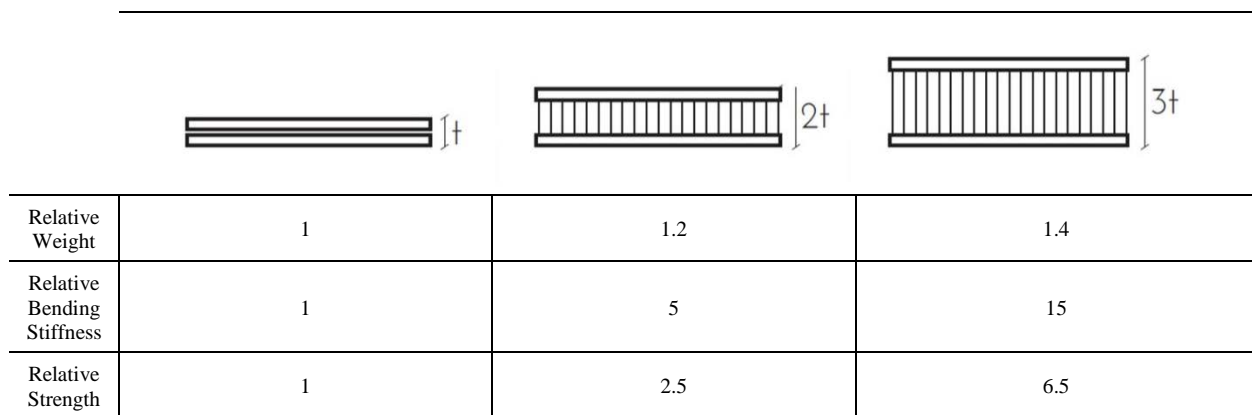


Fig. 2: Benefit of Sandwich structures

It should be noted here that the presented Fig.s are project specific, calculated for this particular application based on experimental values, and are therefore lower to what theory describes or what can be found in literature (Ashby 1998, Petras 1998 etc) which usually refers to a composite panel with honeycomb polymer matrix. However, one can easily understand that the strong point of such a structure is the improved behaviour in two indices: strength to weight and stiffness to weight.

It is fascinating how such structures appear commonly in nature from the beak of a bird to the bone of a cuttlefish. This is also true in a microstructural level (Ashby, 1990). This type of structure has been adopted by the Built Environment where we see a plethora of application taking advantage of the principle of sandwich structures ranging from cladding elements to floor panels. Insofar as glass sandwich panels are concerned, there is a small range of applications, making always use of opaque core materials such as FRP (Composite glass unit, Helmus, Mevissen) or Aluminium honeycomb (Berkeley Hotel Façade, Arup/Bellapart). So far, glass has not been considered for the core elements due its brittle nature: glass deforms only elastically until it breaks and therefore does not constitute the optimal solution for a structural core. However, glass is transparent and due to the recent developments in the adhesive industry, new design possibilities arise. All-glass sandwich panels could provide grounds for the elimination of substructure in structural glass applications, increasing transparency. The aim of this research is to investigate the potential of all-glass sandwich panels and define the extent to which such application would be feasible.

3. Investigation of different sandwich core topologies. Validation through experimental and numerical study

3.1 Core topologies

Sandwich panels can be constructed making use of the sandwich theory, by connecting two glass skins with a glass structural core. Two main core topologies are described in literature, namely homogenous cores, and non-homogenous cores. The latter can be subdivided into 4 categories: a) Punctual Support, b) Uni-directional support, c) Regional Support and d) Bi-directional support (Fig. 3)

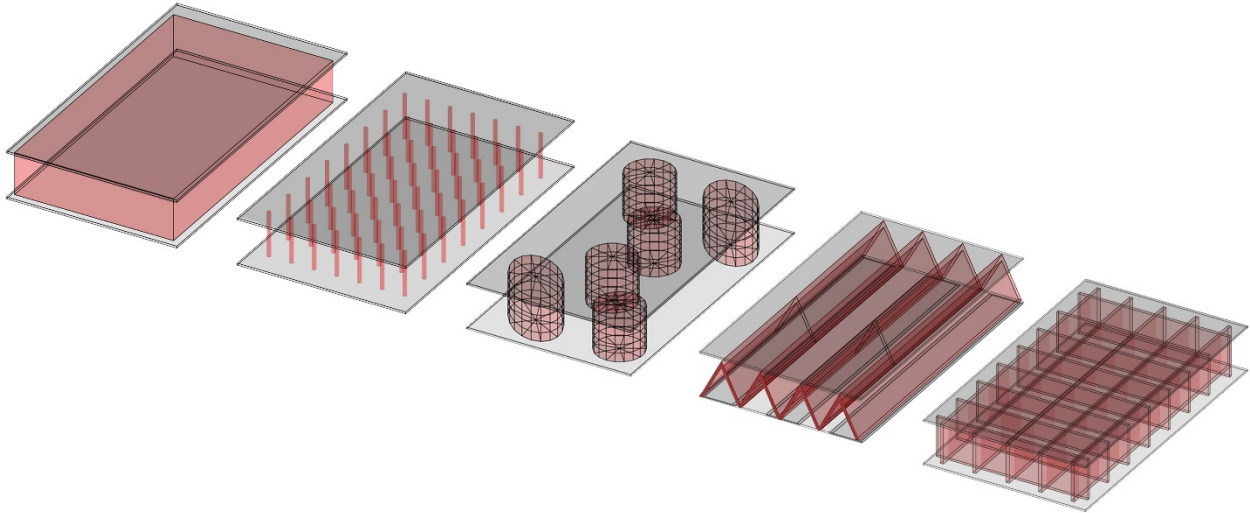


Fig. 3: From left to right: homogenous support, punctual support, regional support, linear support and bi-directional support

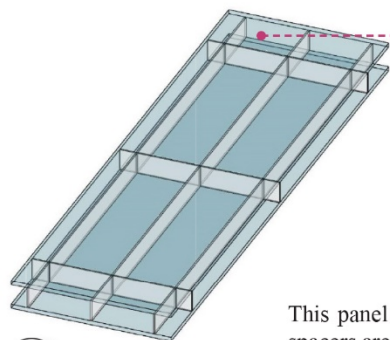
Based on this classification (Ashby, Wadley, Thomsen) seven different panels were initially designed, constructed and tested, representative of all the non-homogenous alternatives. Ready-made, standardized, objects such as glass bowls and glasses were employed for the core elements to ensure that all elements are of the same exact dimensions with controlled tolerances. In Fig.4 an illustrated overview of the developed sandwich panels is provided. The option of the homogenous core was not explored since the aim of this research is not to investigate core materials other than glass. The seven panels, measuring 1000x300mm each, were designed to have the same stiffness. This would facilitate the comparison of the results given by the three main design procedures:

- Pre-dimensioning: hand calculation with a graphical analytical method (H.G Allen, 1969)
- Detailed Calculations: Finite Elements Analysis
- Evaluation: Bending Tests

3.2 Construction of specimens

The seven panels, shown in fig.4, were constructed using monolithic annealed glass without any safety implementation. This deliberate choice was based on the fact that the specimens were not associated with any application in the built environment and the failure of monolithic glass would be more easily linked to the failure mode. The core elements are bonded to the skins using a high strength and high stiffness UV-curing transparent acrylate adhesive. This adhesive was selected because of its mechanical and optical properties. The main drawbacks would be that due to its high stiffness, it does not accommodate thermal movements and cannot be used to compensate for size deviations. However, this would help exclude cohesive and adhesive failure from the failure modes of the system and allow the research to focus on sandwich structures.

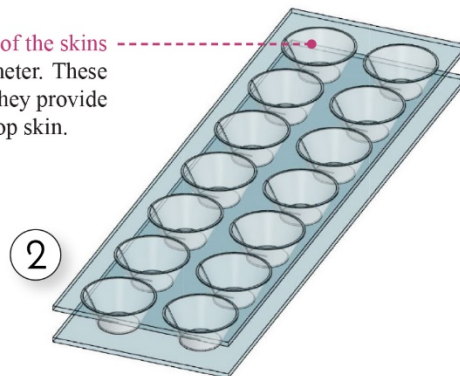
The bonding process is carried out in three steps. Initially, the surface of all the glass elements (skins, core) is cleaned and degreased using propanol. Secondly, the adhesive is applied on the surface of the spacers and is allowed to cure under UV radiation for 4 seconds. This provides partial adhesion while the glue is still in a viscous state and therefore can be easily cleaned. Finally, the glue is cured by UV radiation for one minute until it gains its full strength. There is a clear relationship between the thickness of the adhesive and its strength and therefore, a topology-specific wooden laser-cut mould is used to ensure that the thickness of the adhesive layer is lower than 3mm.



Bidirectional Support of the skins.

This panel is made with glass stripes 3mm thick and 40mm wide. The stripes are glued to each other with acrylate adhesive. The stripes are supposed to provide bidirectional support to the skins and a very good shear transfer in 2 directions.

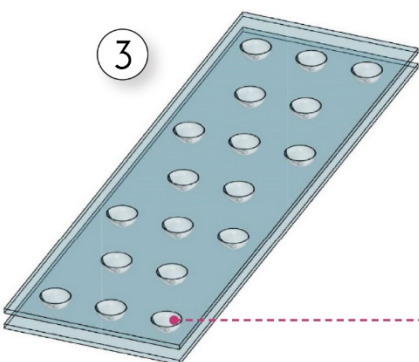
1



Regional Support of the skins

This panel is made with glass bowls 120mm in diameter. These spacers are relatively cheap and thanks to their shape they provide very good shear transfer between the bottom and the top skin.

