Exploring the potential of glass sandwich structures for relatively lightweight planar elements with high stiffness and controlled transparency.
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<td>DR. IR. FRED VEER</td>
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<td>DR. -ING. MARCEL BILOW</td>
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<td>IR. FAIDRA OIKONOMOPOULOU</td>
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<td>EXTERNAL EXAMINER</td>
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ACKNOWLEDGEMENTS

Studying at TUDelft has been a unique experience. I maintain I highly benefited from this 2-year experience in multiple ways. Most importantly, the programme of Building Technology introduced me to what is now my passion: Facade Engineering and Structural Glazing. I am very happy that I managed to combine those two in this graduation project which constituted a unique experience for me. Retrospecting on my very first days in this project I can remember moments full of excitement and anxiety which were followed by a significant number of sleepless nights but also long days in the workshop to build the specimens. However, there are no words to express how happy I am with the outcome of this project, which would not have been possible had it not been for the contribution of so many people.

First of all I would like to thank my main mentor Dr. ir. Fred Veer for a significant number of reasons. First of all, his experience with glass and research in general was an invaluable asset. It is extremely important to know that when you ask one question you will get the right answer. Secondly, I appreciate the way he chose to guide me by ensuring the research goes on smoothly but by also giving me much freedom and without restricting my creativity. Furthermore, I am grateful for all the time Fred spent to reply to my countless e-mails, to supply me with the materials needed to make the specimens, to arrange and conduct the bending tests and to provide feedback on my design choices. Last but not least, I consider Fred also a mentor in life as I feel that the approach he takes in dealing with every topic with professionalism is highly inspiring. I appreciate that he was trying to push me to explore my ambitions by showing me all available possibilities but also by sharing with me his knowledge and experience on a variety of topics.

I am highly grateful to Dr. ing. Marcel Bilow, my second mentor who has a special way to give students the motivation to work hard and on the right direction while being friendly and approachable. Marcel was always clear and fair with what he liked and what he did not like about this project. As the co-author of the book “IMAGINE 01”, in which the idea of a glass sandwich panel is presented, he was excited from the beginning of the project until the end. Among others, he particularly assisted me with the detailing part of this project sharing with me his knowledge about facade connections. Finally, Marcel’s experience in construction has been very helpful also insofar as manufacturing of the specimens is concerned providing me with information regarding glass and laboratory tools.

I must admit that had it not been for the contribution of ir. Faidra Oikonomopoulou I would not have chosen this as my graduation topic and now I am more than grateful I did. With her experience on structural glazing Faidra was already aware of the potential of glass sandwich structures and she pointed this out to me at an early stage. Furthermore, she shared with me all the experience she built during the construction
of the Crystal Houses in Amsterdam which helped me start my research from an advanced stage. But most importantly I would like to thank Faidra for being extremely enthusiastic but also for helping me find the solution to numerous problems that came up during this 7-month process.

I would like to thank James O’Callaghan whose enthusiastic feedback reinforced my aspiration to do my graduation thesis on this subject but also because with his consults throughout the year he helped me stay on the right track. I would also like to thank Christian Louter and Telesilla Bristogianni for their time and input in a number of aspects in this project. Finally, a big part of this project was the construction of the specimens and I am grateful that Kees Baardolf was always in the workshop to help me.

I would also like to thank Vicente Plaza Gonzalez, my friend and “co-inventor” of the glass sandwich panel throughout the course Technoledge Structural Design who encouraged me to work on this topic individually. I would like to thank my friends Duc Ngo, Popi Papangelopoulou as well as Aristotelis, Menelaos and Thanos for their input, ideas and encouragement throughout the process. I would also like to thank my girlfriend Lydia for her patience during the graduation period and Mustafa Nazari for the practical assistance he provided.

I would like to thank my parents Manolis Vitalis and Antonia Gonidaki as everything I have done in my life till now is thanks to their contribution.
This report discusses the process followed during the period from P1 to P4 for the graduation project: "Sandwich Panel: Exploring the potential of glass sandwich structures for relatively lightweight elements with high stiffness and controlled transparency". The report is divided into 5 chapters, namely 1) Research Framework, 2) Literature Study and 3) Initial Design (Design proposal), 4) Initial -> Final Design and 5) Final Design.

The first chapter is the research methodology followed from P2 to P5. It contains all relevant information including the problem statement, the background, the research question, the objectives, the research design etc. In the end of the chapter, a graduation time plan is presented that illustrates how time was managed during this process.

The second chapter discusses the literature survey conducted for the needs of this research aiming to find the literature gap and "mould" the research topic. The first part of the literature is divided into two domains: a) Material (glass properties) and b) Geometry (Sandwich panels). Initially, a research on general aspects of glass as a structural material is presented including, glass types and safety implementation. It is followed by an investigation of sandwich structures from their significance in nature to their failure modes. The second part of the literature survey is divided into 3 parts according to the three layers of sandwich panels: a) skins, b) adhesive layer, c) Core. As far as the skins are concerned, properties of the material are the main determining factor. As for the adhesive layer, bonding glass to glass techniques were later investigated. The core was the most important part of the research. Initially, sandwich structures were classified according to the core topology in order to see what is available and what the main advantages and disadvantages of each core topology are. At the same time, ways to stiffen glass were studied with a focus on sandwich structures.

The 3rd chapter focuses on the design task used as a case study in this process: the glass floors of the Acropolis Museum in Athens, Greece. The design intent is briefly presented emphasising on the potential of such an element. Furthermore, the glass elements to be used are predimensioned according to Eurocode 1 (Chapter 6) and the boundary conditions are defined. Finally, the 7 elements to proceed with during the period P2-P3 are demonstrated with an emphasis on the diverse core topologies.

The 4th chapter constitutes the main body of this research and describes the process followed from P2 to P3. A method(toolbox) to calculate and
therefore design glass panels is introduced including a graphical-analytical method, Finite elements Analysis (FEA) and bending tests. The results of the FEA and the bending tests are compared until a state of correlations is reached, providing therefore the author with a safe toolbox to move on with in the following chapter.

In chapter 5 the final design is presented in a procedure that is mostly based on the Research by Design approach as the design decisions influence the research process. The findings that are described in the previous chapters are translated into a floor panel taking into account other considerations such as the building integration, detailing, transportation, anti-slip provisions, safety etc. This chapter aims to showcase the potential of glass sandwich panels and prove that such a panel could be used in the built environment.

Finally, in the final chapter the conclusions drawn during this research are presented. Initially, there is an analysis of the conclusions that belong to each chapter as a way to summarise the findings from the different parts of the research. Furthermore, the overall conclusions are presented with an emphasis on the design parameters, possible improvements or alterations and finally on the potential of such a structure.
ABSTRACT

Keywords:
transparency, sandwich structures, glass, core topologies, glass floors, optimisation

Transparency is embraced more and more in contemporary architecture and therefore glass has become one of the most important materials in the building industry. In structural glass applications the elements are dimensioned based on stiffness and strength requirements. This research investigates the potential of glass sandwich structures as a way to create planar elements with a high stiffness to weight ratio and reduce material consumption in structural glazing applications. The design focuses on the replacement of the glass floors of the Acropolis Museum in Athens with an aim to a) reduce material consumption, b) eliminate the supporting substructure and c) propose an optimised design. 7 different core topologies are designed 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 suitable to be used in the aforementioned application. The topology that fulfills the structural and aesthetical requirements is furtherly investigated and its structural behaviour is “deconstructed”. The knowledge acquired through this process is used to optimise structurally and aesthetically the panels of the new glass floors. Finally, a design toolbox is devised which consists of three phases: a) graphical/analytical calculations (predimensioning), b) Finite Elements Analysis (detailed calculation) and c) Bending Tests (evaluation). In general, this research proves the advantage of glass sandwich structures over laminated glass in stiffness-dominated designs but also discusses the importance of integrating the process of selective distraction into the design.

Additional information:
Throughout this research, 9 specimens were built in total. 7 small (1000x300mm) and 2 big ones (2000x400mm). Those were tested in the department of Mechanical, Maritime and Materials Engineering at TUDelft under the supervision of Dr. ir. Fred Veer.

The research consists of 4 parts. The first part discusses the literature survey conducted for the needs of this research aiming to find the literature gap and formulate the research topic. The second part focuses on the available possibilities and aims to assess the behaviour of 7 different core topologies. The 3rd part focuses on one topology, the behaviour of which is furtherly investigated. In the 4th part, a design toolbox is made and applied to the design task: the replacement of the glass floors of the Acropolis museum. Linear though the process might seem to be, constant reevaluation was needed to reach the final results.
Nomenclature:

\( a \) = Panel length
\( A \) = Area of applied load
\( b \) = Beam width
\( D \) = Panel bending stiffness
\( EC \) = Compression modulus of core
\( Ef \) = Modulus of elasticity of facing skin
\( F \) = Maximum shear force
\( GC \) = Core shear modulus - in direction of applied load
\( GL \) = Core shear modulus - Ribbon direction
\( GW \) = Core shear modulus - Transverse direction
\( h \) = Distance between facing skin centres
\( kb \) = Beam - bending deflection coefficient
\( kS \) = Beam - shear deflection coefficient
\( K1 \) = Panel parameter (used for simply supported plate)
\( K2 \) = Panel parameter (used for simply supported plate)
\( K3 \) = Panel parameter (used for simply supported plate)
\( l \) = Beam span
\( M \) = Maximum bending moment
\( P \) = Applied load
\( Pb \) = Critical buckling load
\( q \) = Uniformly distributed load
\( R \) = Ratio \( GL/GW \)
\( s \) = Cell size
\( S \) = Panel shear stiffness
\( tC \) = Thickness of core
\( tf \) = Thickness of facing skin
\( V \) = Panel parameter (used for simply supported plate)
\( d \) = Calculated deflection
\( sC \) = Core compressive stress
\( sCR \) = Critical facing skin stress
\( sf \) = Calculated facing skin stress
\( tC \) = Shear stress in core
\( m \) = Poissons Ratio of face material
\( l \) = Bending correction factor for Poissons Ratio effect
# 0. Research Framework

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**Choose Type of Bread**

- Annealed Glass
- HS Glass
- FT Glass

**Serving**

- Adhesive
- Safety?
- Transparency

**Single/Double?**

- Calculate core thickness
- Calculate Skin thickness
- Core Density?
How to Build Your Own Sandwich:

- Choose Ingredients:
  - Bidirectional
  - Unidirectional
  - Regional
  - Punctual

- Add Greens:
  - Sustainability
  - Transportation
  - Optimisation

- How Hungry Are You?
  - Design Loads
  - Boundary Conditions
  - Connections
In this Chapter, the Research Framework is discussed. This was presented during P2 and guided the research making clear what the relation between Research and Design is. In this chapter, the Problem Statement, the Objectives and The Research question are formulated. Finally, the time planning as well as the allocation of tasks in the periods between P1 and P5 are presented.
//BACKGROUND

Throughout the course “AR0105 Technoledge Structural Design” (Q3/2016), attended in a group with Vicente Plaza Gonzalez, we designed a building application with horizontal glass elements of 9.00 x 3.20 m and 6.40x3.20 m. Hence, we encountered the problem of having to introduce portal frames that did not match with our architectural intent of having a clear interior space. What is more, we wanted to “deviate” from the existing methods of building with glass, namely a) fins, b) cast glass, c) corrugated glass. Therefore, we had to come up with a planar element with a high stiffness to weight ratio and thus we introduced a glass “sandwich” panel comprised of 2 glass panes separated by glass bore tube spacers. These panels were used as roof and floor elements designed to carry a dynamic load of up to 5 kN/m². The panels were developed further by the means of removing glass spacers close to the points where minimum stresses are induced and therefore ending up with an element with lower specific density in the core. At the final presentation, the result was praised and all supervisors suggested that the panel should be developed further under the context of a graduation project.

//PROBLEM STATEMENT

Transparency plays a major role in contemporary architecture and therefore glass has become one of the most important materials in the building industry with a significant number of applications varying from standardized curtain wall systems to structural glazing applications. In general, the thickness of glass panels is defined by their maximum stresses and deflections which in turn are a function of their stiffness. This is especially important for horizontal elements, where self-weight is a determining factor for the deflection and therefore for the thickness of the laminated panel. One solution that is available in the industry...
is laminated glass but one can easily understand that even though by laminating glass we can stiffen a glass section by increasing the thickness, the weight and material consumption are significantly increased as well. This creates usually a very busy structural setup (figures R3, R3) resulting in a very distinct and particular architectural expression: that of frequent glass fins. In many cases, extraneous structure is added to the building in order to carry vertical loads. This creates a lot of destruction and disturbs transparency which is essential in glass structures. Hence, one can easily understand that the industry lacks a solution to the problem of increasing the stiffness of glass without disturbing transparency and without increasing its weight. So, how can we create a self-bearing transparent, stiff and lightweight panel out of glass?
The aim of this research will provide the market with a technique that would allow the creation of a customizable sandwich planar element, able to accommodate floor, roof as well as façade solutions. In general, there is a three-fold value of the graduation project in the larger social and scientific framework: Material Development, Geometry Development, and Sustainability.

Material and Geometry Development: Glass is a relatively new yet up-and-coming structural material. It is used more and more structurally in a way to reduce metal substructures and provide maximum transparency. With this research, I aim to provide the glass industry with a new way of using glass in planar elements. This may revolutionize the way of designing with glass which currently is limited to glass bricks, glass fins and corrugated glass. One reason why glass is the only material used as a spacer is also that my purpose is to push the material to the limits. At the same time, this research will ideally constitute a significant addition to the sandwich technology.

Sustainability: Nowadays, sustainability is more pressing than ever and there is a need to think of the embodied energy of the materials we use and an even higher need to reduce material consumption. The great advantage of glass as a material is its endless recyclability. Glass can be 100% recycled without losing its strength and purity. One other important aspect of glass is that it controls the solar energy that enters the building and thus assists in heating up the building in summer as well as reducing electricity consumption for lighting. Another advantage would be the low embodied energy of glass. The embodied energy of glass is really low and comparable to the embodied energy of wood, making glass one of the most sustainable materials overall. Finally, by using the material in the most efficient way, not only can it reduce the material used in the element itself but it could also inherit the redundancy of the substructure. In modern facades, a lot of extra material is used in the façade substructure. If the element is stiff enough it can be attached to the main structure or it can constitute the structure by itself.

The objective of this research is to explore the potential of glass sandwich panels and propose a method to design a stiff and relatively light-weight planar element.

Sub-objectives
- Define the glass type to be used (annealed, heat-strengthened or fully-tempered)
- Implement safety
- Explore anisotropy of the core
- Define topology of the core
- Define sealing methods and conditions under which the panel can be integrated into a building structure
- Define connection method (type of adhesive and application) between the spacers and the glass panes
//RESEARCH OUTCOME

The research will have 3 main directions:

a) A new design for the glass floors of the Acropolis Museum in Athens, Greece. The new design will be able to illustrate the potential of glass sandwich structures insofar as transparency, safety and most importantly stiffness to weight is concerned.

b) Test results of the lab performance of different versions of the sandwich panel. Different configurations and core topologies will be tested and compared. The outcome of this process will be a report that will show a clear understanding of how to create such a panel and its behavior under different types of loading.

c) The optimized version of one panel with a very clear topology. Since this constitutes a research on a new structural element the design will try to address different options and configurations.

//CONSTRAINTS

Who: The research is addressed to that fraction of the market that is interested in a new transparent expression and in a stiff and relatively light-weight planar element.

Where: The research will yield generic results applicable into all types of buildings. Therefore, the measures will be made in laboratory conditions. However, a case study will be also used as a proof of concept and this will define the design loads, the boundary conditions and the main function. Intentionally, a quite demanding and challenging design task is chosen so as to promote the full potential of the sandwich element. Even though there is a high potential in roof and facade elements, the one that is most challenging structurally, the floor element, stood out to me. As far as stiffness to weight is concerned, floor elements are extremely demanding because they have to withstand the live load of people as well as the self-weight of the panel. Hence, the main task is to replace the glass floors of the Acropolis Museum, with the new elements that will be much more transparent and will allow visitors of the museum to look at the archaeological excavations.

What: The material that will be used for the core is also glass. That way the research can explore other parameters. More specifically, the research will focus on 4 parameters, namely a) glass type, b) topology of the core, c) optimization of the sandwich panel, d) building integration. More analytically:

a) Glass type
Based on the design demands, the glass type will be chosen among annealed, heat-strengthened and fully tempered glass. Safety must be also implemented.

b) Topology of the core
Glass forming techniques and sandwich topologies will show the way to the topology optimization of the glass sandwich panel. Hence, diverse topologies will be tested in order to choose the one that will
be elaborated on.

c) Connection between glass panes and spacer. The connection will be restricted to transparent adhesives and more specifically UV curing acrylate.

d) Building integration:
The connections to the building’s structural frame need to be defined as well as the connection between 2 consecutive panels. What is more, spacers will need to be building-specific e.g. adapted to orientation or adapted to function.

//RESEARCH QUESTION

How can we create a lightweight yet stiff planar element out of glass to be used in glass floor applications with selective distraction??

Sub Questions:
- How can we best implement safety in the design of the element?
- Which glass type should be used?
- Which adhesive should be used to bond the skins to the core?
- How can we integrate the glass floor to the building (details, connections etc)?
- Which are the available topologies for creating a core with glass?
- How can we optimize a glass sandwich element?

