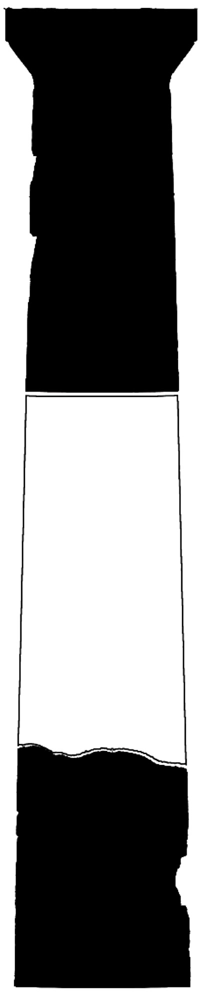

CAST GLASS RESTORATION OF MARBLE MONUMENTS

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ABSTRACT

Keywords: cast glass, restoration, conservation, marble monuments

Historical monuments are one of the best-preserved memories of our past as human species. Despite this, the conservation of these monuments is slowly being put under pressure by rapid economic development and the desire to make as much profit as possible. This development has raised awareness through the world of conservation about the importance of preserving and conserving our heritage. It is, however, hard to obey all the stated values and guidelines with existing materials and techniques. Many guidelines contradict each other, resulting in fierce debates about how monuments can be restored in the best and most appropriate way or whether they should not be preserved at all. Introducing cast glass as a new material into the field of reconstruction and conservation could bring the extremes of this ongoing debate closer together. By introducing a transparent material, in the form of cast glass, it becomes possible to safeguard the structural and mechanical stability of marble monuments and simultaneously allow for observing both its original and damaged state. Moreover, with cast glass, it is possible to re-shape these missing elements of monumental structures very easily and its texture and transparency can be easily altered to give them either a fully transparent appearance or one that resembles of the original material. In this research. the possibilities of using cast glass in restoration projects have been explored by creating a design and production line starting at the analysis of the case study and ending when the final piece is assembled. Using key conservation values like preserving authenticity, minimising visual impact and allowing for reversibility has resulted in a cast glass reconstruction design which is according to the conservation guidelines and feasible with the existing production methods of cast glass. The development of new techniques in 3D scanning and additive manufactured moulds allows this process to become more time and cost-effective than currently used conventional methods. By scanning damaged surfaces of the monument in combination with the use of 3D printed sand moulds, glass can be easily cast into complex shapes to fill up the missing parts of the monument. The key to designing these glass shapes lies in understanding and respecting the monument's structural and mechanical behaviour. If these characteristics are translated into the connections, shape and composition of the reconstructed cast glass elements, transparent restoration could become a serious contender for conventional materials in the conservation of monuments.