2



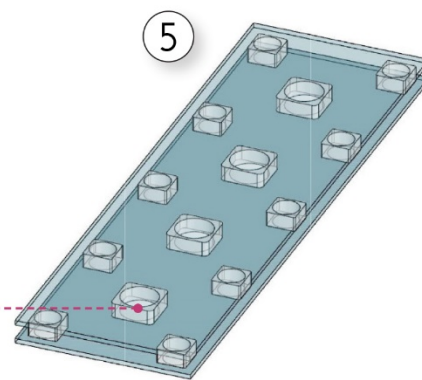
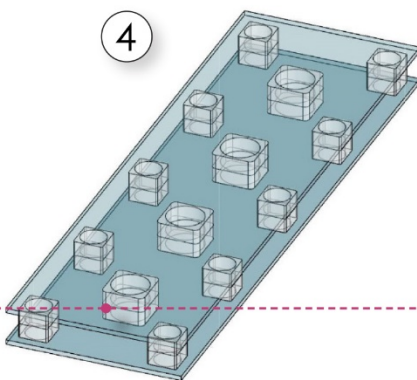
3

This panel is made with small semi-spherical glass bowls. This panel provides really poor shear interaction because it is punctually connected to the skins. The bowls are not arranged linearly but in a 2-3 formation.

Punctual Support of the skins

4

5

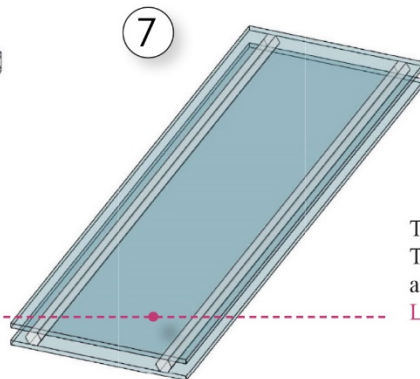
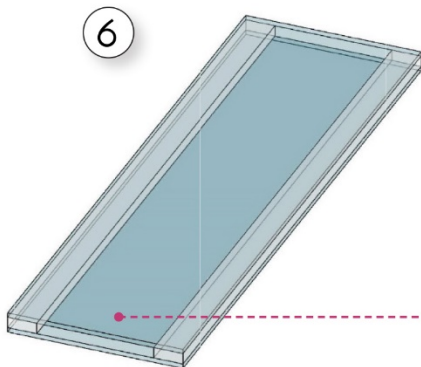


These panels are identical but one has double the height. They are made with candle holders which provide fairly good shear transfer. The purpose of making 2 panels with different core thickness is to compare the effect of thickness in stiffness and strength.

Regional Support of the skins

6

7



These 2 panels feature the same topology. The first one is made with solid glass pieces and the second one with glass rods.

Linear Support of the skins

Fig. 4: The 7 specimens that were designed, calculated and tested.

3.3 Numerical Study

The panels were designed and calculated using Finite Elements Analysis (FEA) with the FEA software ANSYS. The structure was modelled as monolithic using infinite stiffness for the bonded surfaces. This assumption is made on the grounds that the strength of the adhesive is much higher than the strength of glass and therefore would help reduce calculation time. This simplification was verified with a number of test models that proved that the stress induced in the adhesive layer is negligible. For certain, this assumption cannot be made when thermal movements are to be accommodated. In Fig. 5, the structural model is shown which aims to simulate a four-point bending test.

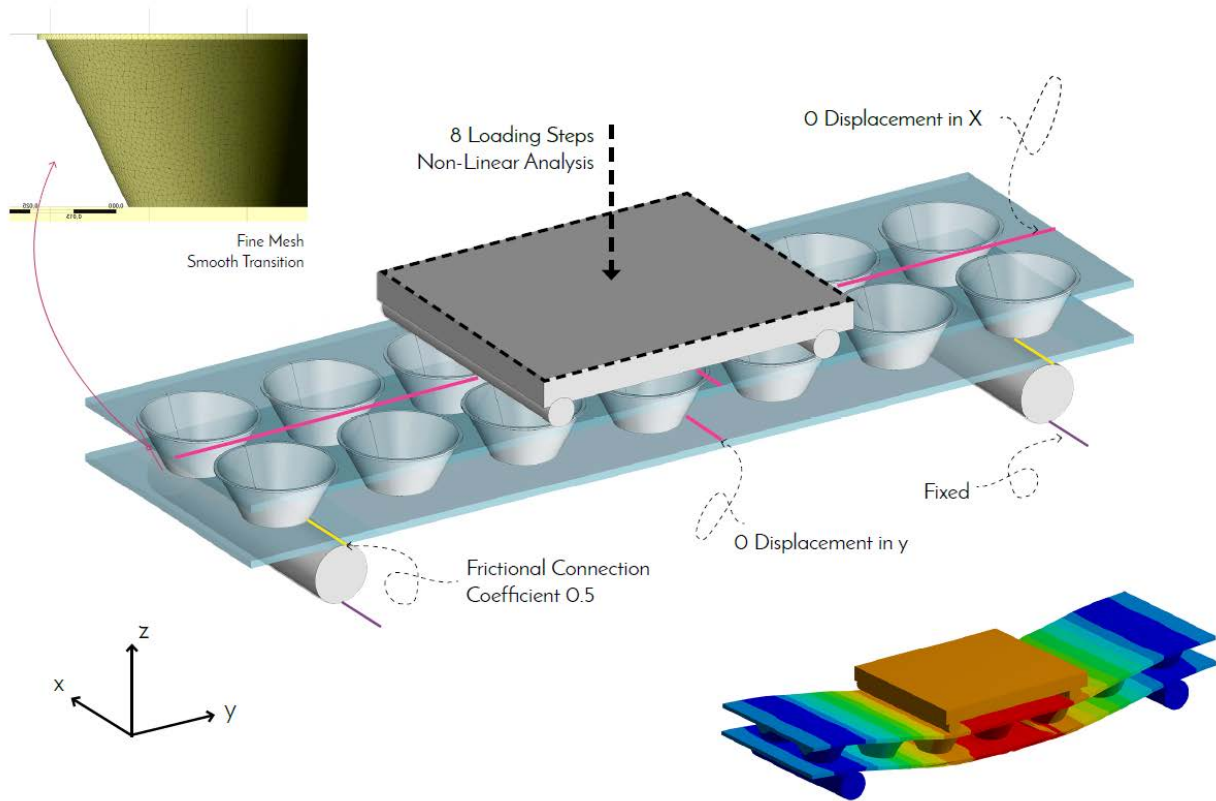


Fig. 5: Principles of structural model / simulation of bending test

3.4 Bending Tests – Procedure

The panels were tested by means of a 4-point bending test. The reason that a 4-point bending test was preferred over a 3-point bending test is that the former gives a whole region of maximum bending moment rather than a single point. So instead of forcing the panel to break directly in the middle, the test would help identify the weakest point or region of the panel facilitating the diagnosis. Fig. 6 shows the exact bending test configuration and how this is compared with a 3-point bending test.

As mentioned before, when a panel is subject to bending the bottom skin should be tension-stressed, given that the core provides sufficient composite action. This means that panels that exhibit a good sandwich behaviour are expected to fail at the bottom skin. On the other hand, if the two skins behave independently, on account of the core not transferring shear properly between them, the panel is expected to fail either at the top skin or at the core depending on where higher stresses are induced. When the core fails to guarantee the composite action, the effect of telegraphing is introduced resulting in a dimpled top skin and therefore potential indentation. Hence higher strain is expected around the spacers. This is the reason, two panels with exactly the same spacer distribution but different core thickness were made. Sandwich theory dictates that doubling the height of the core will result in a seven-fold increase of the bending stiffness. This assumes 100% shear interaction between the two skins which in reality is not true as the thicker the core is the lower the shear interaction will be.

The panels were compared in pairs in order to identify the strong and weak points of each topology. The crack propagation was carefully examined in a way to completely assess the behaviour of each panel and finally the results were compared with the outcome of FEA. The correlation between the bending tests and FEA helps validate the structural model and identify ways of making it more accurate.

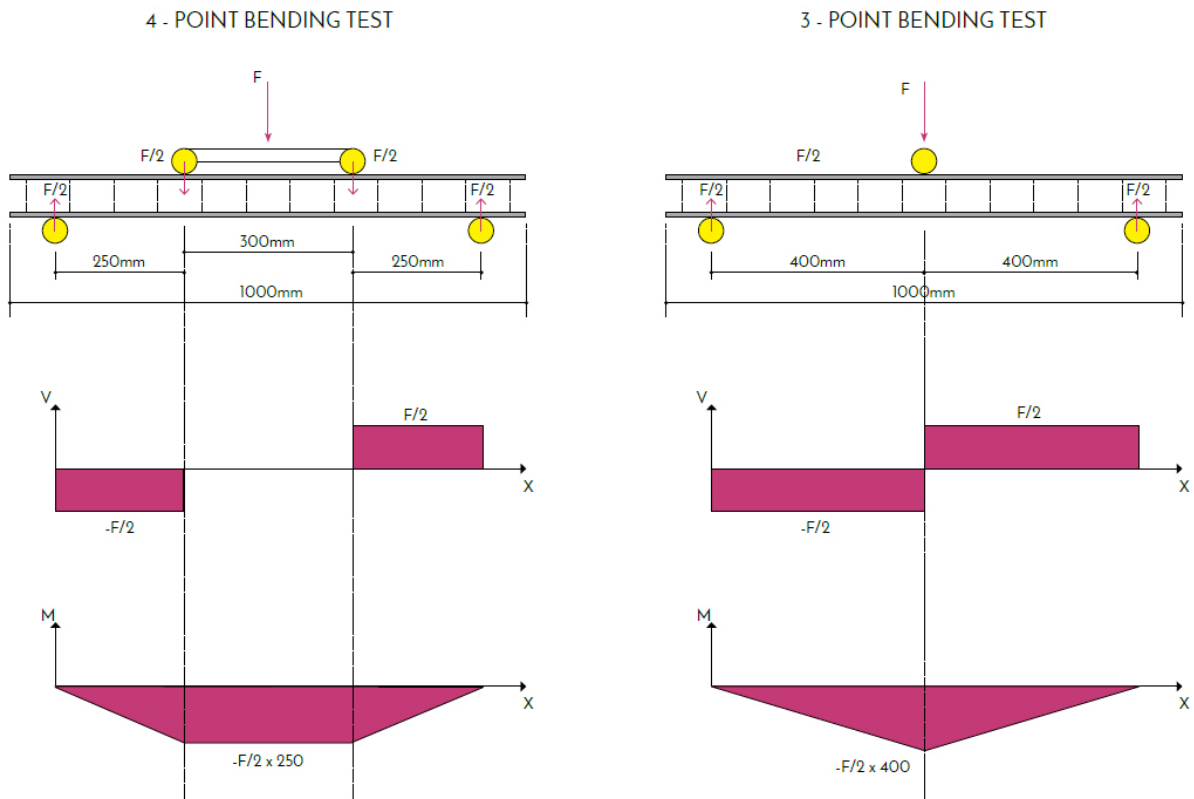


Fig. 6: Comparison between a 4-point bending test and a 3-point bending test

3.5 Bending Tests – Results

As far as core topologies are concerned, panels that belong to the same class are compared. The similar topology allows for safe conclusions to be drawn. A brief presentation of the results gathered during the first series of tests is presented in this chapter.