//RESEARCH DESIGN

In this research, three main research strategies are selected, namely a) Research by Design, b) Simulation and c) Experiment.

a) Research by Design: This refers to the design of a building or to the renovation of an existing one. In this research, the case Study of the glass floors of the Acropolis Museum is used so as to define design loads, boundary conditions and functions. The loads will be defined in accordance with Eurocode 1 and will be used to dimension the panels. The design requirements will also guide the optimization of the panel.

b) Experiment/Lab: Initially the intersection of the 3 following sets will be found: a) What are the available sandwich topologies? b) What are the available ways of forming glass? c) What are the available means in the lab? 6 topologies will be derived (Figure R4) and proceed to further investigation. The possible configurations will be tested in a lab. The purpose of this is to reevaluate the structural calculations but also to compare different topologies. The specimens will be structurally tested by the means of 3-point or 4-point bending tests in the lab of Mechanical Engineering at TUDelft. The specimens will be scaled according to the available spacers. The results can be extrapolated to a bigger element according to the formulae provided in the next chapter.

c) Simulation (structural calculations): The configurations that will derive from the design will be evaluated by structural calculations (hand and numerical).
In general, the method followed is simply linear, trying not only to reach the final design goal but also to explore the potential of glass sandwich structures, using the design as a proof of concept, as a guide for calculations and as a guide to building integration. Hence, after the literature research is finished, a number of possible solutions will be tested. The one with the most potential will be picked after that, it will be tested extensively to collect statistics, it will be optimized and the design proposal will be finalized. More specifically:

P1-->P2
From P1 to P2, most of the time was dedicated to the research survey in a way to investigate the material and sandwich structures. The first part of the literature is divided into two domains: a) Material (glass properties) and b) Geometry (Sandwich panels). Initially, I researched on general aspects of glass as a structural material including, glass types and safety implementation. Later, I investigated sandwich structures from their significance in nature to their failure modes. The initial research helped me define which is the right literature to be studied, in order to merge the material and the geometry part. I divided this into 3 parts according to the three layers of sandwich panels: a) skins, b) adhesive layer, c) Core. As far as the skins are concerned, properties of the material are the main determining factor. As for the adhesive layer, bonding glass to glass techniques were later investigated. The core was the most important part of the research. Initially, sandwich structures were classified according to the core topology in order to see what is available and what the main advantages and disadvantages of each core topology are. At the same time, I was researching on the available techniques of forming glass in order to conclude on which are the best possibilities to move on with. In the end, 6 topologies are selected to move on with in the process from P2 P3. Finally, independently from the previous research, ways to stiffen glass were studied with a focus on sandwich structures. The emphasis was put into the glass honeycomb panels, designed by Rogers+Partners and Arup and built by Bellapart.

P2-->P3
During this time the 6 aforementioned topologies will be tested and compared according to the following qualitative and quantitative criteria:
Qualitative: Optical quality, Controlled transparency, Design potential for future purposes Quantitative: Stiffness/Weight ratio, Manufacturing time and complexity, Abundancy
This means that 6 specimens will be manufactured and will be structurally tested by the means of bending test. The specimens will be preferably made with the available means of the glass lab. Also, the process will involve hand-calculations, force flow design, 3D modelling, and probability / consequence analysis. Hopefully, this process will be finished 3-4 weeks before P3 so that we can safely interpret the results and conclude on which will be the one I will elaborate on.

P3-->P4
During this period, the chosen topology will be elaborated on. It will be implemented into the design proposal, it will be extensively tested to gather statistics and most importantly it will be optimized using the graphical method that was defined in the literature research. The process will also include detailing with a focus on the integration to the building structure. If needed adjustments to the research framework will be made. The outcome of this period will be the design of the glass floor of the Acropolis Museum, verified by the results of the structural tests.

P4-->P5
During this period, no further developments will be made. I will focus on the presentation, the report and on solving possible problems that might come up during the process. My goal is also to make a scale model of the final panel and use it as a demonstration model.
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<td>Dimensioning of the panels</td>
<td>100%</td>
</tr>
<tr>
<td>Study Precedents</td>
<td>100%</td>
</tr>
<tr>
<td>Forming Design proposal</td>
<td></td>
</tr>
<tr>
<td>Topology 1 (Manufacturing &amp; Calculations)</td>
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</tr>
<tr>
<td>Topology 2 (Manufacturing &amp; Calculations)</td>
<td>0%</td>
</tr>
<tr>
<td>Topology 3 (Manufacturing &amp; Calculations)</td>
<td>0%</td>
</tr>
<tr>
<td>Topology 4 (Manufacturing &amp; Calculations)</td>
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<tr>
<td>Topology 5 (Manufacturing &amp; Calculations)</td>
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<tr>
<td>Topology 6 (Manufacturing &amp; Calculations)</td>
<td>0%</td>
</tr>
<tr>
<td>Structural Tests &amp; Interpretation of results</td>
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</tr>
<tr>
<td>Final Design of the floor</td>
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</tr>
<tr>
<td>Detailing &amp; Integration</td>
<td>0%</td>
</tr>
<tr>
<td>Optimization of the panel</td>
<td>0%</td>
</tr>
<tr>
<td>Construction of optimized panel</td>
<td>0%</td>
</tr>
<tr>
<td>Structural tests &amp; interpretation of the results</td>
<td>0%</td>
</tr>
<tr>
<td>Report and Presentation</td>
<td>0%</td>
</tr>
<tr>
<td>Formulate future research</td>
<td>0%</td>
</tr>
<tr>
<td>Final Panel</td>
<td>0%</td>
</tr>
<tr>
<td>Prepare for P5</td>
<td>0%</td>
</tr>
</tbody>
</table>
In this chapter the literature review is discussed. The Chapter is divided into 2 parts. The first part is material-oriented and deals with the properties of Glass. The second part is Geometry-oriented and discusses Sandwich structures. Finally, a number of precedents is presented and their relation with this research is defined. Generally, the Literature study was a crucial part of this thesis as it shaped the topic and moulded the research.
LITERATURE STUDY
In this chapter, the literature that was studied during the period P1→P2 and is pertinent and relevant to the topic, is discussed and is commented on. The literature is divided into 2 parts. The first part is related to glass and its properties whilst the second part focuses on the analysis of sandwich structures. In general, the scope of the literature is to provide useful insight on how to build a sandwich panel with glass. Only after knowing deeply the material properties and the theory of sandwich panels can we build a sandwich panel out of glass and test it.

---

Material: Glass

Initially, the material of glass is studied and the general theoretical research over the material properties is presented with a focus on its sustainable significance. What is more, the way glass is used as a structural material in buildings is discussed with a focus on different typologies and safety issues that come up when building with glass. The final part of this chapter is mostly related to the construction of the sandwich panel discussing ways to shape glass, in a way to seek different possibilities as far as the core topology is concerned, and presenting available glass-to-glass bonding techniques, so as to define ways to bond spacers to the glass faces.

//2.1 What is glass?

One could simply say that glass is the transparent material that we use in windows, tableware and doors. However, there are different definitions that explain what glass is and in fact, it is quite interesting to look at glass from different perspectives. In literature there is a significant number of diverse definitions from a plethora of diverse perspectives.

First of all, Glass is a material with certain characteristics and properties and as with every other material, the material is defined by its properties. For long, glass was considered a “fourth state of matter” before realizing its liquid-like structure (Le, Bourhis, 2014). However now glass is studied and defined based on the arrangement of the molecules of a material. Let’s see some different definitions given to glass.
According to Eric Le Bourhis “glass can be considered as a frozen liquid for which viscosity becomes so high that the atomic motions have slowed to the extent that characteristic relaxation time exceeds the observation period” (Le, Bourhis, 2014).

Christian Schittich defines glass as: a solidified liquid and a uniform material, which thanks its transparency due to a very complex and random order in which the molecules are arranged. Because glass works as a combination of various molecular bonds, no chemical formula can be given. Therefore, glass does not have a melting point when heated, but it gradually changes from a solid to a liquid state. When you compare glass to other crystals, it stands out by the fact that its properties do not depend on the direction in which they are measured, whereas other crystals do. Glass exhibits amorphous isotropy, which means that the properties are independent of direction of the material. (Schittich 1999).

In Ullmann’s Encyclopedia of Industrial Chemistry Glass is defined as a non-crystalline amorphous solid that is often transparent and has widespread practical, technological, and decorative usage in, for example, window panes, tableware, and optoelectronics. Scientifically, the term “glass” is often define in a broader sense, encompassing every solid that possesses a non-crystalline structure at the atomic scale and that exhibits a glass transition when heated towards the liquid state (Wikipedia, retrieved in Dec 2016).

What one may observe is that the definitions are based on the arrangements of the molecules in an amorphous formation as opposed to a crystalline structure. The term “glass transition” refers to the opposite of supercooling and hence, the transformation of a “glassy” or brittle material into a viscous state as it gets heated. Morton Tavel, a professor of physics at Vassar College argues that glass is not a solid but should be considered a supercooled liquid (https://www.scientificamerican.com, retrieved in Nov 2016).

//2.2 Structure and Composition of Glass

In the previous chapter it was made clear that glass has a very distinctive composition and a specific molecular structure. By reading the definitions one can argue that steel behaves the same way as glass and has similar properties. But as it is already mentioned, one material has to fulfill 2 re-
requirements to be considered glass: It has to be an amorphous solid and it must exhibit the glass transition. There are some Polymers that have an amorphous structure but do not exhibit the glass transition. Same, some metals exhibit glass transition but not a long-range order.

In general, materials can be classified into four categories according to the bonds they form (Askeland, 1989; Ashby and Jones, 1991; Mozdierz et al., 1993):

a) metals
b) ceramics
c) polymers
d) composites.

This classification is based on the different types of bonds formed between the atoms of the materials. This implies that properties of the materials are more or less decided by the structure at the nanoscale. This is true for many properties e.g. elasticity, thermal expansion; while defects happen to play a major role in others e.g. diffusion, fracture, plasticity (Le, Bourhis, 2014).

In that sense, glass can be considered a ceramic as its atoms form either a covalent or ionic bond. So what distinguishes glass from other ceramics? Glass does not exhibit a long-range order due to its amorphous composition.

There are different types of glass but generally glass consists of the following: silicon dioxide (SiO2), calcium oxide (CaO), sodium oxide (Na2O) magnesium oxide (MgO) and aluminum oxide (Al2O3). SiO2 is found in concentrations from 65%-80%
SiO₂ is mainly found in sand and rocks. However, it is important that sand be purified before it can be used for production of glass. The calcium oxide, which comes from limestone, is added to the mixture and adds a certain hardness to the end product. The sodium oxide, which is the third main component and can be obtained from soda ash, lowers the melting temperature of the glass which is beneficial for the production process. (Akerboom, 2016)

If special properties are desired, other materials (such as magnesium oxide or aluminum oxide) can be added to the previously mentioned raw materials. The percentage of each of these ingredients can also vary for different little variations in the glass. This will mainly influence the melting temperature and/or the strength in the glass. The European Standards in EN 572 Part 1 describes the boundaries in which the production of this glass should be executed to be able to guarantee a certain quality and safety. In most cases, a small amount of waste glass is also added to the mixture, since this is already melted it makes the melting of the raw materials easier. (Schittich 1999)

As it was mentioned before, glass is the product of the cooling process of a viscous material, the molecules of which cannot form a long-range order. In figure 3, the molecular structure of glass is presented in comparison with a crystallized structure of SiO₂ (figure 2)

Figure 2: Crystalline form of SiO₂
Source: Haldimann, M., et al. (2011)
Is glass always transparent? The answer is no. There are certain types of glass that are opaque.

<table>
<thead>
<tr>
<th>Optical quality</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transparent</td>
<td>33</td>
</tr>
<tr>
<td>Translucent</td>
<td>0</td>
</tr>
<tr>
<td>Opaque</td>
<td>13</td>
</tr>
</tbody>
</table>

Figure 4: Transparency of glasses
Source: CES 2016

In Figure 4 we see a CES generated diagram that shows different glass types classified according to their transparency. But what makes glass transparent?
In order to find out why glass is transparent we need to go down to the sub-atomic level. As shown in figure 5, each atom consists of a nucleus and a number of electrons arranged in different energy states. When a photon hits an electron, if the energy is enough for the electron to move to another band, then it is absorbed. This occurrence is technically called band-to-band transition.

With glass this cannot happen, as the energy states are far away from each other and the energy provided by visible light is not enough to stimulate this transition. We know that:

\[ E = \frac{hc}{\lambda} \]

Where \( E \) is the photon energy, \( h \) is the Planck constant, \( c \) is the speed of light in vacuum and \( \lambda \) is the photon’s wavelength. This means that the photon Energy is inversely proportionate to the wavelength. This explains why glass partly absorbs UV.

Then another question might come up. Why is glass transparent and not sand which is made of silicone dioxide? "Sand, is so filled with impurities..."
that light simply scatters outward incoherently and does not pass through to a not, retrieved in Dec 2016)

//2.3 Different Glass Types.
//Mechanical and Thermal Properties of Glass

As mentioned before, Glass belongs to the family of ceramic and thus exhibits high stiffness and elevated yield stress, allowing for small elastic and reversible deformations until failure. Glass presents elevated chemical and thermal resistances. Glass is brittle with low toughness and thermal shock resistance (Le, Bourhis, 2014). Glass as it was mentioned before is a brittle material that exhibits no plastic behavior like metal for example.

According to the composition of glass, 5 different types of glass are recognised: Quartz Glass, Soda Lime Glass, Borosilicate Glass, Lead Glass, Alumino Silicate Glass. In the following sub-chapters the aforementioned glass types are presented:

Soda Lime Glass

This constitutes the most commonly used type of glass. The main advantage of this type is that it can be processed in lower temperatures and therefore it is much more cost-effective to be produced in higher quantities.

Due to the addition of soda in glass, there is a number of limitations related to its thermal properties: The service temperature as well as the thermal resistance are lower compared to other types of glass. Typical uses include: windows, bottles, containers, tubing, lamp bulbs, lenses, mirrors, bells, glazes on pottery and tiles. (CES 2015).

Quartz Glass

This type of glass exhibits no impurities and consists of 99.9% SiO2. Knowing that the impurities are added to glass in order to lower its process temperature, we easily realise that that of Quartz glass is really high making its production much more pricey. This type of glass is usually utilised in high temperature applications such as envelopes for high wattage lamps.
Borosilicate Glass

This is another type of glass with strategically added impurities. B2O3 (boron oxide) is added in order to lower the viscosity of glass while not changing its resistance to thermal shock. This is another pricey type of glass but is commonly used in cases when high temperatures are to be reached.

Alumino Silicate Glass

This glass type contains different kind of impurities usually aluminum oxide in a concentration of about 15%-20%. This glass type can withstand very high temperatures and thermal shocks and is considered to be the intermediate between soda-lime and quartz glass. Typical uses of this type of glass are: combustion tubes, gauge glasses for high pressure steam-boilers and halogen-tungsten lamps which operate at temperatures as high as 750 degrees Celsius. (CES 2016)

Lead Glass

This type of glass is commonly used in decorative glass objects. Lead oxide PbO is used because it has a very high refractive index causing a brilliant sparkle (CES 2016). To prevent a risk to human health, the lead is carefully locked inside the chemical structure of the glass (Akerboom 2016).

Ceramic Glass

This is the product of the controlled crystallization of glass causing it to exhibit amorphous as well as crystalline parts. Since, as said before, transparency does not depend so much on the molecular arrangements of materials but mostly on the subatomical structure, ceramic glass can still
This is the young’s modulus-thermal expansion coefficient diagram for different types of glass. Ashby (2001) suggested plotting $aE$ versus $E$ in a log - log diagram, since in such a plot $aE$ contours are shown as parallel lines: $E$ constant implies $\log aE = \log E + \text{constant}$, which for a log - log plot is represented by a straight line of slope -1. On a same line, the value of $E$ product is then a constant and is defined as the performance index as regards thermal shock stresses. Observing that $aE$ is expressed in megapascals per Kelvin (MPa K$^{-1}$), the materials shown on the same line are submitted to identical thermal stress amplitude under the same thermal variation amplitude. For instance, along the line indexed 1 MPa K$^{-1}$, all materials would experience thermal stresses of 100 MPa amplitude when submitted to an instantaneous (this hypothesis allows neglecting of thermal conductivity mentioned above) thermal shock of amplitude 100 °C (Le, Bourhis, 2014).

The $aE$ value of different glasses is comparable. Quartz Silica is below 0.1 MPa/K while soda-lime could be submitted to thermal stresses of about 0.5 MPa/K. This is why borosilicate glass is used in cases where thermal shock resistance is the main requirement. However, when tempering is the main purpose, elevated $aE$ indices are required. For that reason, soda lime glass is more commonly used.

In Figure 8 the resistance to Thermal Shock is presented in a Fracture Toughness/E-Thermal expansion coefficient (Ashby 2001). In this chart we see the clear difference between Soda Lime, Borosilicate and Quartz.
If we compare glass and steel we can easily see that the two materials have very different thermal expansion coefficients. In fact the coefficient of glass is lower than that of steel:

\[ a_{\text{glass}} = 9 \times 10^{-6} \text{ (1/K)} < a_{\text{steel}} = 12 \times 10^{-5} \text{ (1/K)} \]

This creates a number of problems especially in facades where steel is used as a connection. For that reason, when glass touches metal, usually a silicon rubber gasket is added between the two.

Figure 8: Resistance to thermal shock
Source: CES 2016

Figure 9: Broken glass due to different thermal expansion
Source: Haldimann, M., et al. (2011)
As far as mechanical properties are concerned, Glass can be considered an amorphous material, but this doesn’t mean that there is no structure in glass. At a nano-level, some primitive shapes can definitely be identified by the organization of silicon and oxygen atoms. The absence of a crystal raster in the material prevents dislocations and therefore excludes any plastic behavior. Because the covalent bonding between the atoms cannot easily repair after being broken, local stresses around a defect will cause bond failure and therefore increase local stresses. Glass can only deform elastically or fracture. (Veer 2007)

In figures 11 and 10 we can see a comparison between glass and steel in stress-strain diagrams.