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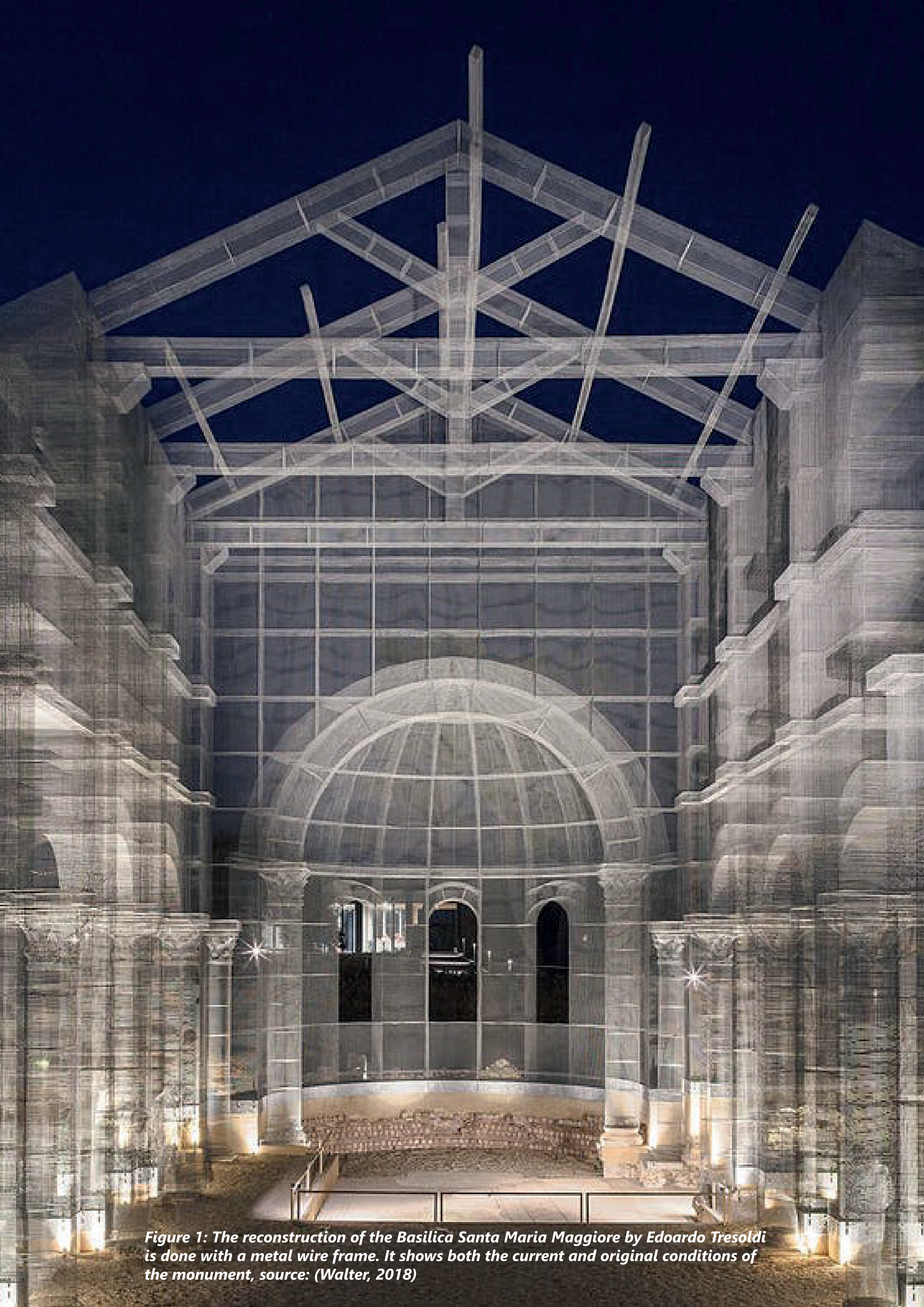


Figure 1: The reconstruction of the Basilica Santa Maria Maggiore by Edoardo Tresoldi is done with a metal wire frame. It shows both the current and original conditions of the monument, source: (Walter, 2018)

01.

RESEARCH FRAMEWORK

1. RESEARCH FRAMEWORK

1.1 Problem statement

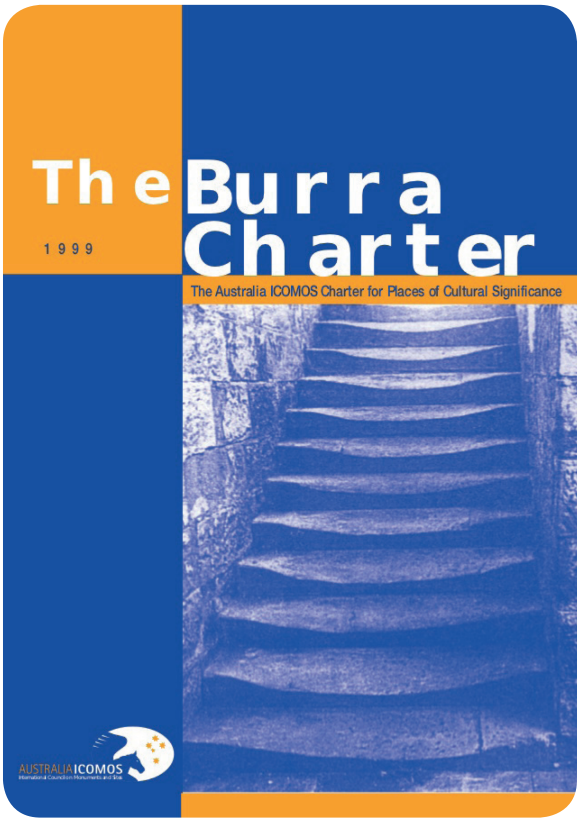


Figure 2: Front page of the Burra Charter, source: (Australia Icomos, 2013)

Architectural heritage is one of the most visible remains of our history. It shows how we lived, worked, and thought in eras, which go back to the time of the first ancient civilisations. To keep these stories alive, architectural conservation has become a very popular topic in these times, where economics has become the leading factor in deciding whether a building should be preserved or not, (Orbasli, 2008)

The Burra Charter from 1999 defines architectural conservation as "all the processes of looking after a place to retain its cultural significance". This includes regular maintenance but also restoration and reconstruction, (Orbasli, 2008). However, which consequences do these interventions have on the monument and the stories it tells us?