- Comparison between panels 6 and 7:

Panel 6

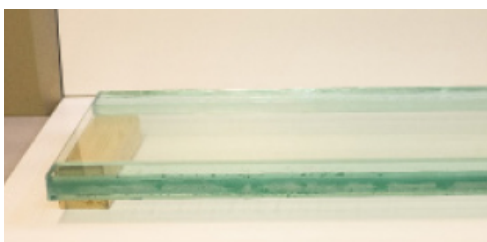


Image 2: photo of the panel



Image 3: panel penetrated by the support

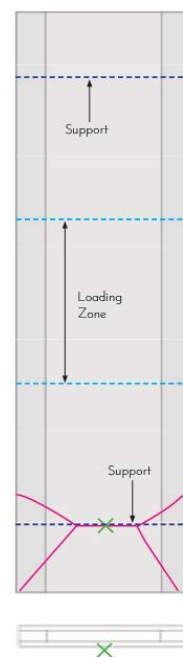


Image 1: fracture pattern

Panel 7

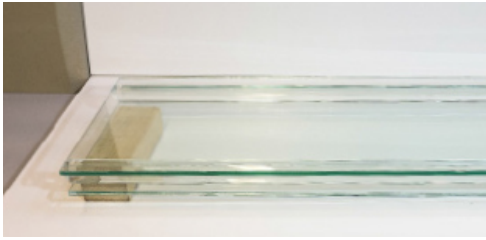


Image 5: Photo of the panel



Image 6: panel penetrated by the support



Image 4: Fracture pattern

Both panels exhibit very good structural behaviour. As a result, the highest stresses are induced due to the support reaction at the bottom plate which is tension stressed. The “challenge” with this particular topology is that the part between the two spacers is exposed to double curvature creating very clear weak and strong areas in the panel, which should be taken into account. Hence, spacing between the spacers needs to be carefully designed.

- Comparison between panels 4 and 5:

Panel 5



Image 8: Photo of the panel



Image 9: panel after test

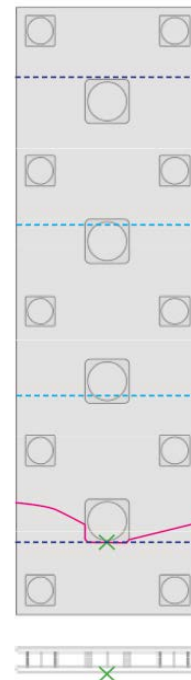


Image 7: fracture pattern

Panel 4



Image 11: photo of the core of panel 4



Image 12: failure of the panel

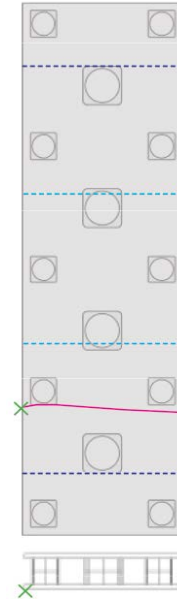


Image 10: fracture pattern

The comparison of the 2 panels gives an insight concerning the importance of the shear interaction and its relation with the effect of telegraphing. As mentioned before, the higher the core thickness is, the lower the shear interaction will be. This assumption was proven by the bending tests. The panel with the double core thickness broke under lower loading. This is because there is clear indentation at the bottom skin. Hence, closer to the spacers higher strain appears and therefore higher stresses are induced. On the contrary, the panel with half the thickness behaves exceptionally well and behaves as expected, breaking due to the support reaction at the bottom skin. This proves that an increase of the core thickness should be always followed by a densification of the core if the same structural behaviour is to be sustained.

- Comparison between panels 1 and 3

Panel 1



Image 14: photo of the panel



Image 15: panel after the test

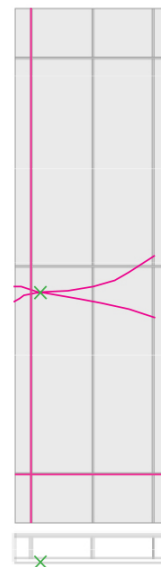


Image 13: fracture pattern

Panel 3

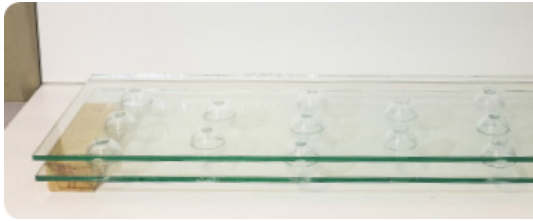


Image 17: photo of the panel



Image 18: panel after the test

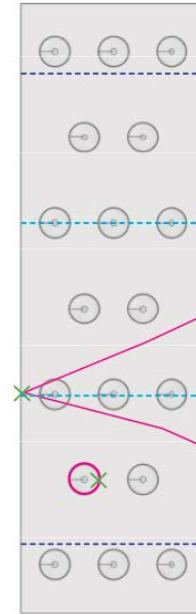


Image 16: fracture pattern

These 2 panels are comparable in the sense that they are the only two that exhibited early failure. This is because in both panels the core broke first causing the skins to behave independently. The first panel was designed deliberately in such a way that the core is very weak. That way, this kind of behaviour was also examined. As shown in the pictures, after the core breaks, the panel does not behave like a sandwich and the two skins bend independently. Even though, the percentage of sandwich behaviour is low, the panel still behaves partly as a sandwich and therefore the bottom skin breaks first. FEA revealed that the panel with bidirectional support should have been the best in terms of structural behaviour. However, this was not the case as any inaccuracies in construction could result in the core stripes breaking really fast leading to unexpected early failure.

- Panel 2

Panel 2



Image 20: photo of the panel



Image 21: panel after the test

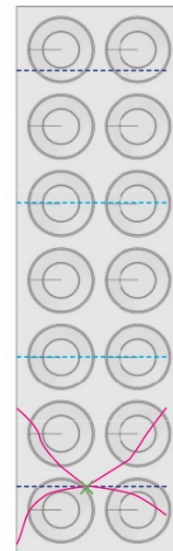


Image 19: fracture pattern

Panel number 2 is the panel with the highest stiffness to weight ratio as it combines the benefits from both regional and linear support of the skins as the cups are distributed in a linear array. What is interesting about this topology is the orientation of the spacer defines the mechanical properties of the panel. If the cup is facing downwards shear is

distributed properly from the top to the bottom skin and therefore this configuration would be ideal for a stiffness oriented design such as a glass floor. The other orientation of the spacer would ensure better distribution of stresses at the tension stressed skin and therefore would be ideal for strength dominated design such as glass stairs. The following chart shows all the results of the bending tests.