This research focuses on soda lime glass which is the glass type most commonly used in buildings. In Table 1, its properties are compared with the properties of borosilicate glass.

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Soda-Lime</th>
<th>Borosilicate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>kg/m³</td>
<td>2500</td>
<td>2200-2500</td>
</tr>
<tr>
<td>Young’s Modulus</td>
<td>GPa</td>
<td>70-75</td>
<td>60-70</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>-</td>
<td>0.22</td>
<td>0.2</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>MPA</td>
<td>30-35</td>
<td>22-32</td>
</tr>
</tbody>
</table>
One can easily understand why soda lime is commonly used. It is significantly cheaper than borosilicate (see Figure 12), it can be tempered more easily due to the higher $aE$ index and exhibits a lower softening point due to the soda imperfections.

Table 1: Mechanical Properties of S-L Glass and Borosilicate Glass

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Value Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness</td>
<td>kg/mm²</td>
<td>440-485</td>
</tr>
<tr>
<td>Compressive Strength</td>
<td>MPa</td>
<td>360-420</td>
</tr>
<tr>
<td>Softening Point</td>
<td>Celcius</td>
<td>726</td>
</tr>
<tr>
<td>Price</td>
<td>Euro/kg</td>
<td>1160-1370</td>
</tr>
<tr>
<td>Shear Modulus</td>
<td>GPa</td>
<td>28</td>
</tr>
</tbody>
</table>

Figure 12: Price of different glass materials
Source: CES 2016
The problem with glass is that its strength varies on account of flaws of the material. These flaws can be a) surface-edge flaws, b) bubbles and inclusions.

The Griffith Theory for crack propagation in brittle materials

Consider a crack of length 2a subjected to a uniform stress then:

\[ \sigma = \left( \frac{2\gamma}{\pi a} \right)^{1/2}, \]

\( \sigma \) = stress, \( \gamma \) = bond energy

Crack propagation occurs when the released elastic strain energy is at least equal to the energy required to generate new crack surface (SRM Uni-
The theory of Griffith was motivated by 2 facts:

- The stress needed to fracture bulk glass is around 100 MPa (15,000 psi).

- The theoretical stress needed for breaking atomic bonds is approximately 10,000 MPa

//2.4 Safety

Given that flaws in glass decrease its strength, annealed glass is considered to have 20MPa Tensile strength. However, this constitutes 1 in 10,000 statistical failure stress, meaning that 99.99% of glass will be stronger. But we need to allow for the fact that maybe the glass will be weaker. On these low maximum stresses we still need to apply a safety factor. (Veer 2016). Glass as a structural material has very high potential but its brittle behaviour poses a number of challenges. Glass never exhibits a warning and on account of the aforementioned imperfections, we need to be prepared for the worst case scenario. According to professor Rob Nijssie it is very important to make sure that before a part of the structure fails, it gives a warning. Most of the times, it is also important to take into account the abundance of the whole structure in the sense that if one part of the structure fails, the load needs to be guided to the ground through other components.

For that reason, a number of different ways to increase safety are introduced as a way to reduce risk. But first we need to define what risk is:

Risk = probability x consequences

Another way to define is based on a simple arithmetic model that includes also the weighted factor of the exposure of a structural element. A safe structure follows this rule:

Probability (WS) x Exposure(BS) x Consequence(ES) < 70

The formula is calculated based on those scenarios:

<table>
<thead>
<tr>
<th>Probability</th>
<th>WS</th>
<th>Exposure</th>
<th>BS</th>
<th>Consequence</th>
<th>ES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intentionally or Unintentionally</td>
<td>3</td>
<td>structural element</td>
<td>6</td>
<td>complete failure</td>
<td>3</td>
</tr>
<tr>
<td>Virtually impossible</td>
<td>0.1</td>
<td>Very rarely</td>
<td>0.5</td>
<td>First aid</td>
<td>11</td>
</tr>
<tr>
<td>Practically impossible</td>
<td>0.2</td>
<td>Several times</td>
<td>1</td>
<td>Minor Injury</td>
<td>3</td>
</tr>
<tr>
<td>Possible but very unlikely</td>
<td>0.5</td>
<td>Monthly</td>
<td>2</td>
<td>Serious injury</td>
<td>7</td>
</tr>
<tr>
<td>Only possible in the longer</td>
<td>1</td>
<td>Weekly</td>
<td>3</td>
<td>One dead</td>
<td>15</td>
</tr>
<tr>
<td>Uncommon but possible</td>
<td>3</td>
<td>Daily</td>
<td>6</td>
<td>More than one</td>
<td>40</td>
</tr>
<tr>
<td>The best possible</td>
<td>6</td>
<td>Constantly</td>
<td>10</td>
<td>Catastrophe, many deaths</td>
<td>100</td>
</tr>
</tbody>
</table>
As it was mentioned before, there are ways to reduce either the probability or the consequence, by strengthening glass and increasing its ultimate limit state, by providing a sacrificial layer, by controlling the way shards are spread after the breakage of glass etc.

**Ways to increase safety:**

1. **Strengthening glass**

Before explaining strengthening methods, we need to discuss what annealed glass is first. Annealed glass is the most commonly used and produced type of glass. Its strength is considered to be 20 MPa. Annealed glass is the product of gradual and careful heating and cooling so that the stresses remain the same in the whole height of the section and therefore we expect that it has a perfect elastic behaviour until it breaks. Annealed glass exhibits corrosion and thus, if corrosion is taken into account, a strength of 6 MPa needs to be considered. When this type of glass breaks, it does so in big shards and thus annealed glass is considered hazardous when not laminated.

So, apart from annealed glass which constitutes the most commonly produced glass type, 3 other types of strengthened glass should be considered. The strengthening process can either be tempering or chemical.

- **Heat Strengthened:**

Glass is vulnerable to tensile stresses. For that reason, glass is treated in such a way that at the end of the process, the faces are subjected to compressive stresses. This process relies on the fact that after the glass is heated to around 620°C, a process which is called annealing, faces are cooled down faster than the inner part of glass. We may consider that the strength of heat strengthened glass is 40 MPa.

- **Fully tempered glass:**

This is the type of glass that can withstand the highest stresses: 80 MPa. The production process of this type of glass is very similar to that of heat-strengthened glass, only that the surface of the glass panes is prestressed even more. Since heat strengthening and tempering are comparable treatments, there are set stress levels by The Glass and Glazing Federation Glazing Manual to define the difference. (Alsop 1999). The breaking pattern of this type of glass is much different than the breaking
pattern of annealed and heat-strengthened glass in the sense that fully tempered glass breaks in smaller pieces. This happens because the energy that is released is much higher. Theoretically, this type exhibits the safest after break behaviour but
It is important to mention that every treatment such as drilling, chamfering etc before tempering the glass.

**Chemically tempered**

This is a type of glass that thanks to a chemical process becomes 5-6 times stronger than annealed glass. The process is based on an ion exchange that takes place at the surface of glass. Glass is placed in a potassium ion bath and is heated up to 350°C until sodium and potassium ions exchange places.

This type of glass breaks in big and pointy shards similar in size to annealed or heat-strengthened glass. For that reason, when safety should be implemented, glass should be laminated so that the shards stick to the interlayer.
2. Reinforcement

As in reinforced concrete, glass can also be reinforced. Concrete is useless structurally unless reinforced. Glass can be reinforced on the side that is subjected to tensile stresses so as to mask its weaknesses. The problem with this solution is that this creates some distractions that are visible.

3. Lamination

One way of strengthening glass is by lamination. Initially, this increases the thickness of the pane and increases the inertia of the section. That way, the deflections are lower, the stresses induced are lower and the element is less susceptible to bucking. This decreases the factor of probability. What is more, lamination can provide some abundance and therefore if one pane breaks the other can still carry the load. This measure decreases the consequence.

We use different materials to laminate glass:

PVB - SentryGlass - EVA - Resin

PVB is cheaper and the one that is commonly used. SentryGlass is the strongest providing some abundance to the structure.

The problem with lamination is that in some cases there is not 100% shear interaction and hence we cannot consider that:

$$t_{tot} = t_1 + t_2 + t_3 + ... + t_n$$
4. Sacrificial Technology

As mentioned before, lamination can add some abundance to the structure. A sacrificial layer may be added to the glass structure as an addition that will absorb the energy of an impact and break, protecting at the same time the rest of the structure. This sacrificial layer is considered as an extra weight to the calculations while its structural significance is neglected.

![Sacrificial Layer](image)

//2.5 Why glass? Is glass Sustainable?

Glass is used more and more nowadays because it serves the contemporary need for transparency. Glass is especially used in facades as it gives the architect the chance to visually connect the interior with the exterior while keeping away the elements (Gio Ponti, 1956).

<table>
<thead>
<tr>
<th>Durability</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Water (fresh)</td>
<td>1</td>
<td>Excellent</td>
</tr>
<tr>
<td>Water (salt)</td>
<td>1</td>
<td>Excellent</td>
</tr>
<tr>
<td>Weak acids</td>
<td>1</td>
<td>Excellent</td>
</tr>
<tr>
<td>Strong acids</td>
<td>1</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Weak alkalis</td>
<td>1</td>
<td>Excellent</td>
</tr>
<tr>
<td>Strong alkalis</td>
<td>1</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Organic solvents</td>
<td>1</td>
<td>Excellent</td>
</tr>
<tr>
<td>Oxidation at 500°C</td>
<td>1</td>
<td>Excellent</td>
</tr>
<tr>
<td>UV radiation (sunlight)</td>
<td>1</td>
<td>Excellent</td>
</tr>
<tr>
<td>Halogens</td>
<td>1</td>
<td>Limited use</td>
</tr>
<tr>
<td>Metals</td>
<td>1</td>
<td>Limited use</td>
</tr>
<tr>
<td>Flammability</td>
<td>1</td>
<td>Non-flammable</td>
</tr>
</tbody>
</table>

![Durability of glass](image) | Source: CES 2016
One can easily observe that glass is a very durable material compared to other transparent materials especially when it comes to UV resistance. That is one of the main reasons that glass is usually used in applications that are exposed to the elements.

"Glass is a mysterious material. On the one hand it is transparent: about 95% of the light passes unhindered through a 10 mm thick glass plate, on the other hand: water cannot pass through the glass. I don't know any other material that has these contradicting properties. If we realise that glass is basically made from 75% (molten) sand and 25% chalk and soda, all three abundant materials on Earth, and can be recycled 100%, it is a sustainable material indeed. Furthermore it does not rot, it does not corrode and can be cleaned easily with water. Plentiful considerations to look at glass like the building material of the Future.

These are, however, all technically driven considerations, there are also sociological important arguments. [...] Modern, democratic society calls for transparent behaviour of all participants in our society and the fact that everybody is able to see what is going on inside any building that is cladded with glass in the facades gives a remarkable boost to the controllability and the responsibility of each participant in society. Of course the need for privacy is a naturally felt fact and we don’t want to live in a “1984”- like world with 24h/7d control by the authorities. But if you decide to close the curtains or shutters you make a statement that you are out of the control of society and therefore are not any more transparent in a sociological way. This is a modern and most complicated discussion: what is to be preferred? Transparency or Privacy?” (Rob Nijssse, 2015)
Nowadays, sustainability is more pressing than ever and we have to look for materials that are recyclable but also have low embodied energy. Hence, the life-cycle of glass much longer. The great advantage of glass as a material is the fact that it is 100% recyclable without loss in quality or purity and it can endlessly be done. One other important aspect of glass is that it controls the solar energy that enters the building and thus assists in heating up the building in summer as well as reducing electricity consumption for lighting. One other important aspect of glass is its low embodied energy. In Figure 25 the embodied energy of glass is presented in relation to that of other materials such as wood and steel.

<table>
<thead>
<tr>
<th>Material</th>
<th>MJ/kg</th>
<th>CO2/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>15</td>
<td>0.85</td>
</tr>
<tr>
<td>Aluminium</td>
<td>155</td>
<td>8.24</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>112</td>
<td>5.23</td>
</tr>
<tr>
<td>Stainless</td>
<td>56.7</td>
<td>6.15</td>
</tr>
<tr>
<td>Timber (general)</td>
<td>8.5</td>
<td>0.46</td>
</tr>
<tr>
<td>GFRP</td>
<td>120</td>
<td>5.80</td>
</tr>
</tbody>
</table>

The embodied energy of glass is really low and comparable to the embodied energy of wood, making glass one of the most sustainable materials overall.
//2.6 Shaping Glass - Core Topology

The history of glass-making can be traced back to 3500 BC in Mesopotamia, but Mesopotamians may have created second-rate copies of glass objects from Egypt, where this complex craft actually originated (https://www.sciencenews.org, retrieved in 2016). Other archaeological evidence suggests that the first true glass was made in coastal north Syria, Mesopotamia or Egypt (Glassonline: the history of glass, retrieved in 2016). In this chapter, the current technologies of shaping glass are presented.

- Float Glass

For certain, this suggests the most commonly used technique for flat elements. The whole industry is standardized around this method as all equipment including transportation vehicles are adjusted to the so-called “jumbo plate” of 6x3.21m. "This method is still being used at this very moment, although modernized, and it describes a huge lane on which the viscous glass melts over a bath of molten tin and forms a layer of 6mm thick. At the inlet of the lane, temperatures of 1000 °C occur, which is slowly cooled down to 600 °C at the outlet of the lane. When the glass plate is through this lane, the slow, highly controlled cooling process begins to ensure no residual stresses remain before the glass can be cut to size”. (Schittich 1999).

Figure 26: Float glass process | Source: Schittich 1999
One important thing to notice is that the cooling process is extremely important so that the stresses of the panel can be controlled. One other thing that the designer needs to consider is the available thicknesses that are frequently produced in the industry: 2, 3, 4, 5, 6, 8, 10, 12, 15, 19 (and 25) mm.

Notice that usually the aforementioned dimensions have some tolerances due to production inaccuracies of up to 10% for a pane of 2mm.

Producing glass panes of different thicknesses than the nominal is possible but is not standardized and would have an extra cost. At the same time, the maximum possible production of float glass needs to be taken into account:

Production of one float line:
- 900 m float glass (4mm) per hour
- 700 tons per day
- 70,000 m² float glass (4mm) per day
- 35 full trucks per day (presentation Louter, 2016)

Figure 27: Exceptionally large glass pane (25x3.21m) produced in China | Source: presentation Louter 2016
- Studio Glassblowing

This is a technique generally used for producing decorative and functional, hollow and open-ended vessels. The method develops in 5 stages. Initially, a piece of glass is loaded on a preheated to around 600°C piece of blowing iron. Then, air is blown in so that the laded glass takes a preliminary shape. Afterwards, it is inserted into profiled formers or moulds that help give the final shape to the vessel. In the next stages, pucellas are used in order to reduce the neck of the vessel and later, the vessel is transferred to a kiln for annealing.

This constitutes a process with very high environmental impact but lately there have been some developments towards that direction. Soda-lime glass is most commonly used for vessels and borosilicate for laboratory equipment. This technique produces shapes with a maximum shape factor of around 5 and is not ideal for intricate shapes (Thompson, 2011).
- Lamp-working

This is one very famous technique used to produce hollow shapes using heat and manual forming by skilled lamp-workers. This method, also known as “flameworking”, makes use of borosilicate glass which is heated up to 900°C. At this stage a glass cylinder of predefined diameter and wall thickness can be easily formed in different ways based on the fact that the part that is heated has a different viscosity and thus can be easily shaped. Even though, the principle is the same, there are 4 different techniques that can be used depending on the desired shape. These techniques (figure 29) are: a) Blowing, b) Hole Boring, c) Bending and d) Mandrel forming.

It is important to notice that the final product has to be annealed in a kiln at around 570°C and then cool down safely to prevent residual stresses. Lamp-working is mostly used to create intricate shapes from jewelry to lab equipment (Thompson 2011).
Figure 30 Lamp-workers at the "Leidse Instrumenmaken School (LIS) | photo taken by the author

Figure 31 Lab equipment made by lamp-workers at LIS | photo taken by the author
Glass Extrusion

Glass Extrusion is similar to steel extrusion or pultrusion of composites for instance. A predetermined and heated portion of glass is pushed through a die to form the desired profiles. There are 2 types of extrusion, horizontal and vertical. The former is considered to be better in terms of linearity while the latter is better in terms of maximum length of the produced profile.

The profiles in figure 33 are profiles designed and produced by SCHOTT using Borosilicate glass. They are produced with horizontal extrusion and thus, they exhibit some eccentricity which can cause a structural problem.
-Glass casting

Cast glass has been a glass production method since the Roman age and is an ideal solution for extraordinary 3D shaped objects and for achieving monolithic elements with a thickness of over 25 mm. With the use of a preformed mould, hot molten glass can be poured in. Sand, plaster or graphite is usually used as a material for the mold, whereas wood is most commonly used to make a template. This template is tightly pressed into the mould material to make a clean impression and then forms the mould. When the mold has been finished, first a release agent is applied before hot glass is poured in at temperatures of about 1200 °C to allow it freely to fill the mould (Akerboom 2016). The Swedish artist Bertil Vallien perfected this immediate and dynamic method in the 1980s.