A part of the history of a building lies within the damage it has severed over the ages. These damages are just like scars on your skin. Each one tells a story about what happened when you got it. The same accounts for a building, each missing part, damaged column, burn mark, and bullet hole tells something about the wars, battles, fires, and other disasters the building has been through over the years. What happens with these remembrances when a building is fully restored to what it looked like two millennia ago?

In addition to that, how does one know when a building should be conserved and who decides which degree of conservation should be applied? Who is responsible for maintaining the identity and historical value of the monument? These questions are very hard to answer and mostly do not give one single solution. There are international charters with various conservation principles, however, these are only general guidelines and no strict rules, (Oikonomopoulou, et al., 2016). The room for interpretation in these guidelines has fed the discussions about how, why, and when we should conserve. Authenticity and how to maintain it during the conservation is one of the main topics in this discussion, (Stanly-Price, 2009). The main question within the field of architectural conservation seems thereby to be: How can we maintain our heritage, while simultaneously preserving its cultural identity and authenticity?

According to Oikonomopoulou (2016) and Barou et al. (2018), the key lies within the materialisation. If traditional materials are used in conservation, it could cause a conflict between the old and the new elements. However, using modern materials could influence the aesthetical appearance of the building while simultaneously it would damage its identity and authenticity. Instead of these conventional materials, cast glass could be a very good alternative to fill up the missing pieces of the structure, (Barou et al., 2018). It is a very strong material, the shaping possibilities are almost endless since it can be cast into almost any shape and with postprocessing, the appearance of the glass can be altered very easily and, most importantly, glass has almost the same thermal expansion coefficient as marble, which allows for a good hybrid, structural performance. Its texture and transparency can be manipulated so that it looks exactly like marble or kept completely transparent, which makes it possible to simultaneously show both the original and current state of the monument, thereby maintaining its identity and authenticity.

1.2 Objectives

Following the problem statement, the objective of this research is to develop a method for using monolithic cast glass elements of substantial mass to restore missing pieces in marble monuments, while still respecting and preserving their identity and authenticity. This main objective can be split into two main parts: structural restoration, which can be translated to the physical and mechanical compatibility, as well as a solution that is aesthetically compatible and visually subtle. The key to the restoration lies within a thorough investigation of the monument and how the intervention could be applied in a way to:

01 **restore** the structural stability and integrity of the monument,

02 **protect** it from further damage, caused by the outdoor conditions or human influence

03 and do this in such a way that the actions are **reversible** and can be undone easily.

To do this in the least intrusive way, it is important to fully understand the characteristics of cast glass. There are only a few examples where cast glass has been used as a construction material and none of them included large parts. Also, other characteristics, like optical properties and durability need to be understood. With this knowledge, it will be tried to:

04 obtain the desired grade of **transparency** and type of **texture** of the glass,

05 create a **subtle distinction** between the old and new parts,

06 and thereby simultaneously showing the **original and current** state of the monument.

1.3 Research Questions

These objectives stated above, combined with the problem statement, the main research question of this thesis can be stated as follows:

"To which extent can monolithic cast glass components of a substantial mass be used to reconstruct structural elements in marble monuments, while simultaneously complying with the international conservation guidelines?"