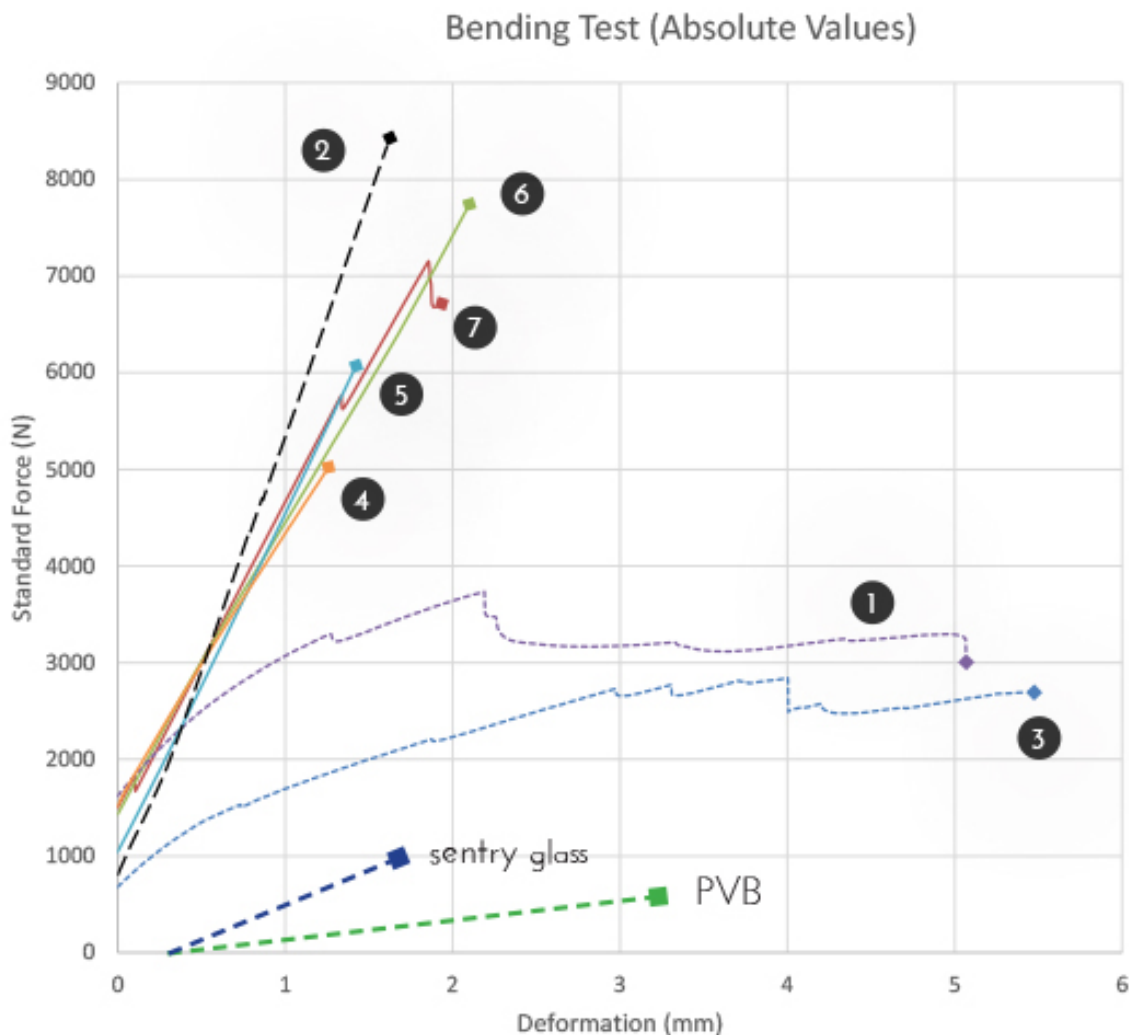


Fig. 7: Deformation Force Diagram / bending tests

Looking at the diagram (fig.7) generated by the bending tests a number of observations can be made. Initially, it is very clear that all sandwich solutions behave significantly better than a simple laminated glass with either PVB or Sentry Glass which confirms the assumptions made at the research framework dictating that an all-glass sandwich panel would be stiffer than solid or laminated glass. Secondly, glass sandwich panels are not only stiffer but also stronger than solid sections of the same weight. The latter is expected to fail under the load of less than 1000N while certain sandwich panels withstood 8 times this load. Furthermore, it is worth observing the behaviour of the two panels (prototypes 1 and 3), the core of which failed first, as they exhibit a plastic behaviour after the failure of the core. Finally, comparing the panels with regional support to the panels with linear support of the skins, the latter provides better shear interaction and hence higher stiffness but the former exhibits higher values of stiffness to weight. This is because the regional spacers are hollow and much lighter than the continuous and linear. This must be taken into account when designing with glass sandwich panels as weight has a clear influence on costs, embodied energy as well as on the dimensions of the substructure.

3.6 Conclusions after the first set of tests

After the first set of tests a number of safe conclusions can be made concerning the structural behaviour of the seven topologies:

- All panels broke at the bottom skin which means that all of them partly exhibited a sandwich behaviour
- In some panels, the core spacer broke first. These are the panels which exhibit lower shear interaction and at the same time consist of a weak core. Those panels are likely to break between the loading zone and the support.

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- Most panels broke closer to the support which is where higher stresses are induced, directly at the bottom plate.
- The comparison of panels 5 and 6 highlights that shear interaction is of equal importance to the thickness of the core as far as stiffness is concerned. There is a correlation among density of the core, thickness and stiffness.
- Linear support of the skins provides higher stiffness
- The sandwich behaviour is beneficial also for the strength of the panel, provided that the shear interactions is sufficient
- The way the spacers are placed influences the behaviour of the panels
- There is a correlation between the results of the Finite Elements Analysis and the results of the bending tests. Even though the deflections are not high, the non-linear analysis behaves much better than the simple linear with one loading step.
- After the failure of the bottom skin, the neutral axis shifts closer to the top skin and the panels does not behave as a sandwich anymore. As a result, the panels instantly breaks without any warning. Safety measures should be applied.

4. Case study design: Glass sandwich panels as an alternative/proposal for the glass floors of the Acropolis Museum. Optimization of the structural performance of the panels through numerical studies and experimental validation.

A case study was used in order to proceed with the design further and explore the potential of its use in the Built Environment. The case study that was selected is the replacement of the glass floors of the Acropolis Museum in Athens, GR. The said project was selected because it is a structurally demanding application of structural glass and does not currently fulfil the design intent. The floors were supposed to be as transparent as possible so that the visitors of the museum would be able to appreciate the beauty of the ancient monuments that sit under those floors. However, this is certainly not the case as a dense system of high steel beams blocks the view. From all 7 topologies one was chosen to be elaborated on. The topologies are compared according to the criteria shown in fig. 8 and are comparatively classified. The one that performs better is given the indicator “1” and the rest are relatively positioned. Insofar as the qualitative criteria are concerned, it is important to mention that the authors referred to the case study in order to define which topology should be used for this particular design. The component/geometry that performs significantly better than the rest is the topology with the regional support of the skins, as it delivers the highest stiffness to weight ratio and an exceptional optical quality. In the next chapter, the design of the floor is made using this topology.

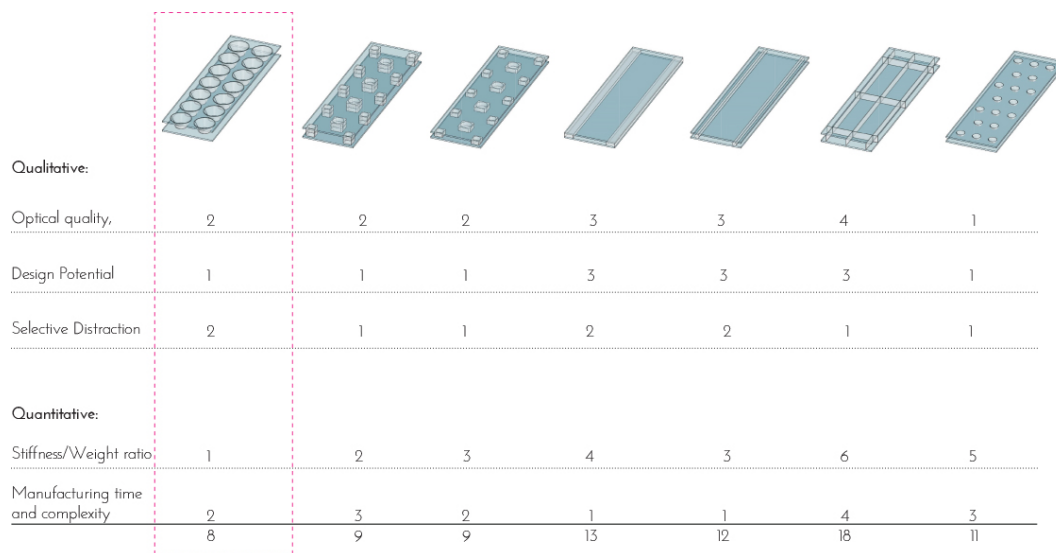


Fig. 8: Comparison of panels

4.1 Design of the glass floor

The particularity of the Acropolis Museum glass floors is that they hover over a number of archaeological excavations. They act also as a display and therefore they have to be as transparent as possible. Looking at the existing situation a number of observations can be easily made. Initially, the floors are not highly transparent since they feature a number of really high steel or concrete girders. Hence, the visitors of the museum can only look at what the beams are framing for them. Usually, this is an opening of 1.00x3.00m. As a result, the visitors cannot get

the big picture and are not able to conceive the scale of an ancient city. What is more, no anti-reflective coating is used and therefore the glass panels that were used are highly reflective. Those parameters are taken into account while designing the glass sandwich panels mentioned before.

In order for the visitors to conceive the actual scale of the monuments and experience the old city of Athens, the spacers are distributed according to the projection of the monuments on the level of the sandwich panels. This means that there is a densification of spacers over the outline of the artifacts. This cannot be materialized just by placing the spacers arbitrarily in the panel. Hence, defining some patterns with which the panel can have the required structural performance and at the same time correspond to the outline of the artifacts is essential. As far as the glass type is concerned, annealed glass was not considered appropriate for this application as it corrodes resulting in a three-fold decrease of its strength. Even though fully-tempered glass is four times stronger in tension and does not corrode, it breaks in very small shards and therefore cannot carry any load after breakage. Hence, the only safe solution is heat-strengthened (HS) glass thanks to which, thinner and therefore lighter glass sections can be used. Even though HS glass is more costly, less material can be used with multiple benefits in transportation costs, substructure dimensions and embodied energy.