Figure 34 Cast Glass | source: http://www.lindafrazer.com/Courses/course_2.htm, retrieved in 2016

Figure 35 Cast Glass made by TUDelft

Left: Crystal house bricks | source: http://infinitelegroom.com

Down: Cast glass column made by Akerboom in 2016 | source: Akerboom 2016

LITERATURE STUDY
- Water Jet Cutting

Water Jet Cutting is one way of cutting shapes out of planar glass elements, resulting possibly in intricate shape like laser cutting. Water, usually mixed with abrasives is dispensed with very high pressure, around 4000 bar, through the glass pane following the pattern given in the CAD file. One of the main advantages of the technique is that it constitutes a cold forming technique and in that sense, it does not produce a heat-affected zone (HAZ), which can be critical in structural glazing (Thompson 2011).

Generally, some grinding is needed after cutting or generally some other kind of finishing to produce nice and safe edges. One can easily understand the potential of this technique in designing intricate shapes (figure 37) for stacking as well as in creating decorative applications. Last but not least, the process is one of the most environmentally safe in the sense that no vapours are created and water is cleaned and recycled in a closed system.
Joining glass is one of the main challenges that the glass and facade industry is facing nowadays. There are 4 ways of joining glass:

- Mechanical joining by making holes in the glass and using bolts
- Chemical joining using adhesive bonding techniques to join the glass together
- Chemical joining by soldering the glass
- Physical joining by welding the glass by local melting on the two faces (Veer 2005)

In this chapter we will look at all those methods elaborating more on the adhesive bonding technology which is the one that is used for the construction of the sandwich panel.

- Mechanical connections

This type of connections is not new. It has been used for decades in steel construction. It involves drilling the material to be joined and even though for steel this is not an issue, it causes a number of problems to glass related to its brittle behaviour. Hence, tempering the glass is needed and also finishing time is significantly increased. No matter how much time we spent in finishing, drilling is the same as creating an artificial defect on the surface of the glass and thus making it less strong. When this type of connection is used, extra measures need to be taken so that metal does not touch glass (Veer, 2005). In general, even though this type of connection has several advantages such as it not being toxic, we cannot neglect the significant disadvantages it poses. There are 2 types of mechanical connections, namely bolts and embedded-laminated connections, presented in Figure 38.

Figure 38 Apple Store Bolt Connection
Source: https://nl.pinterest.com/pin/511932682612061467/ lu-sistemler.html
In general, point supports should be avoided as the material might not be able to redistribute the stresses induced around the small hole. Another type of mechanical support is the linear support which is introduced when the load is perpendicular to the plane.

"In some applications glass connections can be soldered. This is usually done to seal vessels and locally join glass to metal. The nature of the soldering process makes it almost impossible for large objects. Soldering is thus a niche technique for point or line connections without large scale application". (Veer, 2005)

- Physical Joining by welding / glass fusion

This type of connections is very common in glass blowing as well as in the making of pieces of art. Two or more pieces of glass are heated up to a temperature of 750-1000°C (depending on the glass type) and they are allowed to cool down together until they mix together. As always, the cooling process is very important when preparing glass pieces as, if not done correctly, the glass will break. It is also important that glasses with the same thermal expansion coefficient and viscosity be used as joining different glass types together would result in the creation of residual stresses in the material. Due to the nature of this technique, it

Figure 39 Fused glass by the glass artist Steven Tippin
Source: http://www.steventippin.com
- Adhesive Bonding

Dr.ir.Fred Veer, in his research paper entitled: “The Possibilities of Glass Bond Adhesives”, that was published in 2005 gives the advantages of such a connection:

“The conventionally considered disadvantages are:
- adhesives deteriorate under influence of water
- adhesives are difficult to apply evenly on the surface of the glass
- adhesives are not suitable for bonding large areas of glass unless the specimen is autoclaved
- curing of an adhesive is difficult to control with conventional two component adhesives which start to cure after mixing
- adhesives generally creep under sustained loading

The main advantages of adhesive bonding are:
- no holes and thus no stress concentrations
- no need for tempered glass by eliminating and thus more reliability and safer failure behaviour
- potential for 100% transparency by obviating the metal bolts
- suitable for small and large area’s

(Veer 2005)

However, after 2005 the aforementioned disadvantages were eliminated, with the only disadvantage of adhesives being the environmental impact of those connections. Dr.ir Christian Louter and Dr.ir.Fred Veer tested in 2008 several glass specimens after exposure to 60°C and after 8 weeks of salt-water-spraying to see how different types of adhesives perform under high solar gain and with moisture. In this research, it was proved that as far as temperature is concerned, acrylates perform better than the rest. Moisture does not have a significant effect on the residual strength of glass elements. In general, when choosing the right adhesive there are many parameters that are involved as shown in Figure 40.

<table>
<thead>
<tr>
<th>Fabrication</th>
<th>Materials to be joined</th>
<th>Surfaces of elements to be joined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refurbishment and Maintenance</td>
<td>Adhesive Fixing</td>
<td>Preliminary surface treatment and activation</td>
</tr>
<tr>
<td>System And Loading</td>
<td>Contact Material</td>
<td>Type of adhesive, adhesive geometry, thickness etc</td>
</tr>
<tr>
<td>Constructional Tolerances</td>
<td></td>
<td>Atmospheric influences</td>
</tr>
</tbody>
</table>

Figure 40 Parameters that influence the selection of adhesives | Weller 2005
The more viscous an adhesive is, the more difficult it is to remove the air bubbles that are formed when spreading it. However, low viscosity adhesives tend to emit higher quantities of vapour during curing which might create condensations that cause undesired permanent textures and tears in the adhesive layer (Teixidor 2010). The most common types of adhesives used are the following: Epoxy (two-component), Acrylate (different types and usually UV curing), Polyurethane, and Silicone. In figure 41 an overview of the properties of the aforementioned materials

<table>
<thead>
<tr>
<th>Adhesive type</th>
<th>Shear strength [MPa]</th>
<th>Curing time</th>
<th>Color</th>
<th>Gap-filling capacity [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy</td>
<td>18 (^{b)})</td>
<td>&gt; 10 hours (^{d)})</td>
<td>grey</td>
<td>up to 5</td>
</tr>
<tr>
<td>Acrylate-1</td>
<td>23 (^{b)})</td>
<td>30-60 sec. (^{c)})</td>
<td>transp.</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>7 (^{b)})</td>
<td>&gt; 8 hours (^{d)})</td>
<td>transp.</td>
<td>0.05 – 0.1</td>
</tr>
<tr>
<td>Silicone</td>
<td>1.06 (^{c)})</td>
<td>&gt; 7 days (^{f)})</td>
<td>black</td>
<td>6 - 15</td>
</tr>
</tbody>
</table>

Figure 41 Overview of types of adhesives | Source: (Louter, Veer, 2008)

Generally, the thickest and adhesive layer is, the lower its elasticity but the higher its strength (Weller 2005).

- **Silicones:** Generally they are used to enhance mechanical connections. Due to their paste-like nature, silicones are used to even out tolerances and to absorb deformations that occur between structural elements. Structural silicone is generally black but lately Transparent Structural Silicone Adhesive (TSSA) is used. However, the use of this is inherited by its extremely high cost. Generally, on account of their elasticity silicones are not strong adhesives and generally more than 6mm are needed to make a good connection. Another important consideration is that silicones might exhibit a yellowing effect after a while. Last but not least, another thing that needs to be considered is that the silicone should be constructed in such a way so that it can dry-out (Weller 2005)
- **Polyurethanes** are not UV resistant in contrast to silicones. They also belong the category of elastic adhesives and have higher strength than silicones. They are usually used in glueing windshields and this is the reason they are covered with black coating to protect them from UV radiation. Hence, in structural glass applications where maximum transparency is needed, this type of adhesive is not used in structural glazing applications where maximum transparency is required.

- **Acrylates**: These adhesives consist of a type of resin that is applied on the surface and an activator that is responsible for curing. They cure in room temperature, just like epoxy adhesives and this clearly constitutes a major advantage of this type. One big disadvantage is that due to the fact that acrylates are low-viscous adhesives and are applied in thin layers, they cannot be used to even out tolerances. In fact, the tolerances that can be handled are 0.1-1mm (CES 2016). The adhesive also has an unpleasant smell and can be toxic. This type of adhesive cures when exposed to electromagnetic light or ultraviolet radiation.
- **Epoxy** This is a type of thermosetting adhesive with relatively high tensile strength of up to 45MPa. Most epoxy types are two-component adhesives that cure at temperatures from 20 to 120°C (CES 2016). It constitutes a very brittle type of adhesive that is not able to absorb stresses but in general it has high resistance to moisture and chemicals and a relatively good fatigue strength at high temperatures (Weller 2005). Epoxy usually comes in grey colour but transparent adhesives are also available.

As said before, epoxies usually come in 2 components that when mixed together they cure to create a plastic material. It is important to notice that once the 2 components are mixed, there is limited time to adjust the pieces. These structural adhesives provide high shear and peel strengths, depending on the formula, and better heat and chemical resistance than other common adhesives. In general, epoxy adhesives have the highest overall strength and offer the best performance and most resistance to high temperatures, solvents and outdoor weathering (http://solutions.3m.com).

Figure 45 Application of epoxy and acrylate adhesives
Source: (CES 2016)
Sandwich Structures

In this chapter we will look at the characteristics of sandwich structures. Initially, the reason why a glass sandwich structure is the topic of this research will be explained. Furthermore, sandwich structures will be discussed through a historical background from their appearance in nature to their use in cases where high stiffness to weight ratio is used e.g. in aviation industry. Then, the different structural and physical characteristics of this type of structures are discussed. Finally, the use of this principle in floors is presented in a way to introduce the topic of the research.

//2.8 Why sandwich structures?

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 load bearing material is held at maximum distance from the neutral axis and thus increases the shape factor of the element. In figure 46 we can see the difference between a solid section and a sandwich section of the same weight but of different thickness.

<table>
<thead>
<tr>
<th>Relative Bending Stiffness</th>
<th>1</th>
<th>8</th>
<th>42</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative Bending Strength</td>
<td>1</td>
<td>3.5</td>
<td>9.2</td>
</tr>
<tr>
<td>Relative Weight</td>
<td>1</td>
<td>1.2</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Figure 46 Benefit of sandwich structures

Note that these are results calculated with ANSYS for the material of glass and are therefore different to 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 true strong point of such a structure is the improved behaviour in two indices: strength to weight and stiffness to weight.
//2.9 Historical Analysis

It is extremely interesting to look for sandwich structures in nature. It is remarkable that in nature we can find many applications of the sandwich theory in cases where high rigidity and stiffness are required along with low weight. Given also the Darwin’s theory of evolution, we can see that some organisms and species have evolved in such a way that their structure is a determining factor as far as survival is concerned. It is a similar approach to engineering which is mostly connected to observation and optimization of structures according to the design loads.

“According Darwin’s theory, complex creatures evolve from more simplistic ancestors naturally over time. In a nutshell, as random genetic mutations occur within an organism’s genetic code, the beneficial mutations are preserved because they aid survival -- a process known as “natural selection.” These beneficial mutations are passed on to the next generation. Over time, beneficial mutations accumulate and the result is an entirely different organism (http://www.darwins-theory-of-evolution.com, retrieved in 2016).”

So, one can easily understand why some species have developed very stiff structures that serve their functionality. In figures 47 and 48 typical applications of sandwich structures in nature are presented in different scales down to nanostructures.
As said before, sandwich structures are exhibited everywhere in nature. This is also true on a microstructural level. In Figure 53, different properties of sandwich geometries are presented. -a- represents a wood-like structure with a hexagonal pattern with transversal symmetry. -b- is representing a palm like tree (Figure 48) the cross section of which features fibers in a cellulose foam type core. It uniform n-plane and has translational symmetry. -c- has a s structure of concentric cylindrical shells separated by a foam matrix like the stem of some plants. -d- layered structure, a sort of multiple sandwich-panel, like the shell of the cuttle fish; it has orthotropic symmetry (Ashby 1990).
Figure 49 Microstructure of a cuttlefish bone
Source: Cadman et. al 2013

Figure 50 Cuttlefish
Source: https://wall.alphacoders.com

Figure 51 Bone of a Cuttlefish
Source: http://www.wikiwand.com

Figure 52 Surfboard | Source: http://www.petsprin.com
Engineering imitated nature and has already used this type of structures, mostly in aerospace engineering where structures need to be light - to reduce fuel usage- but are also stiff, strong and capable of absorbing mechanical energy in case of an impact.

The first ever honeycomb to be used in sandwich structures was patented in 1904 by D. Budwig and refers to the production of paper honeycomb (Figure 56). The first time such structure was used seeking for structural efficiency was in 1983 for the wings of the plane Havilland Mosquito bomber. Actually, WWII speeded up the development of such materials which evolved around the industry of aerospace engineerings. The first applications were based on wooden balsa cores glued to stiffer wooden faces (usually plywood). 1945 first all-aluminum sandwich panel was produced, made possible by the development of superior adhesives. In 1946 the first application of fiberglass honeycomb (Hexcel) on fuel cell support panels (Joyce 2003). One of the most advanced sandwich structures at the time was used in the aircraft B-58 in 1958 made out of duralumin alloy (Figure 57). First honeycomb applications had limited lifespan and posed extreme maintenance challenges. Wooden sandwich panels were not able to withstand micro organisms and tropical humidity. It was not until 1970 and the construction of the aircraft B-70 Valkyrie that sandwich panels were considered an ideal solution for aircrafts. This was made with titanium and brazed stainless steel honeycomb.
Figure 57 Convair B-58 Hustler scheme
Source: http://en.aviapro/blog/convair-b-58-hustler
The building industry used the expertise provided by the aviation industry to produce lightweight panels for roof, wall and floor applications. Depending on their use, they have to be stiff, air-tight, water-tight, insulating and especially lightweight. Typical applications include Sandwich panels filled with insulating foam such as EPS. Some of them have embedded rafters to be attached directly to the main structure of the building reducing expenses and labour related to substructure. Typical applications also include spandrel panels to be used in the spandrel area of a curtain wall. The function of those is purely structural as they have to be lightweight to reduce the frame size but also stiff to withstand the wind load. They are available in a plethora of finishes and usually consist of stiff faces and paper core. Last but not least, a typical application of the sandwich panels is the typical polycarbonate panel used in facades in a very simple curtain wall assembly.

Figure 58 Floor Sandwich solutions  
Source: http://www.normanton.co.uk/  

Figure 59 Roof and Facade Panels  
Source: http://www.archiexpo.com/
In figure 58 a number of floor systems that feature sandwich structures is presented. Some of them feature thermal insulation while others have integrated acoustic insulation. Their size is usually around 1x3m and is attached to a crate-like structure. They are available in a variety of thicknesses but are usually around 3-4cm. Thicknesses of 10cm and more are also available and are considered to be self-bearing in the sense that they are attached directly to the main structure.

Finally, sandwich structures are used more and more in furniture design. For instance, IKEA is a company that bases its designs on the principle of flatpack and aims to reduce the cost of furniture by reducing transportation costs. This is why making lightweight furniture is important and therefore, sandwich structures are used more and more.

Figure 60 5 euro-worth lightweight table. It features a honeycomb core. Source: https://www.buzzfeed.com
//2.10 Sandwich Theory

The development of cellular materials has rendered sandwich panels extremely popular and in the last 50 years there has been significant development if this field. But first we need to define what a sandwich structure consists of. This constitutes a type of structure that consists of two thin, stiff and strong skins, b) a thick and lightweight core that transfers the load from one skin to the other, and c) a layer of adhesive between that two that transmits the load from the skins to the core. It is essential that the adhesive layer be strong enough to not delaminate and guarantee structural integrity and rigidity. The purpose of this is to increase the moment of inertia of the panels and thus make it stiffer and stronger in bending. The geometry is very similar to that of an I Beam which consists of two flanges separated by the web (Figure 61).

Sandwich panels will have stiffness and strength criteria to meet. The stiffness of sandwich panels is straightforward to predict but it remains difficult to estimate the strength as well as the shear interaction between the 2 skins (Petras 1998). Triantallou and Gibson (1987) give a very good explanation of how to simplify a sandwich plate into a beam and see how it works. This is presented in Figure 62. When a load is applied this creates some bending deformation and some shear deformation. The addition of the 2 constitutes the total deflection. Also, the upper face is in tension while the skin at the bottom is in compression. The core is under shear stresses while spacing the skins and making sure that the whole structure performs in a homogenous way.
SKIN IN TENSION

CORE IN SHEAR

SKIN IN COMPRESSION

BENDING DEFLECTION depends on the Young’s Modulus of the skins

SHEAR DEFLECTION depends on the shear modulus of the core

Figure 62 contribution of each component based on Petras 1990

Figure 63 Total Deflection of a Sandwich Panel based on Petras 1990
As with every other structure deflections define stiffness and therefore, strength and serviceability. The former is a function of stiffness because the more a structure deflects, the less serviceable it would be. The latter depends on the the young’s Modulus of a Certain Material. But the best way to calculate a periodic sandwich panel is to simply ignore the core in bending and preform the so-called Homogenization (Devries et. al 1989). There are 2 types of homogenization: the simple laminate theory and the energy-equivalence method. The former describes a case where the complex geometry of a sandwich structure is simplified using a solid section of the same thickness but with a lower equivalent Elastic Modulus according to the equation:

\[ E \cdot I = E' \cdot I' \]

\( E \) = Young’s Modulus of Material  
\( I \) = moment of Inertia of the sandwich section  
\( E' \) = equivalent Young’s Modulus  
\( I' \) = moment of inertia of laminated section

_Failure Modes._

It was explained how we can simulate the behaviour of a sandwich panel by homogenization but how do we actually calculate a sandwich panel. First, we need to define the Failure Modes of a sandwich panel. Those are, Stiffness (Excessive deflections), Strength (Face Yielding), Panel Buckling, Shear Crimping, Skin Wrinkling, Intra-Cell Buckling, Local Compression.