This question enhances three main fields of research: "monolithic cast glass components of substantial size", "reconstruct structural elements in marble monuments" and "international conservation guidelines". To answer this main question, these fields will be researched thoroughly, using the following sub-questions:

01. *What is the load-bearing and mechanical behaviour of glass, compared to the marble in ancient monuments and to which extend can it contribute to the structural stability and integrity?*

02. *What are the design limitations of large cast glass elements?*

03. *What is the most suitable production process for making these cast glass elements and does this specific application differs from producing cast glass in general?*

04. *How can the large cast glass elements be respectfully connected to the marble structure?*

05. *What influence do the glass elements have on the appearance of the monument and do they respect the historical value, and thereby the international conservation guidelines?*

1.4 Relevance

This evaluation could set a new tone within the world of conservation. At this very moment, there is no single solution which can enhance all the values that are mentioned in the various published charters and documents. Matching one guideline, it is almost certain that another one is contradicted, feeding the discussions about how conservation should be approached and which values are more important than others. Cast glass could bring the two extremes closer together since it is possible to structurally reinforce the monument, but simultaneously showing the traces of the past. Besides the innovativeness regarding conservation and restoration, casting large glass elements is also a process in development from an engineering point of view. The boundaries are still being explored and are continuously pushed towards their extreme. The size of these cast glass elements in combination with their application create an unexplored challenge from which the limits are still unknown.

1.5 Methodology

To answer these questions the research is split up in two phases. In the first phase, a literature study will be done to understand the principles of the conservation of heritage, the characteristics of cast glass as a structural material and the most suitable way to produce it for this specific case. This research will mainly include books, papers, lectures, internet articles and international charters on conservation. With this gained information a set of guidelines will be made which will be the starting point of the design phase, where a design proposal will be made for a case study project. These guidelines will regard the design limitations of cast glass and the corresponding production process on one side and how these can be applied within the respect of the international guidelines regarding the conservation of heritage on the other. Once these guidelines are set, they will be applied to the chosen case study. This second phase can be seen as research by design. With this research a production method on how cast glass could be used to fill up missing parts in marble monuments. At first, this method will be designed with the aforementioned guidelines, resulting in a design which is technically compatible with the properties of glass and relatively easy and cheap to produce. Once this production line is finished it will be applied to the Greek Parthenon. It could be any marble temple, but the Parthenon is chosen for its extensive documentation and accessibility of a high-resolution scan of one of its columns. The documentation of this case will be collected using digital data and drawings since travelling to Greece is not possible. The design proposal for the specific temple will be evaluated on the intrusiveness of the glass additions and its contribution to the historical identity and authenticity of the building. On this, a preliminary conclusion will be made on the potential of using cast glass elements in the restoration of monuments.

1.6 Case Study

As mentioned in the methodology, the design guidelines and proposed production process will be applied to a case study in Greece. It can be any monument, as long it is made out of marble. This research is not about making a design for a specific case study, but designing a method that can be applied to every ancient marble monument in the world. The case study will only be a test on whether the production method can give the desired results. Given this, a lot of monuments could be used in this research. The Temple of Olympian Zeus in Athens, the Temple of Poseidon in Sounion and the Temple of Apollo in Didyma, Turkey, would all meet the criteria. However, the monument chosen for this research is the Parthenon on the Acropolis in Athens.

Figure 3: Location of the Parthenon

This temple, dedicated to the patron goddess of Athens, is located in the centre of the Greek capital, about 5 kilometres from the Aegean Sea. Standing on top of the Acropolis, overlooking ancient Athens and the Aegean Sea, the temple was built in the fifth century BC. During its lifetime, it has witnessed various civilisations each having their impact on the condition of the marble temple. It has severed several kinds of damages during these periods, but in the 19th-century the first restoration works started to conserve and reconstruct one of the most prominent temples of the classical world. Since then, several restorations have been done to conserve the temple, some more successful than others. Thanks to these restorations, the documentation of the temple extremely extensive, which will be vital for further restorations in the future, (Toganidis, 2007). The well-documented conservation reports, large amounts of collected data in the form of 3D scans and the presence of the original material make the Parthenon an ideal case study for this research project. More characteristics of the temple can be found in Chapter 6.