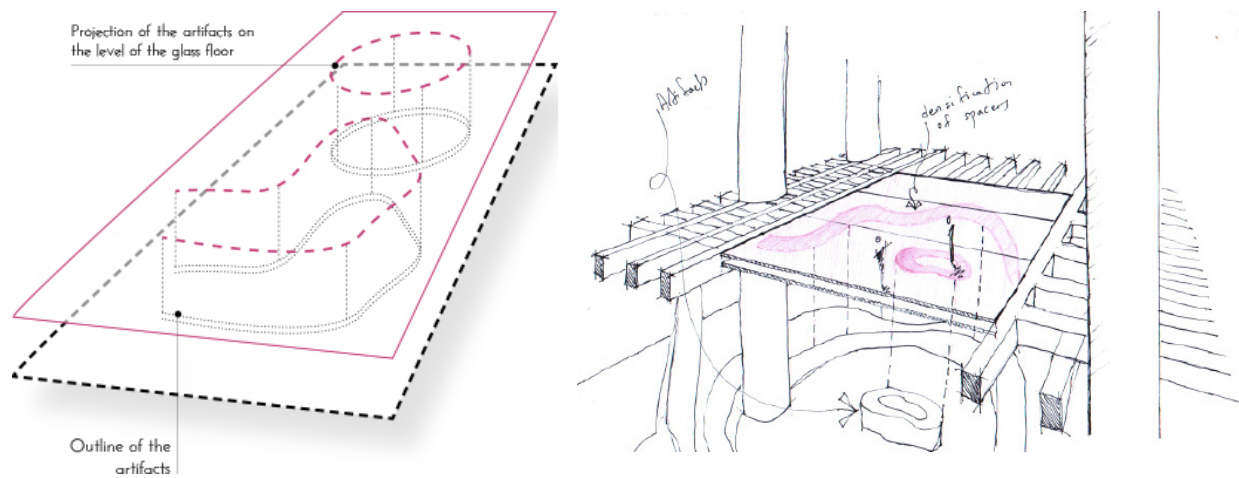


Fig. 9: sketches of the design intent

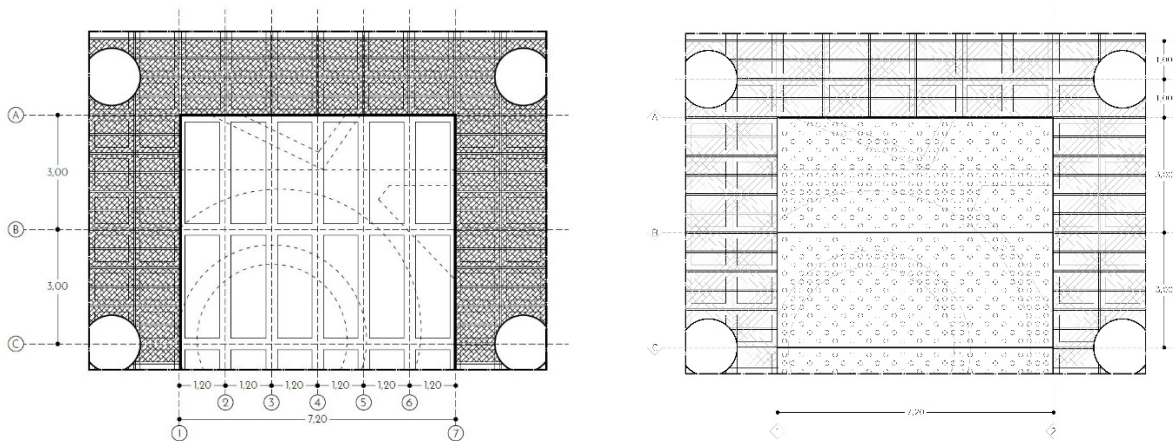


Fig. 10: transformation. Left: existing situation, Right: sandwich panel with spacer distribution

All the panels that were tested exhibited isotropy in the sense that the spacers were distributed in such a way that the flexural properties are the same in both directions or at least that they carry the same properties across the whole length of the panel. However, in order to design a panel with the method of selective distraction it is important that more than one patterns be used at the same time. For that reason, before designing the panel several patterns were tested using FEA. The analysis proved that the total number of the spacers is less important than the way those spacers are distributed. A high number of spacers does not guarantee that the panel will behave ideally. On the other hand, a pattern that transfers shear very well might be able to deliver a better result with a lower number of spacers. As mentioned before, telegraphing is the biggest problem which results in indentation and therefore unexpected results. Through Finite Elements Analysis it is possible to compare the shown patterns (Fig. 11) and try to analyze which one performs better and why. In summary, the analysis showed that the triangular formation 2-1 and the zig-zag pattern (shown in fig.12) perform better as they provide better shear interaction in two planar directions. Fig. 10 shows the transformation from the existing situation to a more transparent glass floor using the selected topology in

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order to reflect the shape of the artifacts on the panel while eliminating the steel substructure. However, the designed panel does not exhibit an isotropic behaviour similar to the one that was tested in the first series of bending tests. Hence, the anisotropic behaviour of the panels should be calculated and tested in order to evaluate what the effect of the non-uniform distribution would be. Two patterns were defined: one with an -X- formation and another one with a zig-zag formation. Fig. 12 illustrates those 2 patterns and how they align with the design intent.

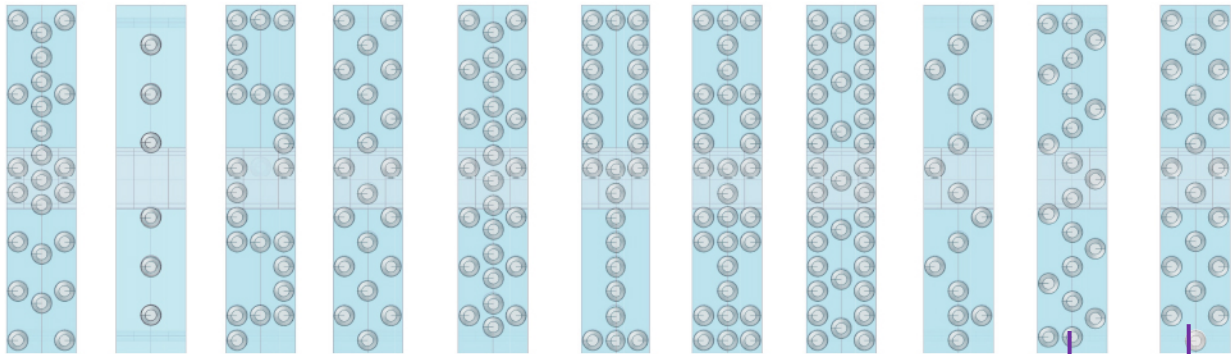


Fig. 11: The behaviour of those panels was assessed with FEA

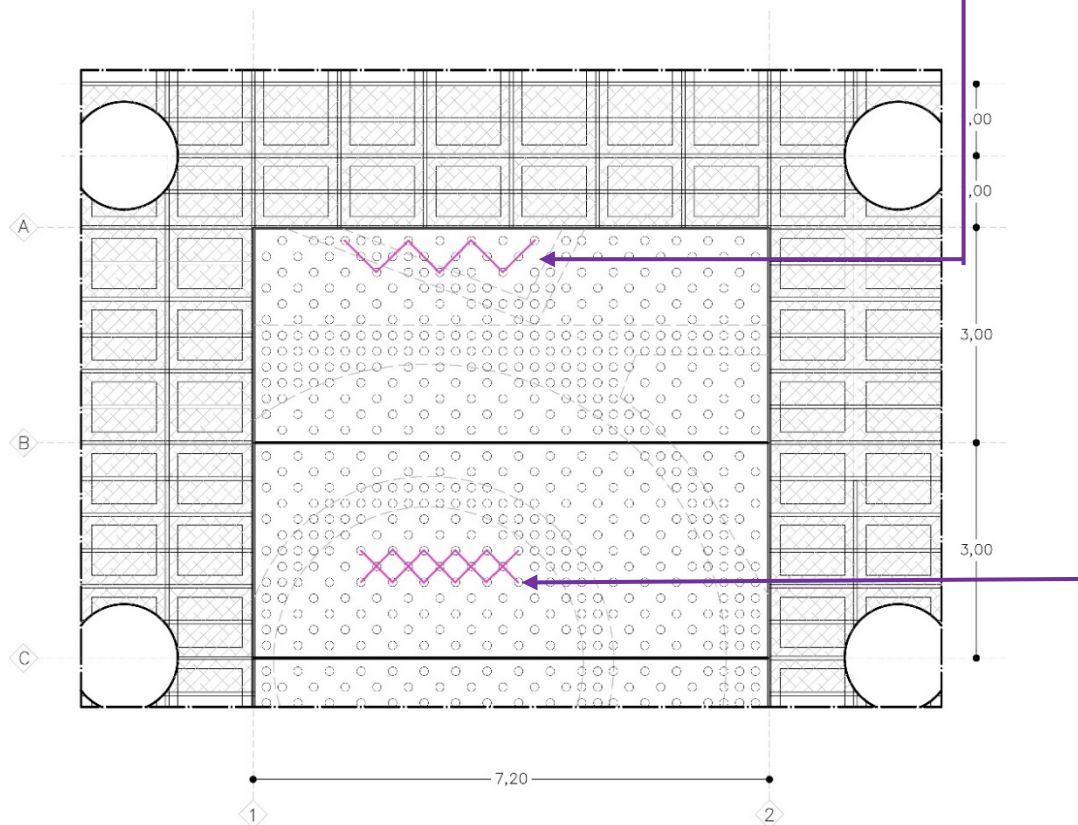


Fig. 12: The repetition of the patterns

4.2 Numerical Design – Experimental validation

In order to validate the patterns, two new panels were designed, measuring 2000x400mm each. Prior to testing the prototypes in 4-point-bending, the two panels were compared in a FEA simulation. The two patterns deliver the exact same results as far as stiffness is concerned. In fact, comparing them with the simple linear arrangement of spacers proves that removing more than half of the spacers does not result in a dramatic decrease of stiffness. If done properly, removing a number of spacers may result in a much more transparent panel. However, both panels deliver poor results as far as strength is concerned. And this is because the telegraphing effect is much more pronounced. Three possible solutions arise:

- Using a stronger glass type
- Change the geometry of the spacer to allow for better distribution of stresses.
- Thicken the glass sections
- Densify the spacers