Whichever of this modes happens first causes the failure of the structure. Let’s look at all of those failure modes.
It is essential that the panel have sufficient stiffness to prevent unserviceable deflections. e.g. people might get scared if a slabs deflects too much.

The stresses induced must not exceed the yield limit state of the structure. This counts for tensile, compressive and shear stresses and therefore it is important that the adhesive must be able to transfer shear loads between the core and the skins. In Glass, the panel is expected to break at the bottom where tensile stresses are induced.
When calculating the reaction forces, it is important to know what the buckling limit of the panel is under compressive load. The thickness and the shear modulus must be high enough to prevent buckling in a global scale.

3. Panel Buckling - Global

Figure 67 Panel Buckling | based on HexWeb 2000

As in panel buckling if the thickness and the shear modulus is not sufficient, the panel will fail from shear crimping.

4. Shear Crimping

Figure 68 Shear Crimping | based on HexWeb 2000
The core compressive strength must be sufficient to resist local loads on the surface of the panel. The panel can also fail if the compressive strength of the core is not enough to carry the load and buckles.

//2.11 Design of a Sandwich panel

How do we design a sandwich panel then? There are a number of steps that need to be taken and are presented in this chapter:

1. Define loading conditions

Initially, the loadcases need to be defined. What kind of load is applied? Only dead load? Live Load? Permanent Load?

How is the load distributed? Uniformly distributed load? End Load? Point Load?

2. Boundary Conditions and Panel Type

The support conditions of the sandwich panel need to be defined early on in the process.

Figure 69 Local Compression | based on HexWeb 2000
3. Define physical/space constraints

At this stage we need to assess the importance of the following parameters:

- Serviceability
- Thickness limit
- Weight
- Safety factors

4. Preliminary calculations

At first we need to make an assumption about the skin thickness and the panel thickness. At this stage the core material and geometry can be ignored.

**Calculate stiffness:**

\[ D = \frac{E_{fx}bt^3}{6} + \frac{E_{fx}btd^2}{2} + \frac{E_{cx}bc^3}{12} \]

and the third term accounts for only 1% if:

\[ \frac{d}{t} > 5.77 \quad \text{and} \quad \frac{E_{fx}t}{E_{cx}c} \left( \frac{d}{c} \right)^2 > 16.7 \]

- Calculate deflection (ignoring shear deflection).

To calculate the deflection we need to calculate the plate coefficients firsts:

\[ R = \frac{G_l}{G_w} \]

\[ X = \frac{a}{b} \]

\[ \delta = \frac{2K_1q b^4 \lambda}{E_f t_f h^2} \]

\[ \lambda = 1 - \nu^2 \]

- Calculate facing skin stress.

\[ \sigma_f = \frac{K_2 q b^2}{ht} \]
- Calculate core shear stress.

$$\tau_C = \frac{K_a q b}{h}$$

All calculations are calculated with a linear analysis.

5. Detailed calculations

- Check for panel buckling
- Check for shear crimping.
- Check for skin wrinkling.
- Check for intracell buckling.
- Check for local compression loads on core.

<table>
<thead>
<tr>
<th>Facing Stress</th>
<th>$\sigma_f = \frac{P}{2t_f b}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel Buckling</td>
<td>$P_b = \frac{\pi^2 D}{l^2 + (\pi^2 D / G_v h b)}$</td>
</tr>
<tr>
<td>Shear Crimping</td>
<td>$P_b = t_c G_v b$</td>
</tr>
<tr>
<td>Skin Wrinkling</td>
<td>$\sigma_{CR} = 0.5(G_v E_v E_f)^{1/3}$</td>
</tr>
<tr>
<td>Intra-cell Buckling</td>
<td>$\sigma_{CR} = 2E_f [t_f / s]^2$</td>
</tr>
</tbody>
</table>

Figure 70 Collection of formulae | source: presentation P. Joyce 2003

Figure 71 Slab description
6. Optimization

We cannot optimize a structure for multiple parameters. We need to select whether it is stiffness dominating design, strength dominating design etc. In our case, stiffness to weight is the most important index. When we compare materials, we select according to the index:

\[ E^{(1/2)}/\rho \]

But Young’s Modulus is a property of the material and not of the geometry. Optimization for sandwich structures is not an analytical process. It is a graphical process from which we can derive the thickness of the skins and the thickness of the core for a given density of the core. For that we need to employ a graphical solution. Let’s say that “l” is the length of the slab, “t” is the thickness of the skins, and “c” is the thickness of the core. We need to plot the diagram of t/l-c/l and hence weight-stiffness.

For that reason we need to define 2 constraints between the 2 factors. The first one is the stiffness constraint as the structure needs to be stiff enough to be serviceable.

The relationship between the two factors for the stiffness constraint is:

\[
\frac{(t/l)}{(c/l)} = \frac{2B_2}{B_1} \frac{G_c}{(c/l)E_f} \left( \frac{1}{(d/P/l)B_2bG_c(c/l)^{-1}} \right)
\]

\( G_c \) = Shear Modulus of the core
\( E_f \) = Young’s Modulus of skins
\( E_a, E_f \) = coefficients that depend on the aspect ratio of the dimensions
\( P \) = load
\( d \) = maximum total deflection

This plots as a curve
There is also the weight restriction:
\[
(t/l) = \frac{W}{C} - \frac{r_c}{2r_f} \times (c/l)
\]

\( W = \) weight,
\( r_f = \) density of skins
\( r_c = \) density of core

This plots as a straight line for a given weight or as parallel lines for different weights.

The optimum design point is found where the objective function (weight function) line is a tangent to the Stiffness Constraint. At this point the optimum (for minimum weight) values of face thickness, \( t \), and core thickness \( c \) for a specified stiffness can be read off the graph.

If the core density were to be considered a free variable then a series of graphs are plotted for successively high core densities, the optimum values of \( c \) and \( t \) and hence weights determined then the actual minimum weight found. In reality, these ‘optimum’ values lead to too large core thickness and too low core densities and some compromises are necessary for a realistic design.
This is a comparison between a laminate, an unoptimized sandwich and an optimized sandwich:

<table>
<thead>
<tr>
<th>Relative Thickness</th>
<th>1</th>
<th>1.2</th>
<th>2.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative Bending</td>
<td>1</td>
<td>0.25</td>
<td>0.025</td>
</tr>
<tr>
<td>Stiffness D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative weight/m²</td>
<td>1</td>
<td>0.345</td>
<td>0.177</td>
</tr>
<tr>
<td>Relative Homogenized</td>
<td>1</td>
<td>0.575</td>
<td>0.077</td>
</tr>
<tr>
<td>Bending Modulus</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E=12D/h²</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

//2.11 Sandwich Topologies / density of the core

Sandwich structure is a very generic term that describes this very efficient type of structure. However, there are many topologies concerning the formation, the density, and the geometry of the core. There is a certain classification according to Ashby and Timoshenko. Sandwich structures are divided into 2 categories, 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. (Figure 73). Haydn N.G Wadley in his paper titled “Multifunctional periodic cellular metals describes the different typologies. The text of this chapter is based on the aforementioned paper.

a) Punctual Support

Fully open cell structures can be created from slender beams (trusses) that in principle can be of any cross-sectional shape: circular (Deshpande & Fleck 2001; Chiras et al. 2002; Wang et al. 2003), square (Kooistra et al. 2004; Rathbun et al. 2004), rectangular, I-beam, or hollow (Queheillalt & Wadley 2005a,b). Evans et al in 2001 proved that according to the application, different trusses can be optimal. Punctually supported sandwich structures can also be subdivided into a1) textile and a2) truss-based cores. The latter also has a plethora of variations such as tetrahedral, pyramidal or three-dimensional kagome structures. K.U.Leuven’s research on lattice materials is pioneering in the field. Even though, the punctual support structures are not known to be the ones with the highest mechanical properties they are the struc-
tured allowing for maximum flow and for lowest relative density of the core. In the case of glass structures this also means that this type of structures could yield the most transparent result.

As far as truss cores are concerned, we can look for 3 different typologies: tetrahedral trusses with three trusses meeting at one face node, pyramidal lattices with four trusses meeting at one face sheet node and Kagome 3d trusses initially presented by Salvatore Torquato at Princeton and refers to a very complex yet very efficient structure.

Insofar as textile lattices are concerned, this is a very popular method of building sandwich panels with wires. This production can be automated with the use of contemporary techniques that allow for weaving wire around rods. Compared to the textile approach, it is more straightforward to maintain the cell alignment throughout the structure at low relative densities. Moreover, hollow tubes can be used instead of solid wires and this enables very low-density lattices to be achieved and truss compressive buckling strengths to be increased by increasing the truss moment of inertia (Wadley 2006).
Homogenous support of the skins
- open cells
- closed cells
- no cells
- Foam cores

Punctual Support
- fully open
- Textile cores
- Truss cores
- Pin cores

Regional Support
- Open to both sides
- Cup shaped cores
LITERATURE STUDY

Unidirectional Support
Open to one side
Corrugated cores

Bi-directional Support
Only open in thickness direction
Honeycomb cores

Non-Homogenous Support of the skins
a) Homogenous Support of the Skins

This type of sandwich panels is used when low-cost production is the main requirement. The main consequence is that the mechanical properties are low. For instance, one can easily compare foams to honeycombs and other topologies in Figure 74 as per strength and stiffness to density. In all properties, homogenous structures stand lower than other topologies. In case of glass structures, this represents the complete laminate.

b) Unidirectional Support of the Skins

This is the type of core that is open to only one dimension. It is the same as rotating a honeycomb by 90 degree, resulting into a prismatic structure. It is most probably the easier one to produce but it has rather low mechanical properties transverse to the corrugations and for that reason, the support conditions are also important. Usually, it is produced by corrugation or by extrusion depending on the material. Prismatic Topologies are divided into 2 categories, namely a) dependent to the thickness and b) independent to the thickness, based on whether the cell’s size of the corrugation depends on the thickness of the panel or not.

b) Bidirectional Support of the Skins

These are also known as honeycomb cores and there is extensive literature covering all topics related to it for a variety of materials. In literature, the term “honeycomb” is not only used to describe the well-known hexagonal pattern but all core topologies that support the skins bi-directionally, are open only in the direction of the thickness and are considered to be isotropic. There is a variety of different geometries ranging from triangular patterns to very complicated shapes. Even though, it is the geometry that provides very good shear stiffness but not equally good compressive strength. Due to the low thickness of the walls, the may buckle.
The production method usually used to produce expanded honeycomb creates some anisotropy because the wall thickness is doubled in one direction only. Unfortunately, this cannot be done with glass. However, available techniques such as water jet cutting can cut intricate shapes out of glass. Figure 76
Figure 78: Honeycomb by cutting the glass section. http://www.computercut.com.au
b) Regional Support of the Skins

This type of structure is usually used in the automotive industry and the packaging industry. The most common geometries are usually produced with thermoforming e.g. cup-shaped core layer. This topology has some very pronounced advantages and disadvantages. The regional support creates almost punctual loads that may result in detrimental stress. However, they provide a very good contact surface, facilitating production but most importantly improving the connection between top and bottom skin and enhancing shear transfer.

//2.12 Precedents

Glass is a relatively new structural material and there is not much development concerning glass sandwich structure. Because, adding a spacer for separation between 2 panels is totally different to basing the whole structural behaviour of the panel on a sandwich structure. However, there are certain examples of such structures that prove the relevance of this research but also reveal that there is a potential for lightweight and stiff transparent panels.
1. The Glas-Sandwich-Aluminiumprofile

This sandwich panel was made in 1998 by the Institute für Stahlbau in Aachen. This panel is supposed to be used in window applications with high wind-loads.

The information below is presented in the website www.facadeworld.com

“Concept: By bounding the panels and the aluminium cubes, the loading capacity can be remarkably increased, another aspect is controlling privacy and sunscreens.

In this project, an aluminum cubes with dimension 4*4 cm were glued in the space between the glass panes. The result is 3*3 m insulating glass pane of normal window glass.

what is really remarkable in this solution is the simple manufacturing process for this simple elements, also the ability to adopt to different load requirements, such as wind loads on tall buildings, due to the full control of the aluminum cubes distribution.

Construction: The aluminum cubes distribution in the space between the glass panes allow the optimum absorption of the shear forces. The connections between the glass and the metal profiles were fixed by transparent high-performance double sided tape.

A variation of the way the panel looks were granted by alternating arrangement of the aluminum cubes. the entire panel was rounded with a moisture absorber pressure chamber, in order to avoid any condensation from the air.” (www.facadeworld.com, retrieved in 2016)

Figure 80 The Glas-Sandwich-Aluminiumprofile
Source: www.facadeworld.com
2. The Glass-Sandwich-wooden boards

A similar was made by the same group and uses wood for spacing the glass panes. The information below is presented in the website www.facadeworld.com

“The reason behind this studies were to find a new creative possibilities for glass sandwich constructions.

By bounding the panels and the fins, the loading capacity can be remarkably increased, another aspect is controlling privacy and sunscreens.

The result is a 3*3 m insulating glass pane of normal window glass, which absorbs the necessary loads through the wood pieces that had been used.

Construction: A wooden fins were arranged in the space between the insulating glass pane to assurance the optimum absorption of the shear forces. In addition two wooden fins placed on the bottom of the glass pane forming a web, these were filled with transparent silicone to transfer the shear forces from the fins to the glass. the upper part connected by transparent high performance double tape with extra Plexiglas bars. the entire panel was rounded with a moisture absorber pressure chamber, in order to avoid any condensation from the air” (www.facadeworld.com, retrieved in 2016)
3. MULTIFUNCTIONAL GLAZING PROTOTYPE FOR COMPOSITE INSULATING GLASS UNIT WITH INTEGRATED SOLAR SHADING, 2002–2003

This is a very interesting project, inspired by Christof Helmus and Marc Mevissen. The beauty of this project is that it integrates climate regulating conditions. Two glass panes are structurally bonded to GFRP profiles of different section. The result is a much stiffer panel with 25mm thickness. “The structural performance of the composite elements is largely dependent on the stiffness of the pultrusions and the adhesive, the layer thickness of the adhesive and the distance between profiles. For a given load, reducing the profile height, the shear modulus of the adhesive, the adhesive thickness or the number of profiles leads to higher stresses in the glass and hence to a higher probability of failure.” (Wurm 2007). In order to prove the assumption the 5 different elements were tested in a 4-point bending test. The deformation reached prior to failure was 140mm which accounts for the 1/20 of the span. What is also important to mention is that the tension-stressed element broke, the panel kept carrying increasing load even after significant deformation.
4. VACUUM GLAZING

Vacuum glazing is a type of IGU that offers very high insulation values with minimum thickness. The cavity between the panes is narrow and therefore, when the cavity is evacuated the 2 panes tend to touch each other and this is highly undesirable. For that reason, there is an array of spacers that alienate the panes from each other. In order to not create destructions and not disturb transparency, the spacers are really small in size and as few as possible. They are usually cylindrical in shape and made out of polymer. Other shapes are also available such as spherical or cross in section. Their size is usually half a millimeter in diameter and arranged in a square array of 20-50mm. Those spacers act as thermal bridges, influencing the thermal conductivity of the unit. Finally, it is also worth mentioning that the small diameter of the spacers creates some punctual loads which may result in detrimental stresses.
5. OKALUX PRODUCTS

OKALUX is a German company specializing in glazing solutions with integrated climate regulating solutions. Their products are designed to fit standardized curtain walls and the thickness of the panels is such that it fits the standard aluminium frames. They offer non-structural glass sandwich panels with opaque, translucent or capillary spacers that act as shaders, diffusers or simply as facade textures. This does not constitute a structural application though. Most of those products are design-based and are meant to be beautiful, to redirect or diffuse light etc.

Figure 86 OKALUX products
Source: http://www.okalux.de, retrieved in 2017
6. BERKELEY HOTEL FACADE - GLASS HONEYCOMP PANEL

This constitutes an extremely interesting application that stretches the limits of the material by applying an innovative solution to an actual building. In this application, glass was chosen because of its texture and durability. However, the GFRP structure that supports the panels needs to be as slender as possible and for that reason the panels have to be relatively lightweight. At the same time, the architect designed a rather diffusing panel which is translucent and not transparent. To sum up the requirements were high specific stiffness and a texture that diffuses light and protects privacy.

Panels are composed of two sheets of glass structurally bonded to a microperforated aluminium honeycomb core by means of a 1.0 mm thick continuous layer of UV-curing transparent acrylic adhesive, creating a true structural composite panel with a peculiar translucent look (Teixidor 2010).

For the core, a microperforated aluminium honeycomb is used for effective shear transfer which is glued to the 8mm fully tempered glass panes by means of an 1.0 mm thick continuous layer of UV-curing transparent acrylic adhesive. This adhesive, climbs to the honeycomb walls by capillarity and creates a safe connection. Also, 2 acrylate lenses per cell are added so as to distort the image you get when you look through the panel. The biggest panels that were produced are 4.85 x 2.30 m in size with a thickness of 25mm. for the roof panels and 87mm for the facade panels.