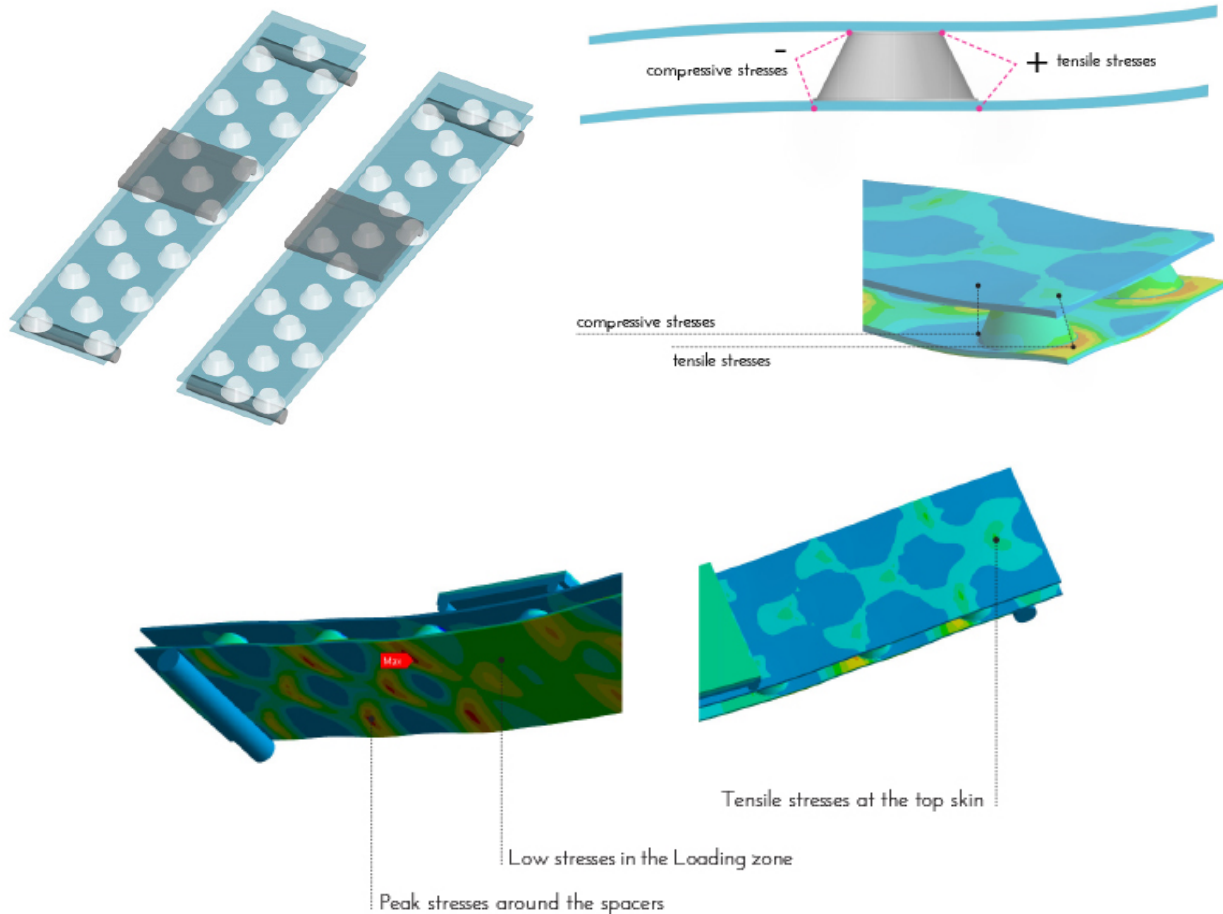


Fig. 13: Structural analysis of the 2 panels

The two panels were then tested by means of a 4-point bending test. The main goal was to compare the behaviour of those panels and derive conclusions regarding the relation of the distribution of the core elements to the stiffness and strength of the panels. Hence, the 2 panels have the same number of spacers but they are distributed differently. The following graph (Fig. 14) shows the stiffness of the 2 panels compared with the stiffness of a laminated configuration of the same weight. Initially, it is worth mentioning that the 2 panels have approximately the same stiffness and both exhibit non-linear elasticity. However, as expected the panel with the zig zag pattern does break with more than 10% lower loading on account of the telegraphing effect. As mentioned before, this effect is more pronounced in the zig zag pattern due to the highest distances between the spacers and this explains also why the panels broke at the top skin. Compared to the simple laminates with PVB and Sentry Glass the sandwich panels are beneficial both in strength and in stiffness. In fact, there is an increase in stiffness by a factor of 6-7 and increase in strength by a factor of 5 compared to a lamination with Sentry Glass or a factor of 9 compared to PVB. This simply means that in order to reach the same values of strength and stiffness we need to use 2-4 times more material (for this particular panel dimension and core configuration). The influence will be even more positive if more efficient topologies are used (see 1st series of test - linear configuration).

FEA (Fig. 13) revealed that stresses are lower within the loading zone while peak stresses are induced between the loading zone and the supports. The bending tests validated this as both panels broke within this zone. Also, both panels broke at the bottom skin, a failure mode that confirms that the panels exhibit adequate composite action. As expected, lamination provides sufficient redundancy to the structure; even after post-breakage the panels lose only a part of their load-bearing capacity.

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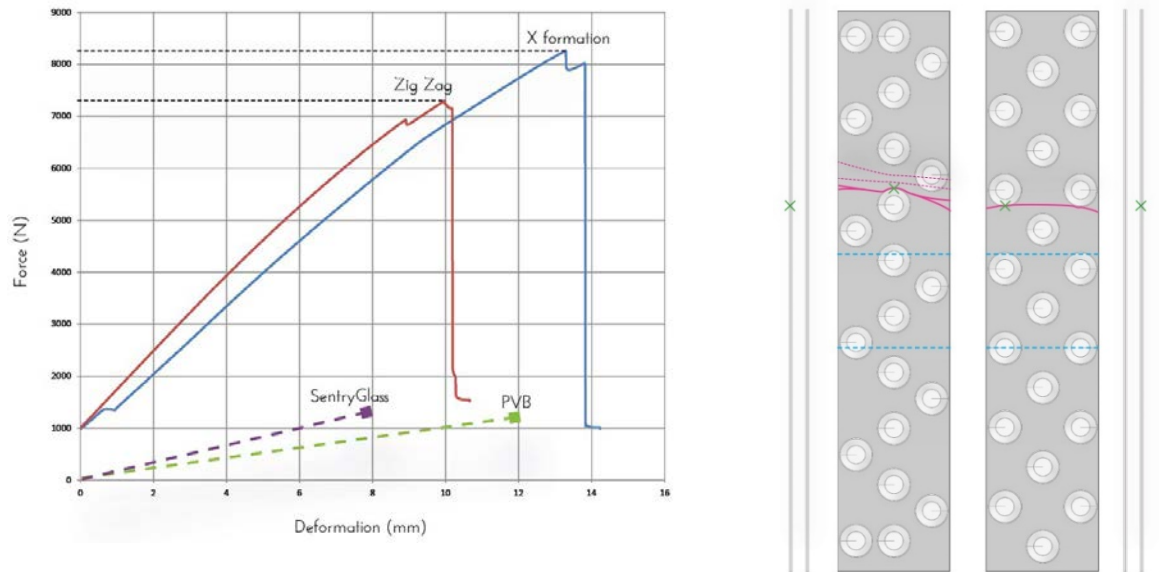


Fig. 14: Results of the bending tests

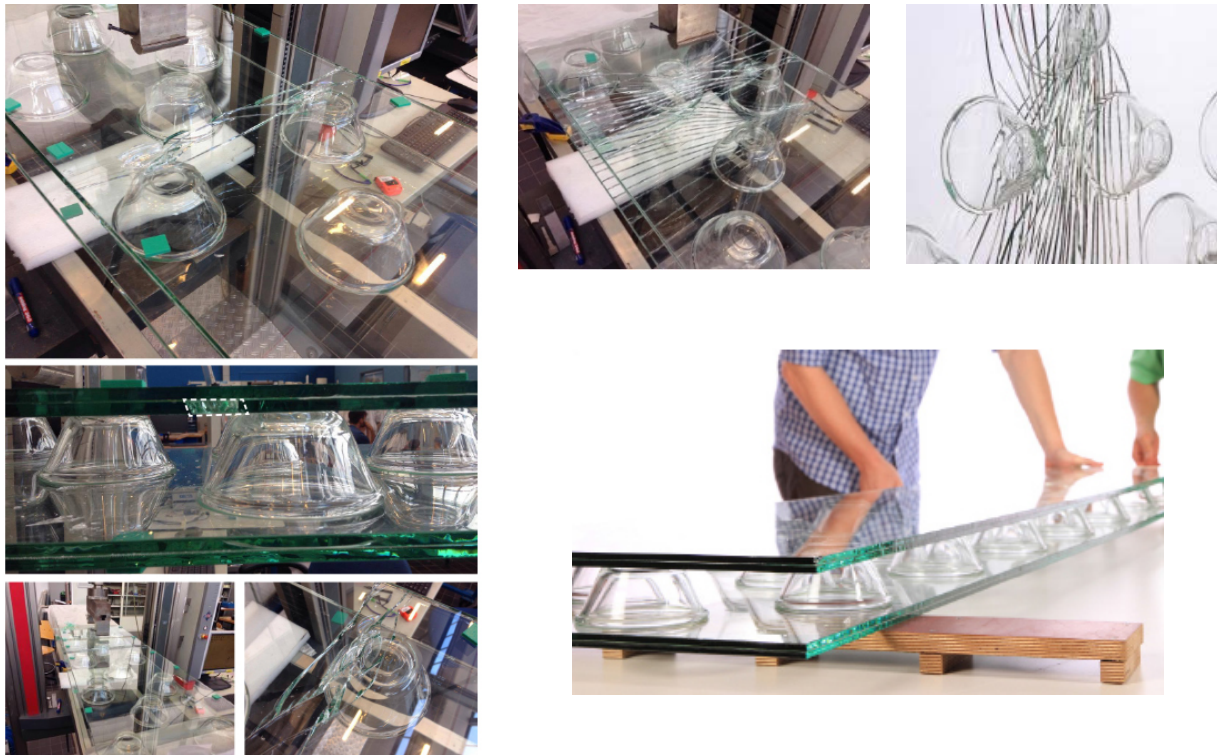


Fig. 15: Photos of the panels before (bottom right) and after (left and top right) the bending tests

4.3 Optimisation of the topology and detailing

With the current configuration, the stress distribution is not uniform and therefore unexpected stress concentration might occur closer to the support. The ideal situation would require a uniform distribution of stresses around the panel. Two approaches were taken towards tackling this problem:

First approach: Initially, more spacers were placed in the regions where higher principal stresses are induced. This does alleviate locally the effect of stress concentrations but this is simply transferred somewhere else. Hence, this process was discarded.

Second approach: From the first approach a very important conclusion is drawn: it is very difficult to deal with local effects in a sandwich panel the behaviour of which depends on the interaction among its different components. Hence, a holistic approach is needed when designing a panel. The whole distribution of the spacers needs to change globally and not just locally and therefore a new grid is introduced based on the magnitude of the shear stresses. The latter are expected to be zero in the middle and higher closer to the support. In this particular topology, shear stresses

account for more than 50% of the principal stresses and therefore should be taken into account. Stresses increase gradually moving from the center to the support. This feature is used to create the second grid using parametric software. The design presented in fig. 16 is the final design which makes use of 23% less spacers. The structural behaviour of the final design was validated using FEA but was not tested by means of a bending test.

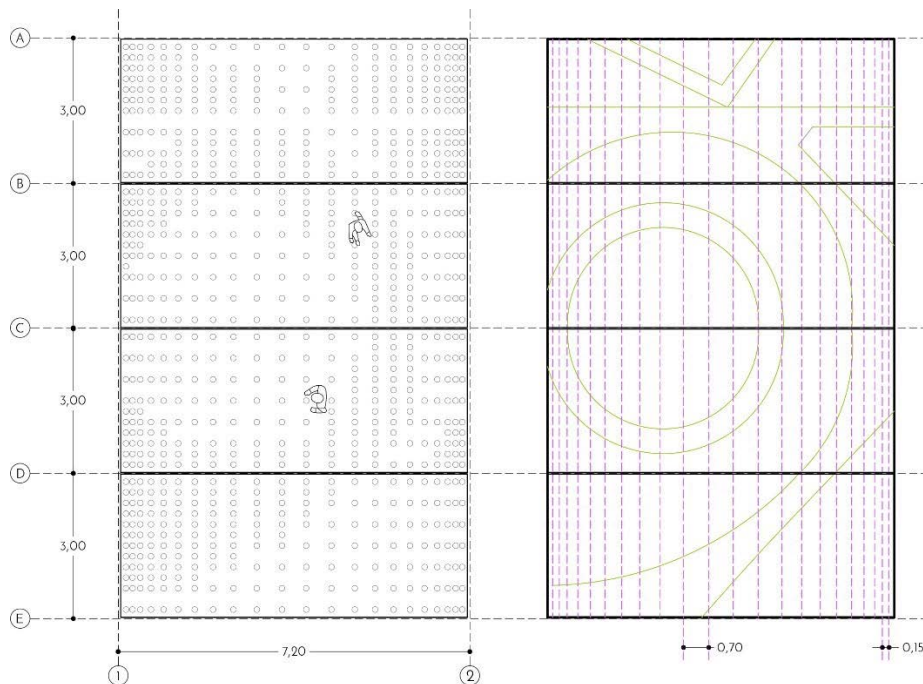


Fig. 16: Optimisation of the panels based on the shear pattern

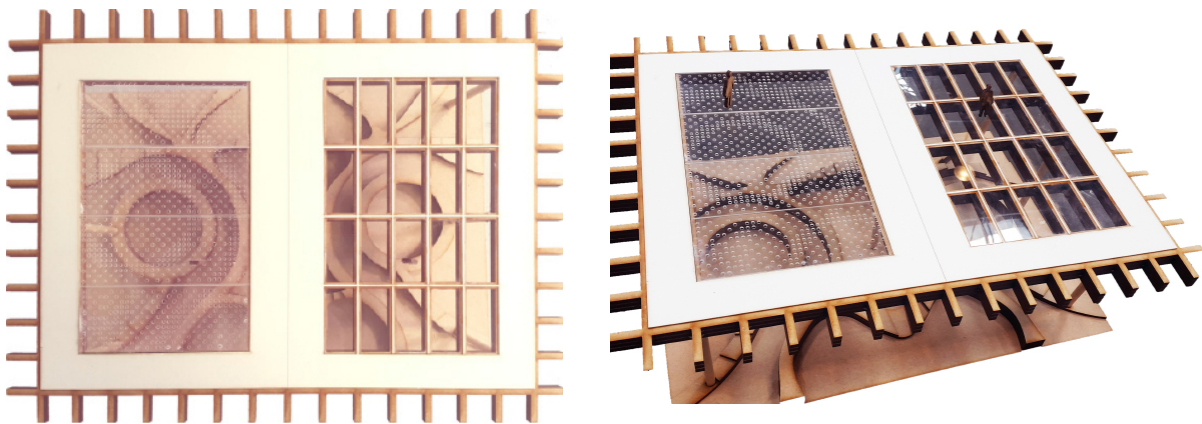


Fig. 17: model comparing the existing situation with the proposal

4.4 Potential integration into the building

To prove the feasibility of the concept, the potential integration of the panels into the building was investigated. It should be noted that this is a theoretical scenario and has not been implemented in the Museum. The panel should be assembled partly in the factory and partly on site. Initially, the glass sandwich panel is framed in factory conditions and is transported on site. To protect the panel during transportation from dust coming through, and from fracture that originates from the edges it is rested on neoprene packers, included in the frame. Then, supporting brackets are adjusted and aligned on site and later fixed to the concrete beam with expansion bolts. Condensation inside the panel could affect the adhesive which deteriorates when exposed to moisture. For that reason, after the panel is completely fixed the desiccant cartridge is pushed into the safety valve and allows the panel to breathe through an otherwise completely air-tight connection. Its purpose is to protect the panel from condensation or significant internal pressure changes. Mechanical filters help avoid dust penetrating the panels. At the same time, a desiccant material absorbs moisture. This self-indicating material should be replaced once every 2 years. Afterwards, the floor system is installed next to the panel. Between the raised floor and the glass panel, a thin and slender drainage gutter profile is installed to channel away rainwater. Finally, all the floor gaps are sealed with silicone to protect the floor from the weather conditions. An illustration of the installation detail is shown in fig.18.

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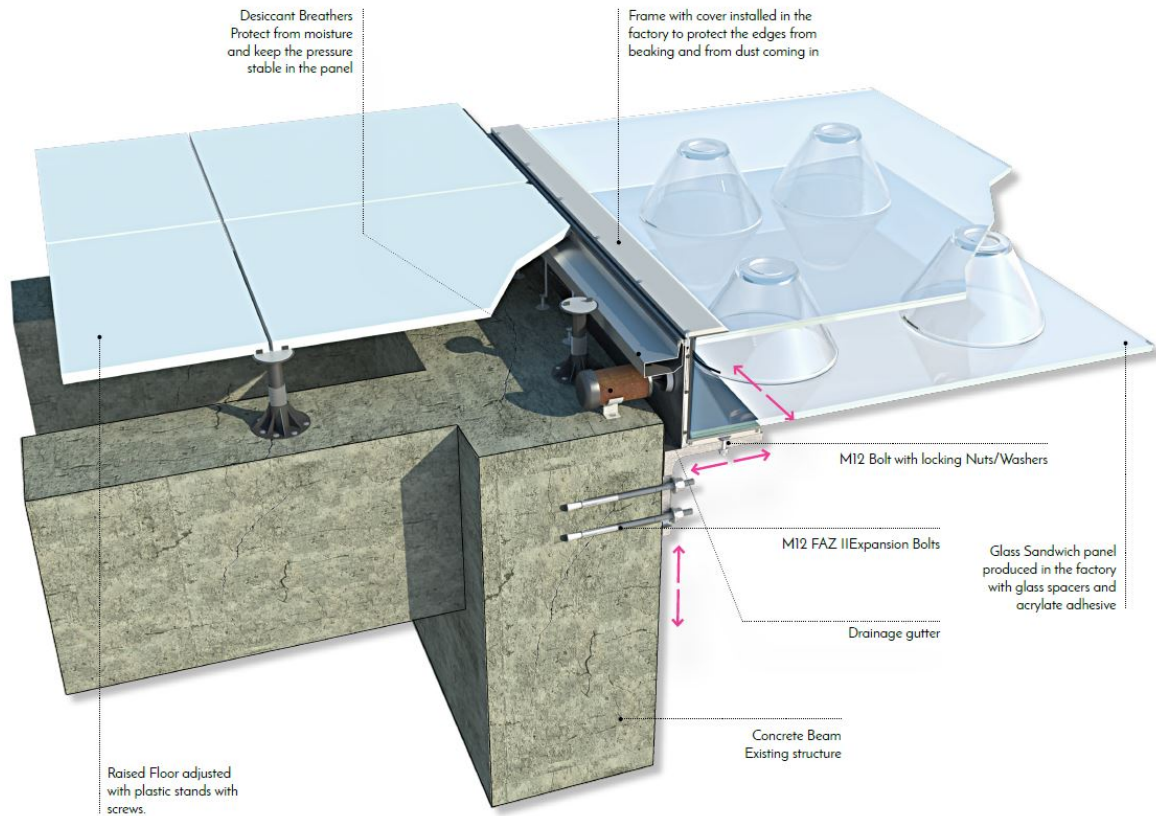


Fig. 18: schematic detail showing the installation of the panels

Furthermore, the panels are expected to deflect in the middle around 12mm under 7KPa. This deflection should be transferred between panels as a soft joint would not be able to accommodate such deflections. For that reason, a connection between the two panels is explored, utilizing interlocking glass extruded profiles (see fig.19). Those profiles are not designed to be continuous in order to accommodate construction tolerances and potential eccentricity.