Figure 87 Glass Sandwich Panels of Berkeley Hotel
Source: Teixidor 2010

Figure 87 Glass Honeycomb panel
Source: Teixidor 2010
Even though after breakage glass stays attached to the honeycomb, in the approachable panels, laminated glass with PVB is used for safety and in order to pass the tests. Extra care was taken to find the best adhesive to be used in terms of strength, optical quality and emissions. “The more viscous an adhesive is, the more difficult it is to remove any air bubbles trapped during production. However, low viscosity adhesives tend to emit higher quantities of acrylic vapour during curing which might create condensations that cause undesired permanent textures and tears on the adhesive layer” (Teixidor 2010). Finally, to secure safety and structural behaviour of the panels, a number of tests were conducted:

- Yellowing of adhesive specimens after a 2000 h irradiation in a sunlight simulator.
- Chemical compatibility of the adhesive with all perimetral sealing materials.
- Fogging of units under sudden temperature changes.
- Moisture ingress through the perimetral seal and/or pneumatic conduits.
- Effect of cyclic temperature variations on the glass-honeycomb bond.
- Tensile resistance of aged glass-honeycomb specimens.
- Compression resistance of glass-honeycomb specimens.
- Bending resistance of aged glass-honeycomb specimens.
- Cyclic bending resistance of glass-honeycomb specimens.
- Long-time bending behaviour of the glass-honeycomb sandwich (creep).
- Impact and post-breakage behaviour according to CWCT Technical Note 42

(Teixidor 2010)
In this Chapter, the Initial Design is presented with an emphasis on the case study. The case study is chosen and the foundations of the Research by Design part of the research are set. This part is separated from the rest of the design process so as to illustrate the difference between the initial concept and the Final application.
INITIAL DESIGN
In this chapter, the design task that is related to the research is presented. Even though I see a high potential in roof and facade elements, the one that is most challenging structurally, the floor element, stood out to me. As far as stiffness to weight is concerned, floor elements are extremely demanding because they have to withstand the live load of people as well as the self-weight of the panel. Also, a lightweight panel could save a lot of material from the supporting structure. Hence, a case study was chosen, able to highlight the potential of such a structure. I chose to elaborate on the glass floors of the Acropolis Museum, make them lighter and more transparent.

//3.1 The Acropolis Museum and why?

The Acropolis Museum (Figure 89), designed by Bernard Tshumi, opened to the public on 20 June 2009 and constitutes one of the most disputable yet important contemporary buildings. The whole building lies on top of some archaeological excavations (Figures 90, 91) and features a number of glass floors through which people may look at the ruins (Figure 92). The design of the floors is rather conservative. It features, 4x12mm glass panes supported by a crate-like structure that consists of 300x550mm hollow steel beams in an array of 2.4x1m
Figure 90 The Archaeological Excavations
Source: personal Archive

Figure 91 The building lies on top of some ruins of ancient Athens. Some of them are also from the Byzantine period
Source: https://www.yatzer.com

Figure 89 The Acropolis Museum
Source: http://www.lindiceonline.com
The glass floors of the museum. The one on the left acts also as a bracing structure between the columns and is made of 90cm-high concrete girders while the one on the right is the one was described before.

Figure 92 Glass Floor with steel beams
Source: http://www.gettyimages.co.uk

Figure 93 Section of the museum
Source: archive of the municipality of Athens
Figure 95 shows the current situation of the glass floor that is presented in Figure 92. In both figures, one can see why the glass floor is not really transparent. In fact, it is really rare to see ruins in an ancient city context, in their real scale and this floor fails to deliver that result. It provides a fragmented view of the excavations and it is a pity that this way, people cannot perceive the scale of an ancient city. The new proposal will substitute the metal-glass structure with glass sandwich elements.

| Table 2: Vertical deflections: Values from Table 8 of BS 5990: 2000 |
|--------------------------------------|----------------------|
| Member supporting partition walls   | Vertical area deflection Calculated from load = imposed loads |
| - Bored after reinforcement         | ≤ 1/300              |
| - Reinforced                        | ≤ 1/300              |
| - Reovable                          | ≤ 1/300              |
| Ceilings                            |                       |
| - Plastered                         | ≤ 1/300              |
| - Surrounded                        | ≤ 1/300              |
| Roofs and flooring                  |                       |
| - Rigid (e.g. ceramic tiles)        | ≤ 1/300              |
| - Flexible (e.g. flexible floor covering) | ≤ 1/350          |

**Table 6.1 – Categories of use**

<table>
<thead>
<tr>
<th>Category</th>
<th>Specific use</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Areas for domestic and residential activities</td>
<td>Rooms in residential buildings and houses, bedrooms and wards in hospitals, bedrooms in hotels and hostels, kitchens and toilets.</td>
</tr>
<tr>
<td>B</td>
<td>Office areas</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Areas where people may congregate (with the exception of areas defined under category A, B and D)</td>
<td>G1: Areas with tables, etc. e.g. areas in schools, cafes, restaurants, dining halls, reading rooms, receptions. G2: Areas with fixed seats, e.g. areas in churches, theatres or cinemas, conference rooms, lecture halls, assembly halls, waiting rooms, railway waiting rooms. G3: Areas without obstacles for moving people, e.g. areas in museums, exhibition rooms, etc. and access areas in public and administration buildings, hotels, hospitals, railway stations, forecourts. G4: Areas with possible physical activities, e.g. dance halls, gymnasium rooms, stages. G5: Areas susceptible to large crowds, e.g. in buildings for public events like concert halls, sports halls including stands, terraces and access areas and railway platforms.</td>
</tr>
<tr>
<td>D</td>
<td>Shopping areas</td>
<td>D1: Areas in general retail shops. D2: Areas in department stores.</td>
</tr>
</tbody>
</table>

*Attention is drawn to 6.3.1.1(2), in particular for C4 and C5. See EN 1990 when dynamic effects need to be considered. For Category E, see Table 6.3.\(^{11}\) NOTE 1: Depending on their anticipated uses, areas likely to be categorised as C2, C5, C4 may be categorised as C5 by decision of the client and/or National annex.

**Table 6.2 – Imposed loads on floors, balconies and stairs in buildings**

<table>
<thead>
<tr>
<th>Categories of loaded areas</th>
<th>( Q_f ) [kN/m²]</th>
<th>( Q_v ) [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Floors</td>
<td>1.5 to 2.0</td>
<td>2.0 to 3.0</td>
</tr>
<tr>
<td>- Stairs</td>
<td>2.0 to 4.0</td>
<td>2.0 to 4.0</td>
</tr>
<tr>
<td>- Balconies</td>
<td>2.5 to 4.0</td>
<td>2.0 to 3.0</td>
</tr>
<tr>
<td>Category B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Floors</td>
<td>2.0 to 3.0</td>
<td>1.5 to 4.5</td>
</tr>
<tr>
<td>Category C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- C1</td>
<td>2.0 to 3.0</td>
<td>3.0 to 4.0</td>
</tr>
<tr>
<td>- C2</td>
<td>3.0 to 4.0</td>
<td>2.5 to 7.0</td>
</tr>
<tr>
<td>- C3</td>
<td>3.0 to 5.0</td>
<td>4.0 to 7.0</td>
</tr>
<tr>
<td>- C4</td>
<td>4.5 to 5.0</td>
<td>3.5 to 7.0</td>
</tr>
<tr>
<td>- C5</td>
<td>5.0 to 7.5</td>
<td>3.5 to 4.5</td>
</tr>
<tr>
<td>Category D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- D1</td>
<td>4.0 to 5.0</td>
<td>3.5 to 7.0</td>
</tr>
<tr>
<td>- D2</td>
<td>4.0 to 5.0</td>
<td>3.5 to 7.0</td>
</tr>
</tbody>
</table>

**NOTE:** Where a range is given in this table, the value may be set by the National annex. The recommended values, intended for separate application, are underlined. \( q_v \) is intended for the determination of general effects and \( Q_v \) for local effects. The National annex may define different conditions of use of this Table.
Figure 95 Schematic section and plan of current situation.
Figure 96 Schematic section and plan of the proposal
The element is dimensioned according to Eurocode 1: Actions on structures - Part 1-1: General actions - Densities/ Chapter 6: Floors. Insofar as category of use is concerned, theoretically the structure belongs to category C3 which refers to museums. However, people choose to stand on top of glass floors and look down and therefore, crowds of people should not be considered as moving. So the application falls into Category C5, susceptible to large crowds. Initially, the element was dimensioned following the "Design Manual" discussed in the previous chapter. So, using rules of thumb and by considering the stiffness of the core negligible I resulted in a predimensioned element (stiffness to weight mode), which I later checked for other Failure Modes. The result is a bi-supported element with a face thickness of 8mm and total thickness of 140mm.

Figure 97 3d visualizations of the new glass floor
$q = 5 \text{KN/m}^2 + \text{dead load}$

Dimensions:
- Length: 7.2m
- Width: 3m
The panel will be made out of SCHOTT extruded cylinders which will be cut carefully in size. This is the most labour-intensive as, in order to make sure that all cylinders will have the same height, they will be subject to meticulous grinding. However, ordering custom profiles is possible and therefore, in a possible industry application, cylinders could be ordered in the desired size. Hence, even though it constitutes a labour-intensive and time-consuming process, I believe it is worth exploring the potential of such an application.

Regional Support of the skins

This panel will be made by industrially produced glass vessels. It is the easiest one to make and therefore the one that is easier to experiment with.

Punctual Support of the skins (Truss)

For this panel, the SCHOTT cylinders will be cut in size and chamfered in an angle. This is not possible to manufacture with the available means and therefore they will be constructed by LIS.
Uni-directional Support of the skins

In order to produce this panel, SCHOTT profiles will be used and placed in the panel as spacers. This is much easier to produce than panels 1 and 3 as no meticulous adjustments need to be done. However, extra care needs to be taken as far as the eccentricity of the profiles is concerned.

Uni-directional Support of the skins

This panel is very similar to panel No5 but it consists of more profiles glued to each other so as to provide better shear interaction in the y direction. The purpose is to explore if stiffness is increased so much to overpower the extra weight added to the core.

Bi-directional Support

The purpose of this is to explore honeycomb-like structures. One of the 2 following options will be selected: a) Water-Jet cut pattern, b) Rectangular float glass elements that form a rectangular honeycomb.
In this chapter, the whole process that led from the initial to the final design is presented. This constitutes the main body of the Research and includes the preparation of the very first specimens, the bending tests, the calculation methods, the manufacturing process etc.
INITIAL -> FINAL DESIGN
3. INITIAL → FINAL DESIGN

In this chapter, the process that leads from the initial design intent, presented in the previous chapter, to the final design decisions. These decisions guided the second part of the research in a Research by Design approach.

This section constitutes a very important part of the research as the concept is proven and the potential is clearly showcased. At the same time, a clear design method is defined, divided into 3 main steps: a) A graphical method to predimension the panels, b) A finite elements model to accurately assess the structural behaviour of the panels and c) the bending test that evaluates the numerical and hand calculations. All these were developed and tested and therefore are presented in this chapter followed by clear conclusion.

//3.1 Substitution

Later in the process and after some meticulous and systematic evaluation of all criteria, some of the six panels that were presented in the previous chapter were supplanted by other topologies, strictly adhering to the strategy of experimenting with all different sandwich core topologies. The panels were substituted due to unaffordability or construction difficulties by some other panels that were cheaper or easier to produce. Some items sold in the market, that could be used were found and used as spacers.
Criteria for selection of spacers:

- Price
- Tolerances
- Accommodate topology

Price constituted one of the main criteria regarding the selection of spacers. The specimens had to be relatively cheap and easy to make. Therefore, panels 3 and 4 were not produced due to unaffordability.

Tolerances constitute one of the important criteria. The acrylate adhesive cannot even out tolerances and therefore all the spacers had to be measured carefully and polished to fulfill the criterion of tolerances. The quantity of glass used in glass vessels, bowls and candle holders that are massively produced is carefully determined and therefore the accuracy is higher than that of float glass.

Most importantly, all the topologies had to be tested and therefore all spacers had to be able to provide one of the following types of support: a)punctual, b) regional, c)linear, or d)bidirectional.
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.

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.

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
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
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
Figure 102 Collection of spacers
3.2 Construction of panels

Spacers are not simply glued to the panels. Some meticulous preparation is needed to guarantee that glass is glued properly and that surfaces are free of grease and dust.

Regardless of the type of spacer 3 steps are followed. In some cases, an optional 4th step is followed, that of glueing 2 spacers together. In general, the 4 processes followed are:

1. Cleaning grease and dust with propanol. This process is extremely important in order to make sure that the pieces are glued properly and the product will not exhibit adhesive failure.

2. Acrylate adhesive is applied carefully on the surface that is glued first. DELO Photobond is stronger than glass and fails under higher stresses.

3. The spacers are glued to the glass panels with UV Curing glue. Initially, the adhesive cures for 5 seconds which is enough to secure the spacer at its place. At this point extraneous glue that flows out of the glueing zone is cleaned with a cloth. That way, high optical quality is ensured. Then, the glue cures for another 45 seconds so as to make sure that adhesion is strong.
PANEL 3
**Panel 4**
PANEL 5
3.3 Design of panels - FEA with Trial and Error

There was only one chance to test the panels in the lab and therefore careful design was needed in order to make sure that panels can be compared and lead to certain conclusions. Apart from the efficiency of the different topologies, some other parameters needed to be tested:

- a) The contact surface between spacer and skins,
- b) The influence of thickness in stiffness and strength
- c) The influence of core density
- d) The influence of shear interaction
- e) The after breakage behaviour of the panels

Having searched the market for a number of spacers, the next challenge would be to distribute the spacers in the core and design the panels in such a way that they can be compared according to the aforementioned characteristics. In order to understand the structural behaviour of the panels Finite Elements Analysis was employed in a trial and error process in order to spot peak stresses and figure out what is the relationship between stress and strain.

Figure 104 Initial FEA Model
The bottom skin is in tension inside the bending zone which proves that the panel exhibits sandwich behaviour.

The top skin is in compression inside the bending zone.

Stress concentration around the supports. This is where the highest normal stresses are induced.

Highest principal stresses outside the main bending zone. It is clear that stresses are concentrated around the spacers.

Edges of the panel move up.

Telegraphing effect between spacers.

Center of the panels exhibits the highest deflection moving down.

Figure 105 Analysis of the first outcome
Maximum Principal Stresses

Figure 106 Analysis of the first outcome_2
Total Deformation
This preliminary FE Analysis gives a first impression on how each spacer would perform. For instance, as shown in Fig 108, it is safe to predict what the influence of the density of the core as well as its geometry would be. A well defined model can yield safe results concerning where peak stresses may be introduced.

A triangulated mesh yields more accurate results and provides a smooth transition between the skin and the spacer. The contact surface between them is modeled as 'bonded’. The adhesive is not modeled so as to simplify the FE model.

On account of the geometry of the spacer, the panel on top exhibits better shear transfer than the panel at the bottom. Hence, low shear interaction between top and bottom skin creates tensile stresses at the top skin and therefore the panel does not behave like a sandwich.

This preliminary FE Analysis gives a first impression on how each spacer would perform. For instance, as shown in Fig 108, it is safe to predict what the influence of the density of the core as well as its geometry would be. A well defined model can yield safe results concerning where peak stresses may be introduced.

A triangulated mesh yields more accurate results and provides a smooth transition between the skin and the spacer. The contact surface between them is modeled as 'bonded’. The adhesive is not modeled so as to simplify the FE model.
The Finite Elements Analysis cannot be conclusive concerning the way spacers are distributed in the core. What is more, the trial and error process may be time-consuming especially when the desired results are not delivered in the first few tries. For that reason, a method to predimension the panels would facilitate and speed-up the process of designing glass sandwich panels. Hence, a graphical method based on the sandwich theory is employed. In general, the whole process of designing a sandwich panel follows a very clear and linear path from the initial analytical dimensioning to the final evaluation with bending tests. More specifically:

1. Graphical/Analytical Method (pre-dimensioning)
2. Finite Elements Method (Accurate dimensioning)
3. Bending Tests Method (Evaluation)

The 3 said methods will be described in the following chapters

//3.4 Graphical/Analytical Methods

When designing a sandwich panel, there are certain parameters that can be either considered as free variables or givens depending on the process that is followed. The main free variables are a) the thickness of the core, b) the thickness of the skins and c) shear interaction between top and bottom skin. The latter is in turn a function of the geometry of the core, the density of the core and also the thickness of the core.
Figure 109 Sandwich behaviour. Shear Interaction between the 2 skins
The shear interaction - the way shear is transferred between the top and bottom skin - plays an extremely important role regarding whether a structure behaves as a sandwich or as simply 2 connected panels. Timoshenko described this with the term "sandwich behaviour". The higher the sandwich behaviour, the more efficient the panel is. Hence, one can easily understand why the core topology and the core geometry are so important.

The shear interaction depends also on the thickness of the core. Simply, the thicker the core is the lower the shear interaction. On the contrary the higher the density of the core is the better the 2 skins interact with each other. However, in the case of all-glass sandwich panels, a thicker core would lead to a less transparent panel and therefore to lower optical quality. For that reason, a graphical method is employed in order to predimension the panels taking also into account the weight constraint.

\[
(t \circ G)(c) = \frac{2B_2}{B_1} \times \frac{1}{cE_iE_c^3} \times \left( \frac{1}{\frac{(d/P/l)}{bG(c)-1}} \right)
\]

Thickness of the skins as a function of the thickness of the core and the shear modulus of the core

Thickness of the core

Stiffness constraint

Shear interaction as a function of the core thickness
Theory dictates that a two-fold increase of the core thickness would lead to an eight-fold increase of stiffness. However, this implies a 100% shear interaction between the skins. As explained before, in reality shear interaction influences the rate of stiffness increase and has to be controlled. One way to figure out the shear interaction is with simple Finite Elements with the Timoshenko method.

The panel is modeled as follows: The bottom place is fully fixed and therefore not allowed to move or rotate. A Load P is applied in-plane on the top surface and by measuring the directional strain in certain points of the panel the shear modulus of the core can be easily determined. A simple increase in the thickness of the core results in an exponential decrease of the shear interaction between the bottom and the top plate. A 2-fold increase in the distance between two consecutive spacers results in a 2-fold decrease of the shear modulus. What is also worth mentioning is that the array of spacers influences also the way shear stresses are distributed. This is also checked in a number of bending tests. A triangular array in an -X- formation is known to provide better resistance in local buckling from end loading.
\[ t(c) = - \frac{1}{2} \frac{\rho_c}{\rho_f} (c) + \frac{W}{C} \]

Thickness of the skins as a function of the thickness of the core.

The green parallel lines in the graph represent different magnitudes of the weight constraint. The slope of the Weight constraint depends on the density of the core and the density of the skins and more specifically on the ratio density of the core/density of the skins. These are generally free variables when designing a sandwich panel but in the case of this thesis, the thickness of the core is design-specific. Hence, with this graphical method it is easy to predimension the panels before going in depth with Finite Elements Analysis.

In this thesis, the thickness of the core is in fact a given as the core spacers are commercially available products. Following the reverse process the density of the core and the density of the skin can be defined and therefore the distribution of spacers and the thickness of glass can be determined respectively. The graph verifies that when the thickness of the core increases, the density must increase to keep the level of the shear modulus the same.
The analysis is more accurate but also more complicated if the strength constraint is introduced. It is thought worth mentioning that for higher skin thickness and lower core thickness the panel fulfills the strength requirement but is not stiff enough. On the contrary, for higher core thicknesses and lower skin thickness the panel might be serviceable but not strong enough. Hence, it is clear that the design should be in the safe region (marked with green colour in the graph).

3.3 FE Method

The graphical method provided an insight concerning the pre-dimensioning of the panels. However, an accurate analysis should be made with Finite Elements in order to spot where local stresses are induced. The diagram below shows the final method used to model the glass sandwich panels.
In this sub-chapter, the analyses of the 7 different panels are presented along with a stress-strain diagram generated by the FEA Software Ansys Workbench. This is compared with the diagram generated by the bending tests so as to find out to what extent they correlate.

As expected, this topology performs very well structurally. The highest deformation is in the middle of the panel. In this panel, the highest stresses are induced in the core due to concentration of shear and normal stresses. After the core breaks the whole panel is expected to instantly fail.
What is very interesting about this topology is that the orientation of the spacer affects the way shear is transferred and therefore affects the deformation and the strength of the panel. Multiple formations are possible. As in the case of the previous panel, the highest stresses are induced outside the loading zone, on the spacer. Hence, the panel is expected to exhibit core failure before skin failure.
As shown in the Force-Deformation graph, this panel does not perform well structurally. It exhibits an early deformation. It is designed deliberately in such a way that shear transfer between the bottom and the top skin is exceptionally poor. Hence, it is expected to fail under lower loading.

Optically, this is one of the most delicate solutions as the optical distraction is minimal on account of the small size of the spacers. However, as it was mentioned before, the punctual support creates some stress concentration and therefore failure of the panel.
Even though the 2 panels feature the same core geometry, their behaviour is dramatically different. Theory dictates that a 2-fold increase of the core thickness will result in a 8-fold increase of the stiffness. However that is not the case since the shear modulus of the core decreases as well.

It is also worth mentioning that the thicker panel is not stronger on account of the telegraphing effect according to which the surface becomes dimple and exhibits higher strain close to the spacers. This proves that increasing the thickness of the core is not enough. A redistribution of the spacers might be needed or even an addition of spacers to increase also the density of the core.
This panel gives the best stiffness to weight ratio when supported bidirectionally. This is because shear is transferred exceptionally well in the longitudinal direction. Hence, it is only natural that the maximum principal stress is induced at the bottom plate, right in the loading zone.
The geometry of the core is directly comparable to the geometry of panel 6. This spacer provides higher contact surface and therefore the panel is stronger and stiffer. However, due to the bigger volume of the spacer, the panel is also much heavier. This would have an influence on the costs, the embodied energy and the dimensions of the substructure.
Comparing the panels gives the expected results as described in literature. Bidirectional support provides the best shear transfer, resembling the behaviour of the honeycomb core. Unidirectional support comes second providing slightly worse shear transfer. Panel number 2 exhibits a very good structural behaviour, supporting regionally the skins. Finally, punctual support of the skins is a very risky topology when it comes to glass sandwich structures as stress concentration occurs.
### 3.3 Bending Tests

In order to check the accuracy of the Finite elements Analysis, a 4-point bending test was chosen. In contrast to a 3-point bending test it provides regions of pure bending and pure shear and thus facilitates the evaluation of the results. The setup that was used is presented in Figure 124. Well-behaving panels are expected to be penetrated by the support which is acting directly at the bottom plate. A 3-point bending test would introduce a point of highest bending stress right in the middle. This would be like forcing the panel to break at this point.

Figure 124 4-point bending test
As mentioned before, the panel exhibits 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. Same is the behaviour of panel no.2. The “problem” with this particular topology is that the part between the 2 spacers is exposed to double curvature creating very clear weak and strong areas in the panel, which should be taken into account.
The panel breaks directly at the support. The fracture pattern has the exact dimensions of the support.
These 2 panels are comparable in the sense that they are the only 2 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 2 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.
Penetrated by the support and breaks right next to the core spacer.
Breaks between the loading zone and the supports due to telegraphing

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, more specifically 5KN. 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.
INITIAL --> FINAL DESIGN

Better Shear trans-
Better Force distribution

INITIAL-->FINAL DESIGN
Figure 125 Deformation-Force Diagram /Bending Tests
Observations:

Looking at the two following diagrams 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-lamm 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 panels withstood 8 times the load. Furthermore, it is worth observing the behaviour of the 2 panels 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.

Figure 126 Stiffness/Weight in Logarithmic Scale
Conclusions after the first set of tests and calculations:

- **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.

- **Most panels broke closer to the support** which is where higher stresses are induced, directly at the bottom plate.

- Comparing panels 5-6 we see that shear interaction is as important as 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 changes 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 that 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.

Figure 127 Bending Test. Warningless Breakage
Qualitative: Optical quality
Design potential for future purposes
Controlled transparency

Quantitative: Stiffness/Weight ratio,
Manufacturing time
<table>
<thead>
<tr>
<th>Qualitative:</th>
<th>Initial</th>
<th>Final</th>
<th>Final</th>
</tr>
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<tbody>
<tr>
<td>Optical quality,</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Design Potential</td>
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<td>1</td>
<td>1</td>
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<tr>
<td>Selective Distraction</td>
<td>2</td>
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<th>Quantitative:</th>
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<tbody>
<tr>
<td>Stiffness/Weight ratio</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Manufacturing time and complexity</td>
<td>2</td>
<td>3</td>
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</table>

**Figure 128 Comparison of panels**

**PROCEED WITH:**
- Optimisation
- Building integrations
- Anisotropy
Relative Comparison:

From all 7 topologies one was chosen to be elaborated on. The topologies are compared according to the aforementioned criteria and are relatively 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 author referred to the case study in order to define which topology should be used for this particular design. The one 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.
In this chapter the Final Design is presented. There is a significant number of design considerations to extrapolate the sandwich principle to a glass floor from the anti-slip coating that needs to be added to the construction details and the way tolerances are accommodated. Finally, all the structural applications are made to check on the structural integrity of the glass floors.
FINAL DESIGN
After the desired topology was defined, a number of design choices are made. This part of the graduation project would be described as Research by Design as research is based on Design choices. Hence, the final floor design was made based on the results yielded by the first part of the research. At the same time, a significant number of new questions arise such as: How can safety be implemented? How do the 3 methods described in the previous chapter apply to the glass floor? How will the sandwich panel be integrated into the existing setting of the Acropolis Museum? In this chapter, the answers to the aforementioned questions are presented.

//4.1 Final Design

The particularity of the Acropolis Museum glass floors is that they hover over a number of archaeological excavations. Therefore, 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.
Small Void between girders
Concrete Columns of the Acropolis Museum

Connection between two consecutive panels
Glass Sandwich Panels with Spacers arranged according to the outline of the artifacts
As mentioned before, the glass floors of the museum have received some critics concerning their transparency. The visitors wish they were able to see the old city of Athens and conceive the actual scale of the monuments. For that reason, 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. That way, the users can conceive the bigger scale of the city while being able to walk in the borders of an ancient house at the same time.

This cannot be materialised just by placing the spacers arbitrarily in the panel. Hence, defining some patterns with which the panel can be constructed is essential. Then the panel should be dimensioned based on the graphical method and then should be validated using FE.

Since the dimensions of the spacers are known, it is easier to define such patterns. However, the thickness of the core is not always a given and therefore multiple stiffness curves should be plotted associated with different core densities to find a range of values that is suitable. Then, with a given density it is easier to define the thickness of the core and the thickness of the skins.

Insofar 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. What is more, even though fully-tempered glass is stronger, it breaks in very small shards and therefore cannot carry any load after breakage. Hence, the only safe solution is heat-strengthened 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.
Projection of the artifacts on the level of the glass floor

Outline of the artifacts

Figure 131 Projection of artifacts

Figure 132 Early Sketch of the projection
The densification of the spacers is materialised according to the artifacts under it. But what about the slip-resistant treatment that should cover the floor to render it accessible? There are many different types and shapes of slip-resistant coating. The method that is most commonly used is sandblasting. However, this would not be ideal for this situation where transparency plays a major role. Hence, glass fritting would be the ideal solution. The existing glass floor features black frits. According to Mr. Anagnostopoulos, the engineer responsible for the foundations of the museum, the black frits were implemented only because it was the only technology that was considered to be maintenance free.

The slip-resistance coating is designed in accordance with BS 8204 Part 3:1993 Section C and therefore with a minimum SRV (slip resistance value) of 60 for wet conditions. For the glass floors that are inside the museum, an SRV of 110 is enough.

As shown in Fig 138 there are many different slip-resistant coating designs and colours. The SRV value is a function of the surface covered, the friction coefficient and the distance between 2 consecutive frits. The pattern chosen is in accordance with the floor pattern and therefore a pattern with circles is considered preferable. Given that the bottom of the spacers is not transparent due to the double curvature, bigger frits are placed at this position and smaller frits outside that region.

Generally there are no clear specifications concerning glass floors there is a part of the British Standards that covers slip resistance for in-situ flooring. This is the BS 8204: Part3: 1993. Apart from this type of specifications there are also some guidelines from the United Kingdom Slip Resistance Group (UKSRG, issue2, 2000). According to those guidelines there are 2 main things...
Figure 135 Satellite configuration

Figure 136 Fritted glass

Figure 137 Option no3

Figure 138 Anti-Slip Coating Patterns
that need to be taken into account when designing a slip-resistant glass floor: The roughness of the surface and the friction coefficients. These may be measured with the Taylor Hobson Surtronic 10 Rtm micro-roughness transducer and the Stanley TRRL Pendulum Coefficient of Dynamic Friction Test respectively. (BS 8204, retrieved in 2017)

In addition, there are 3 main techniques to produce a slip resistant floor, namely: a) sandblasting, b) acid-etched finishing, c) ceramic fritting. Among those, the latter method gives the better result especially in wet conditions. What is more, another advantage of this method would be the abundance of available colours to choose from. For that reason, this type of coating is used in this case study.

Finally, insofar as design is concerned, the main purpose is to keep the floor as transparent as possible, and stay in accordance with the pattern. For that reason, many different solutions were considered but the one that delivers the desired option is the option shown in figures 140-141. Bigger circular frits are placed at the top of the spacers and are mixed with a grid of smaller circular frits. Hence, not only doesn’t it disturb the pattern but it highlights it by emphasising on those spots where the spacer is placed. It is worth mentioning that a “satellite” system was also tested and even though the optical result is acceptable, the slip-resistance it provides is certainly poor.

The fritted pattern follows the distribution of the spacers and highlights the pattern.
Ceramic Fritting / Anti-slip coating

Laminated Glass Panel 6/PVB/6mm

Glass vessels / Spacers glued to glass panels

Laminated Glass Panel 6/PVB/6mm

Figure 140 Exploding diagram of a sandwich panel

Figure 141 3d visualisation
//4.2 Anisotropy

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 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 amount 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 and try to analyse which one performs better and why. In summary, the analysis showed that the triangular formation 2-1 and the zig-zag pattern perform better as they provide better shear interaction in 2 dimensions. Therefore, the panels were designed based on those 2 patterns combined with the one tested in the previous chapter.
The 2 panels that were tested use the same amount of spacers. However, the distribution is different. Panel number one features a more uniform distribution of spacers with equal distance between them. Panels number 2 (zig-zag) has varying distance between the spacers.
Comparing the 2 panels with FEA is the step taken before the bending tests. The 2 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:

a) Using a stronger glass type
b) Change the geometry of the spacer to allow for better distribution of stresses.
c) Thicken the glass sections
d) Densify the spacers
The 2 panels were tested by means of a 4-point bending test. The main goal was to compare the behaviour of those panels and conclude on how the distribution of the spacers in the core of the panels affects stiffness and strength of the panels. Hence, the 2 panels have the same amount of spacers but they are distributed differently.

The following graph 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).
Top panel breaks first due to telegraphing. Lamination works as a safety measure and the glass can still carry load. Bottom pane breaks right after that. Remark: The bottom panel of each lamination breaks first.
Fracture originates next to the spacers. In one of our meetings James O’Callaghan stated: “Stiffness is not glass’ best friend when it comes to connections”. The glue used in those panels is in fact very stiff and therefore stress concentration is created around the spacers. As expected, panels broke directly next to the spacers.
4.3 Building Integration

The panel itself can be considered a product. The method of making a sandwich panel may be considered a new method of designing with glass. However, a glass floor should be integrated into the building site. This involves a number of diverse challenges:

a) The connections to the concrete superstructure  
b) Water management  
c) Connection between consecutive panels  
d) Transportation  
e) Maintenance provision  
f) Fulfill Environmental requirements  
g) Serviceability

Handling those challenges is a case-specific process but general guidelines and recommendations are provided in this chapter based on the case study of the glass floors of the Acropolis Museum. Concerning the environmental requirements, it should be taken into account that such a floor should contribute into the protection of the monuments while elongating its own lifespan.

Figure 148 3D Visualisation of the glass floor
According to EUROCODE 1 there are certain specifications concerning floor systems. More specifically, for public areas where people may congregate loading conditions of 2.0 - 7.5KN may be applied. Generally museums fall into the category C3 and therefore a loading condition of \( p = 5\text{KN/m}^2 \) uniformly distributed load and \( Q = 4\text{KN} \) concentrated point load. However, the glass floors of this museum are expected to accommodate many people at the same time who would stand on top of the panels staring at the artifacts. Hence, the loading conditions of category C5 were considered for the calculations of this project. Those are:

\[
\begin{align*}
p &= 7.5\text{KN/m}^2 \\
Q &= 4.5\text{KN} \\
\text{Maximum deformation} &= d_{\text{max}} = l/500 = 14.40\text{mm}
\end{align*}
\]

This means that the floor system has to be able to withstand a 50% more load. At the same time serviceability is very challenging as 14.4mm of deflection for a span of 7200mm is a significantly high figure. This is why the sandwich structure is very useful in this particular application.

**D1: Connection to the main structure**
- Structural Integrity
- Tolerances
- Water-tight
- Air-tight

**D2: Connection between 2 consecutive panels**
- Dry connections
- Air-tight
- Water-tight
- Stiffen locally

**Figure 149 Challenges**
Figure 150 D1: Detail of the Building Integration
Steel Pedestral
Desiccant Breather
Floor drainage gutter
Flange adapter
4mm Hard Rubber Gasket
Aluminium Frame
Glass Spacer
Glass Sandwich Panel
M12 Bolt with Locking Nuts/Washers
15mm thk Stainless steel bracket with holes to accommodate tolerances
7mm Nylon Gasket
M12 FAZ II Expansion Bolt
Stainless Steel Triangular Support
Existing Concrete Beam
191
Desiccant Breathers
Protect from moisture
and keep the pressure
stable in the panel.

Raised Floor adjusted
with plastic stands
with screws.
Frame with cover installed in the factory to protect the edges from beaking and from dust coming in.

Glass Sandwich panel produced in the factory with glass spacers and acrylate adhesive.

Concrete Beam
Existing structure

Drainage gutter

M12 Bolt with locking Nuts/Washers

M12 FAZ II Expansion Bolts

Figure 151 D1 in 3D Visualisation
1. Frame the sandwich panel in the factory.
   - No dust allowed
   - Protect the edges

2. Install Brackets
3. Adjust screws
   - Adjust vertical tolerances
   - Adjust horizontal tolerances

4. Installation of Desiccant Breathers
   - Push in the safety valve

5. Installation of floor adjustment pieces
   - Use screws to adjust vertical tolerances

6. Installation of floor panels
   - Use edge pieces to adjust horizontal tolerances
The assembly is assembled partly in the factory and partly on site. Initially, the glass sandwich panel is framed in factory conditions and is transported on site. This is a way to protect the panel in transportation from dust coming through, and from fracture that originates from the edges. Then, the brackets are adjusted and aligned on site and later fixed to the concrete beam with Expansion bolts. After the panel is completely fixed the desiccant cartridge is pushed into the safety valve and allows the panel to breath through an otherwise completely air-tight connection. 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 weather conditions.

As far as the desiccant breathers are concerned, their 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. For that reason, a smart IOT system is inserted to remind the maintenance department or spot problems in construction.
A strain gauge can also be added to this system to check periodically the structure but also to provide the museum with a security system. Finally a carbon filter protects the desiccants from vapour released by the glue.

Another important connection is that of 2 consecutive panels. The panels are bi-supported but they cannot simply lie next to each other for serviceability reasons. When 2 panels are connected in the centre there might be a deflection of about 8mm. This could affect serviceability and therefore all panels should deflect together.