5. Conclusions and discussions

A novel all-glass sandwich panel has been presented in this paper as a promising solution for glass elements of an optimized stiffness-to-weight ratio. To validate the concept different sandwich panel geometries have been studied in FEA modelling and prototypes have been tested in 4-point bending. The first and most important conclusion that can be drawn from this research is that the sandwich theory can be implemented in glass applications. It is highly motivating to know that the principles of sandwich structures can be applied to all-glass applications and therefore the only concern is to design the panels efficiently to fit every application. This is the point where parameters such as: transparency, selective distraction, efficiency, type of spacer, design intent, etc. become driving factors of the design.

A simple comparison of the results of both FEA and 4-point-bending tests with the behaviour of an equivalent laminated glass section highlights the dramatic increase in the stiffness/weight ratio together with a positive influence on the overall strength. The ratio stiffness to weight increases by a factor of 6-10 depending on the configuration. This means that material consumption can be reduced up to 60%. Let alone that substructure can be significantly reduced leading to a solution that is much more sustainable and cost-effective. In terms of strength, if the panel is designed correctly, a 4-fold increase might be achieved resulting also in significant reduction of material consumption. A very important benefit of sandwich panels is that they offer infinite design possibilities as far as the design off the core is concerned provided that structural integrity is not sacrificed.

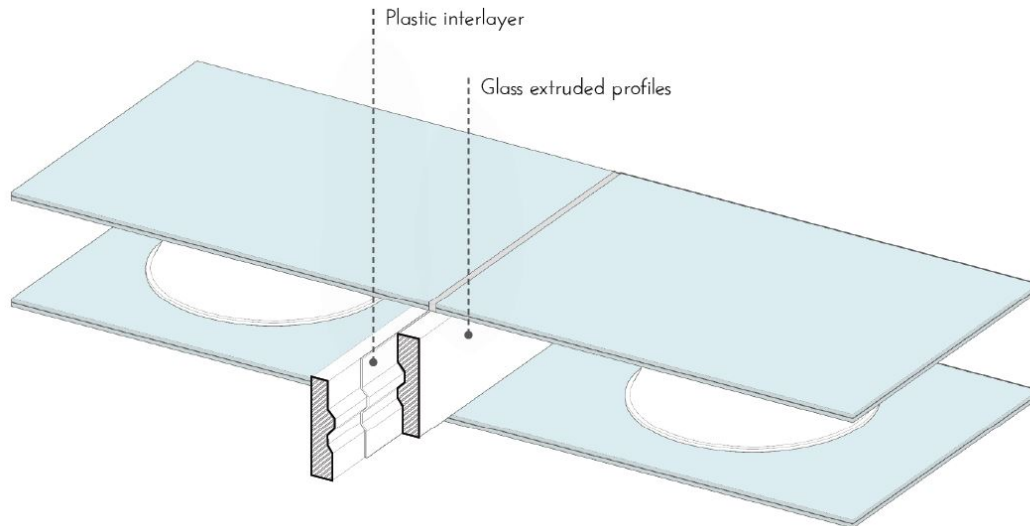


Fig. 19: Detail between 2 consecutive panels

Nonetheless, this does not come without a compromise. Usually, when referring to glass structures, maximum transparency is the next term that comes up. The spacers do create some visual distraction and this is the compromise one should make when using a sandwich structure. Hence, when designing a sandwich panel a collaborative approach should be engaged in the design team as the resulting visual distraction can be turned to a design statement if properly integrated. It is therefore recommended that sandwich structures should not be used in applications where maximum transparency is a prerequisite. However, usually this is not the main design requirement and therefore the concept of selective distraction should be embraced and incorporated into the design from the very first phase.

The research proved that there is an interrelationship among certain parameters namely:

- Core Thickness
- Core Density
- Length of Panel
- Stiffness/Weight
- Strength

Affecting one of the said parameters influences all the rest. For instance, increasing the core density (adding spacers) will result in an increase of both stiffness and strength and therefore the core thickness may be decreased. Some relationships are more complicated. For instance, increasing the core thickness will result initially in an increase of strength, but after a certain point strength will start to drop due to the effect of telegraphing. For that reason, a holistic approach should be taken when designing a sandwich panel as a trial and error process cannot result in an optimised solution.

What is more, there is clearly some room for improvement. Available and affordable means were used to complete this research on time with significant conclusions. Less costly and readily available spacers were used in order to facilitate experimenting. At the same time, the selected UV acrylate adhesive was as it allowed for an easy and fast assembly of the prototypes without the need of special equipment or of a standardized manufacturing process; finally it is so strong that parameters such as adhesive or cohesive failure do not influence this research. However, simple lamination of the skins to the core in an autoclave could speed up the fabrication process and result in a higher consistency of the bond. This was not feasible in this research due to the need for a hands-on approach. It is worth mentioning that this would constitute a different type of research as a PVB or Sentry Glass interlayer would behave differently than the adhesive chosen in this application. Furthermore, even though the research emphasizes on stiffness-dominated design, certain conclusions can be made concerning strength. The research proved that under certain conditions a sandwich structure can be beneficial for the strength as well; in this direction, the contact surface between the spacer and the skins plays an important role concerning how stresses are distributed. Therefore, a strength-dominated design would require the design of the spacer itself to allow for maximum contact surface between the spacer and the bottom skin which is tension-stressed.

This research demonstrates the potential of sandwich panels. Nowadays that transparency is a determining factor of contemporary architecture a stiff and relatively lightweight panel would have many applications. The potential of a

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customisable glass floor is already covered in the previous sections but it is worth mentioning that this type of structure can be extrapolated to facade elements which are also subjected to out-of-plane loading. Initially, highly transparent glass facades but also facades with integrated selective distraction or integrated climate regulating solutions can be constructed using this principle. What is more, glass is commonly used in curtain wall applications which are self-bearing. What if the glass sandwich could constitute an infill panel that would be attached to the main structure of the building and contribute to its lateral stability? These are topics for a future research that would investigate the limits of this type of structures.

Finally, it is worth mentioning that the knowledge acquired through this research was used to design and build a bigger panel (3000x1500mm) for the course: Technoledge: structural glass design given at the faculty of Architecture of the Delft University of Technology. These panels were made using SCHOTT CONTURAX extruded glass profiles as spacers and were designed and assembled by the students who attended the course. The ultimate aim is to produce a bigger panel of about 6000x6000mm to serve as the floor of an exhibition pavilion to manifest the potential of this novel structural glass component.

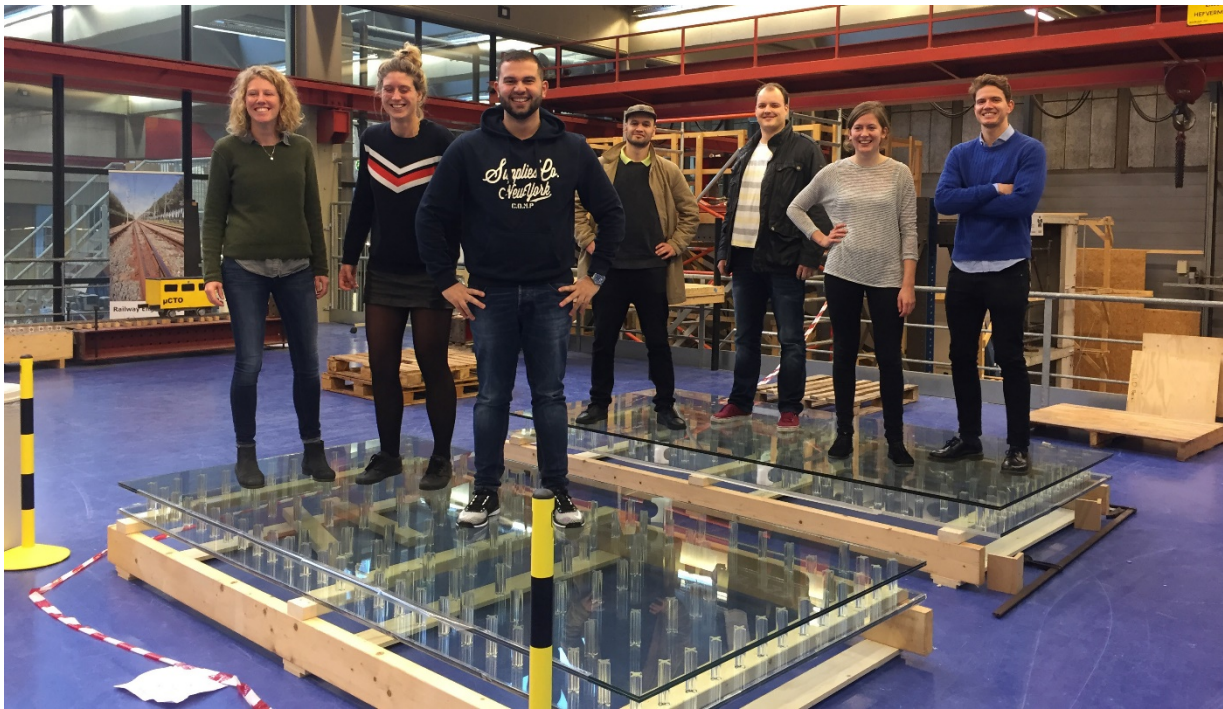


Fig. 20: 3x1.5m designed for the purpose of the Technoledge course at TUDelft

Acknowledgments

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