Typical sandwich panels use a type of interlocking connection which constituted an inspiration for the design of connection D2. Hence, an interlocking connection is introduced with linear extruded profiles which also stiffen the connection locally improving serviceability. Those profiles must be custom made and therefore a new die must be made. A floor of 90m² requires the extrusion of 21m of profile and therefore can justify the extra expenses. The extruded profiles should not touch each other and therefore a Polyurethane rubber interlayer is placed between the two profiles. This has the desired properties as it is flexible and is not affected by the elements. Finally, the connection is sealed with white silicone sealant to render the connection watertight.
Glass Extruded Interlocking Connection
Glass Spacer
Polyurethane rubber interlayer
Weather Silicone Seal
6mm HS Glass
PVB interlayer
6mm HS Glass

Acrylate Adhesive

Figure 156 Detail D2: Connection between 2 consecutive panels in 3D
Maximum deformation in the middle equals to: \( d_{\text{max}} = 8.2\text{mm} < l/500 \)

The middle part is in tension but the stresses are relatively low. This is because of the absence of high shear stresses around the brackets.

The dimpled contour line shows how strain is affected by the distribution of spacers.

Figure 158 Final Panel / Total Deformation

Figure 159 Final Panel Maximum Principal Stresses / Isocurves

Figure 160 Stress Concentration

A: Static Structural
Total Deformation
Type: Total Deformation
Unit: m
Time: 1
9/5/2017 12:35 AM

0.0002351 Max
0.0007501
0.006051
0.0054901
0.0045751
0.003656
0.002745
0.00183
0.00094501
0 Min
Figure 161 First Pattern/model pictures
As it was pointed out during the P4 presentation, 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 dictate a uniform distribution of stresses around the panel. 2 approaches were taken in trying to solve this problem:

1st approach: Initially, more spacers were placed in the regions were higher principal stresses are induced. This does alleviate locally the effect of stress concentrations but this is simply transfered somewhere else. Hence, this possibility was discarded.

2nd 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.

"Long story short: It is not important how many spacers I am stepping on. What is important is whether by stepping on one part of the panel I can trigger the whole panel to absorb that energy and move along with me”

Author during P5 presentation

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. Those are expected to be 0 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. Figure 159 demonstrates the importance of shear stress. Notice that stresses increase gradually moving from the center to the support. This feature is used to create the second grid using parametric software.
As shown in figure 162, with the new pattern the stress distribution is much more uniform and therefore the panel is much more efficient. As expected, there is still a stress concentration around the spacers and around the support but the difference between the magnitude of those stresses and the stresses in the middle of the panel is not high (less than 2MPa). As a result, the maximum stress induced in this case is much lower. This allows for a reduction of the number of spacers and of the thickness of the glass skins and therefore of material consumption in general. The result is a panel that is optimised both structurally and aesthetically according to the requirements of the design.
People walk on the denser region

The grid becomes denser next to the beams and therefore creates less distraction

Figure 163: Final pattern
Figure 164: Comparison between pattern
Final pattern. Notice that the pattern becomes denser towards the edges. The visitor has the chance to see the full scale of the ancient city.

Existing situation. The cage-like structure creates much distraction and the visitor can only look at what the metal beams are framing for them.
CONCLUSIONS & RECOMMENDATIONS

In this chapter the conclusions drawn from this thesis are presented. Initially, the conclusions are discussed per chapter as a way to summarise the results and the findings of each part of the research. Finally, the overall conclusions of this research are discussed along with a number of recommendations for future research.

CONCLUSIONS CHAPTER 0

This thesis is definitely a result of the author’s passion with structural glass and generally with the efficient use of materials. Glass is used more and more in contemporary architecture and therefore dramatic developments in the field of structural glass are taking place every year with glass leading to more transparent buildings but also to applications with ornamental characteristics. The material’s high compressive strength is ideal for columns but when it is combined with horizontal or planar elements, its poor tensile strength leads to really thick glass sections and therefore to overweight structures. The purpose of this research is to investigate how the sandwich theory can be applied to glass applications as a way to enhance the structural efficiency of planar elements. The case of a glass floor is selected because this particular application is structurally demanding and can better showcase the potential of a glass sandwich panel. As a result, the research question is:

How can we create a lightweight yet stiff planar element out of glass to be used in glass floor applications with selective distraction??
A number of Sub Questions are also defined:

- Which are the available topologies for creating a core with glass?
- What should be the geometry of the spacer to accommodate the needs of the chosen case study?
- Which adhesive should be used to bond the skins to the core?
- Which glass type should be used?
- How can we best implement safety in the design of the element?
- How can we optimize a glass sandwich element?
- How can we integrate the glass floor to the building (details, connections etc)?

The answer to the research question and to the sub-questions is given through a process that was divided into two parts which follow the practices of Design by Research and Research by Design respectively. Furthermore, the realistic time planning facilitated the completion of this research with the minimum possible amount of deviations. However, the process was not as linear as it was initially predicted. Hence, a constant process of reevaluation led to the parallel development of different tasks. Finally, it is worth mentioning that some of the panels presented in the research framework were difficult to make due to unaffordability or unavailability of means and were supplanted by other panels the construction of which was much easier to fit in the tight schedule of this research. The scope and the criteria of selection remained the same.

In this chapter the literature review is presented. This part of the research shaped the topic and provided the author with a sound toolbox to design and calculate the glass panels. The abundance of core topologies that are described in literature related to sandwich structures highlights the potential of these applications both structurally and aesthetically and provided
an extra motivation towards the successful completion of the research. What is more, the limited amount of precedents that were analysed at this part prove that there is in fact a need for stiffer planar elements made out of glass. However the insight provided by those applications constituted a driving force for this research.

In this chapter the case study is presented. The main conclusion of this chapter is that the traditional ways of building glass floors do not provide the architect with much design freedom. In fact, the bigger the floor area is, the more pronounced the effect of the tall supporting beams would be. At the same time, the crate-like structure creates a very particular pattern that might contradict with the architectural intent. Hence, a sandwich panel with customisability could be a useful alternative.

This constitutes the longest chapter of this thesis as well as the main body of the research. In this chapter a design toolbox is defined for the scientific analysis of glass sandwich panels. The proposed method consists of 3 main processes that should be followed in this order:

1. Predimensioning with the Analytical-Graphical Method.
2. Structural Analysis with Finite Elements.
3. Panels tested by means of 4-point bending tests.

Conclusions apply to each of the three aforementioned methods. Initially, it should be mentioned that the graphical method becomes more complicated if the strength requirement is taken into account but the result would be much more accurate. Furthermore, insofar as the FEA is concerned
A non-linear model should be considered as, even though deflections are not high, it takes into account the effect of telegraphing. This is the effect that describes the dimpled skins that occur when a regional type of support is utilised. Possible ways to alleviate the effect could be the following:

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

Finally, with regards to the bending tests, a 4-point bending test is considered more suitable for this type of applications as it generates regions of pure bending and pure shear. Hence, it is easier to understand the behaviour and the failure modes of the panels. The conclusions of the bending tests are the following:

• 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.

• Most panels broke closer to the support which is where higher stresses are induced, directly at the bottom plate.

• Comparing panels 5-6 we see that shear interaction is as important as 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 interaction is sufficient.

• The way the spacers are placed changes 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 that 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.

This part of the research focuses on the extrapolation of the results of chapter 3 to the glass floors of the Acropolis Museum. The final distribution of the spacers delivers the architectural intent and showcases the potential of such applications. It is also worth mentioning that when designing a glass floor, apart from the structural integrity a number of design considerations need to be taken into account. Initially, a slip resistant coating needs to be introduced with a pattern that fulfills the standards of BS 8204 and UKSRG (United Kingdom Slip Resistant Group). What is more, support conditions play a major role not only for the force distribution but also for the tolerances in construction. Not only do they need to accommodate the tolerances that occur on account of construction imperfections but also to accommodate the thermal expansion of the elements.
Finally, by comparing the final design with the initial prediction it is very clear that the final panel uses a thicker skin and a thicker core. This is a result of taking into account certain aspects namely Safety implementation, Support reactions and customisation in the form of selective distraction.

OVERALL CONCLUSIONS

IT WORKS !!!

The first and most important conclusion that can be drawn from this research is that the sandwich theory can be implemented in glass applications. By simply comparing the results of Chapter 3 in both FEA and Bending Tests with the behaviour of a laminated glass section the increase in the Stiffness/Weight ratio is dramatic while also influencing positively Strength.

It is highly motivating to know that the principles can be applied to glass 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 determining factors of the design.
When designing a sandwich panel, the author found himself struggling between the ideal and the optimal design. Merriam-Webster online dictionary defines “Optimal” as “the best and the most desirable” while “Ideal” as “what satisfies one’s conception of what is perfect or suitable”. When selecting the core topology to proceed with there are many criteria involved with structural efficiency being only one of them. Optimisation can only be done according to one parameter. However, the glass structure can be considered by definition an efficient type of structure and therefore an emphasis was given to the impeccable delivery of the design intent which relies on the customisability of the panels and therefore the selective distraction. Hence, the author considers the glass sandwich panel a new way of designing with glass and not a specific product. Therefore the principles that lead to an ideal design were investigated and a toolbox to design and calculate a sandwich panel is provided.

COMPROMISE

Unfortunately, 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 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 said distraction should be integrated into the design, same as it is done in the design proposal presented in this report. It is therefore recommended that sandwich structures not be used in applications where maximum transparency is required. However, usually this is not the main design requirement and therefore the concept of selective distraction should be embraced and integrated into the design from the very first phase.

IDEAL Vs OPTIMAL

When designing a sandwich panel, the author found himself struggling between the ideal and the optimal design. Comparing the panel with a simple laminate demonstrates the value of sandwich panels. 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 material consumption.
The research proved that there is an interrelationship among certain parameters namely:

- a) Core Thickness
- b) Core Density
- c) Length of Panel
- d) Stiffness/Weight
- e) Strength

Affecting one of the said parameters influences all the rest. For instance, as described analytically in chapter 3, 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 interrelationships 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, the toolbox provided in this research is a safe way to predict the structural behaviour of the panel and therefore leads to a sandwich panel optimised according to the design requirements. Therefore, it is highly recommended that when designing a panel the directions of the toolbox should be taken into account.

As defined in the research framework the author used available and affordable means to complete this research on time with significant conclusions. Less costly spacers were used in order to facilitate experimenting. At the same time, UV acrylate adhesive was utilised as it is available in abundance, the Glass Research group has already built a high expertise in its use and 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. 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 the behaviour of a PVB or Sentry Glass interlayer would behave differently than the adhesive used in this application.
Furthermore, even though the research emphasised 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 but it is important to state that 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.

POTENTIAL Nowadays that transparency is a determining factor of contemporary architecture a stiff and relatively lightweight panel would have many applications. The potential of a 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 conditions 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.
Aspect 1 The relationship between research and design.

The subject of this thesis is an innovative all-glass sandwich panel which provides the glass construction industry with a relatively lightweight yet stiff planar element. Researching on a new structure leads to extensive use of the trial and error approach. Effective though it might seem to be, a well-formulated research framework is still needed in order to ensure that the thesis can be conclusive in the period from P1 to P5. For that reason, literature review was a key aspect of this research and was based on the investigation of glass as a material and of sandwich structures. This entailed a research on safety measures, adhesives, sandwich core topologies etc. The aforementioned process helped me shape the research and spot the potential as well as the weaknesses of the application.

The Case Study provides the connection between research and design. It is through design decisions that the research is guided. More specifically, the literature study yielded a series of diverse specimens to be tested by means of a 4-point bending test. The results of those tests were not the only criterion to help me proceed with one of those topologies. Design requirements (qualitative-quantitative criteria) were also important insofar as the selection of the right geometry is concerned. Furthermore, the final part of the thesis project is mainly design-based in the sense that the rest of the experiments to be made are guided by design decisions.

Finally, I strongly maintain that the graphical method to dimension a sandwich structure is one of the most important outcomes of this research. It was validated to a certain extent by the bending tests and will be further validated by the future lab experiments. This is the product of both research and design and helped generalise the findings of this research and provide a design toolbox for future purposes.

Aspect 2 The relationship between the theme of the graduation lab & the subject/case study chosen by the student within its framework.

The sustainable graduation studio focuses on innovative applications in the built environment that use Building Technology to provide sustainable and effective solutions to contemporary problems while shaping the future of architecture through research and design. The scope of the chosen case study is to showcase the potential of glass sandwich panels by facing the structural and design challenges of a glass floor. There is a wide variety of glass floors but the majority of them cover very small areas and work mostly as light pipes. This particular case study was chosen because it poses big structural, environmental and design considerations that can be solved using Building Technology with a focus on Structural Design, Facade Design and Material Science. The main goal is to investigate the limits of the material and provide a solution that will be affordable, feasible, efficient, thought-provoking through customisability and will help reduce the embodied energy of glass floors.
Aspect 3: The relationship between the methodical line of approach of the graduation lab and the method chosen by the student in this framework

The approach of the BT graduation lab is highly technical-scientific and aims to support design decisions with calculations and experiments. At the same time, one of the following methods must be utilised: a) Research by Design or b) Design by research.

As far as the technical-scientific approach is concerned, the validation and dimensioning of glass sandwich panels was approached in three ways namely: FEA, Graphical method and Bending Tests. The correlation between the three aims to provide a safe way of predicting the structural behaviour of an all-glass sandwich panel. It is worth mentioning that a significant number of bending tests need to be performed in order to collect statistics and make sure that the concept safely works. However, this is not possible in the context of a Master Thesis due to affordability and strict time limits. The tests are just enough to support the main assumptions and partly evaluate the other 2 methods: analytical and FEA. It is quite clear that the thesis is divided into 2 parts regarding the relationship between research and design. From P1 to P3 the research is following Design by Research approach while from P3 to P5 the approach is mainly Research by Design. Throughout the former period, research provides the tools to design with while throughout the latter, design provides the topics to research on.

Hence, the BT approach is strictly followed throughout the whole process and has yielded the desired results.

Aspect 4: the relationship between the project and the wider social context

There is a three-fold value of the graduation project in the larger social and scientific framework: Material Development, Geometry Development, Sustainability.

Material and Geometry Development: Glass is a relatively new yet up-and-coming structural material. It is used more and more structurally in a way to reduce metal substructures and provide maximum transparency. With this research, I aim to provide the glass industry with a new way of using glass in planar elements. This may revolutionize the way of designing with glass which currently is limited to glass bricks, glass fins and corrugated glass. One reason why glass is the only material used as a spacer is also that my purpose is to push the material to the limits. At the same time, this research will ideally constitute a significant addition to the sandwich technology.

Sustainability: Nowadays, sustainability is more pressing than ever and there is a need to think of the embodied energy of the materials we use and an even higher need to reduce material consumption. By using the material in the most efficient way, not only can we reduce the material used in the element itself but we could also inherit the redundancy of the substructure. In modern facades, a lot of extra material is used in the façade substructure. If the element is stiff enough it can be attached to the main structure or it can constitute the structure by itself. Another advantage would be the low embodied energy of glass. The embodied energy of glass is really low and comparable to the embodied energy of wood, making glass one of the most sustainable materials overall.

Finally, one beneficial aspect of this research, related to the chosen case study, is that the transparency of the floors highlights the importance as well as the scale of the artifacts of the Acropolis Museum. These constitute artifacts from different eras of the Hellenic culture that show the scale of an ancient city and the life of ancient civilisations. With the current setup visitors cannot perceive the scale and this is the reason I strongly believe that an all-glass sandwich floor would constitute an important addition to the museum and to other archaeological places.
Books:


Papers or Journals:


6. Haydn, N., Wadley, G., (2005), *Multifunctional periodic cellular metals*. Department of Materials Science and Engineering, University of Virginia, Charlottesville, VA 22903, USA


Other Academic Material:

1. Akerboom, R., (2016), Glass Columns, exploring the potential of free standing glass columns assembled from stacked cast elements, TUDelft, Department of building Technology


### APPENDIX 1: Coefficients for Calculation

<table>
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<tr>
<th>BEAM TYPE</th>
<th>MAXIMUM SHEAR FORCE $F$</th>
<th>MAXIMUM BENDING MOMENT $M$</th>
<th>BENDING DEFLECTION COEFFICIENT $k_b$</th>
<th>SHEAR DEFLECTION COEFFICIENT $k_s$</th>
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<td>$P l/8$</td>
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<td>$P = q l / b$ Both Ends Fixed</td>
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<td>$P l/12$</td>
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<td>$P l/8$</td>
<td>$1/192$</td>
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<tr>
<td>Central Load</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P = q l / b$ One End Fixed</td>
<td>$P$</td>
<td>$P l/2$</td>
<td>$1/8$</td>
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<td>(Cantilever)</td>
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<td>Uniform Load Distribution</td>
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<td>$P$ One End Fixed (Cantilever)</td>
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<td>$P = q l / b$ One End Fixed</td>
<td>$P$</td>
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<td>Triangular Load Distribution</td>
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Figure 166 Coefficients for slab calculation | HexWeb 2000
APPENDIX 2: Lab Photos
APPENDIX 3: Early Model Photos
Photos taken by Marcel Bilow
APPENDIX 4: Photos of the specimens
OPTIMISATION GLASS TUBES LOCATION SANDWICH PANEL

<table>
<thead>
<tr>
<th>Area</th>
<th>Total weight per panel</th>
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</thead>
<tbody>
<tr>
<td>V0</td>
<td>3.4% 175 kg</td>
</tr>
<tr>
<td>V1</td>
<td>2.3% 117 kg</td>
</tr>
<tr>
<td>V2</td>
<td>2.0% 100 kg</td>
</tr>
</tbody>
</table>

With optimisation V2
Reduction of 75kg per panel

Diameter cylindrical tube: 100 mm

Diameter cylindrical tube: 200 mm