Figure 4: North view of the Parthenon, where clear distinctions between old and new materials are visible, source: (Bouras, Ioannidou, & Jenkins, 2012)

1.7 SCOPE OF RESEARCH

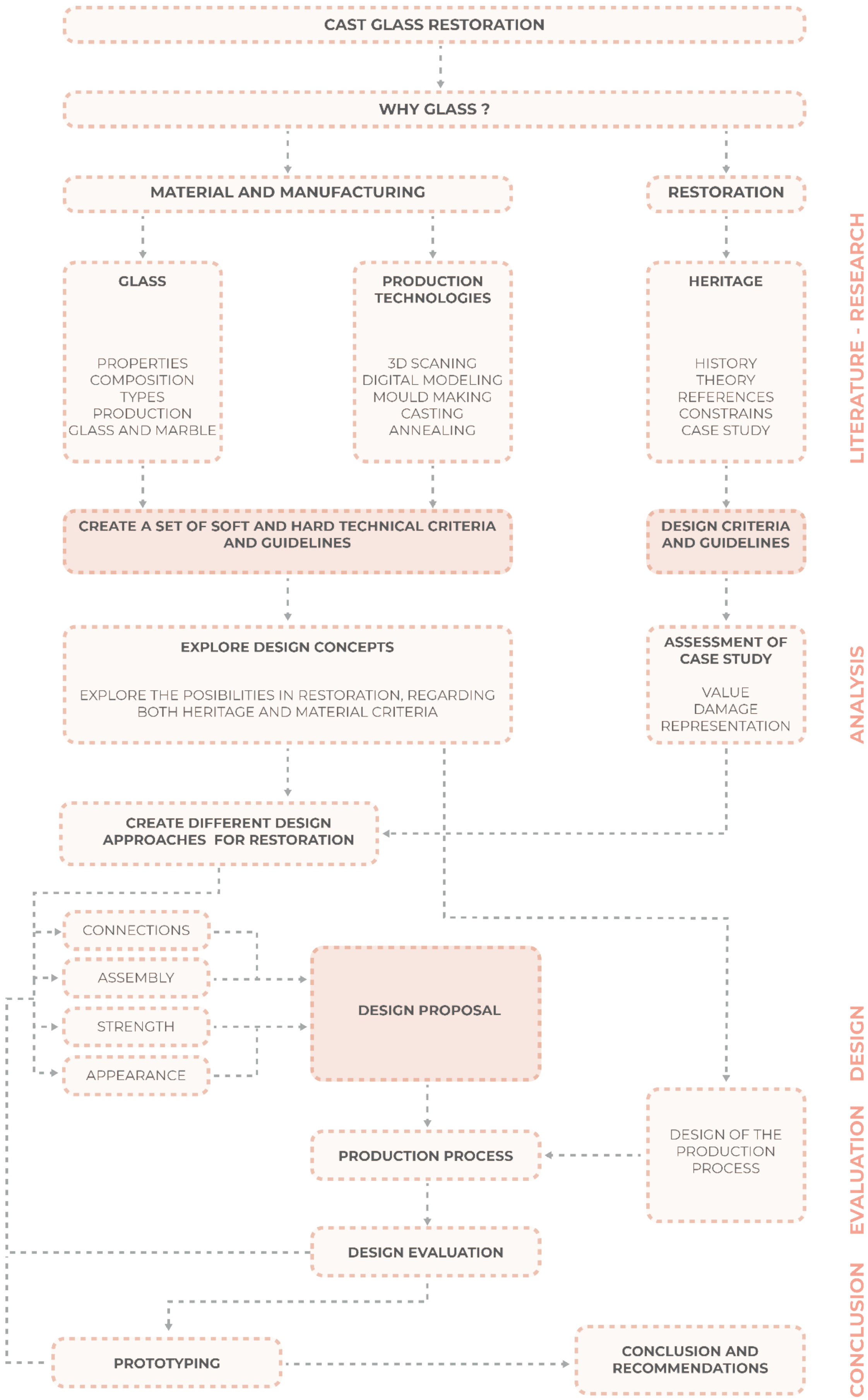


Figure 5: Scope of Research

1.8 TIME PLANNING

The graduation process is built up in five phases, each one ending with a presentation. These presentations divide the period into four parts. P1 officially marked the beginning of the research. However, in the week before this presentation the definition of the problem statement, research question and the scope of research were already started. Thereafter, between P1 and P2, the main focus lied in the gathering of knowledge via literature studies. After P2 the design process started, based on the results concluded from the literature. This design phase will last until midway the third and fourth presentation. Thereafter follows the production phase, where the designed object will be made. These two phases will be based on the 'research by design' principle and thereby contain a lot of feedback loops. Eventually, the design and production process will be evaluated and a conclusion will be drawn about the potential of the cast glass restoration.

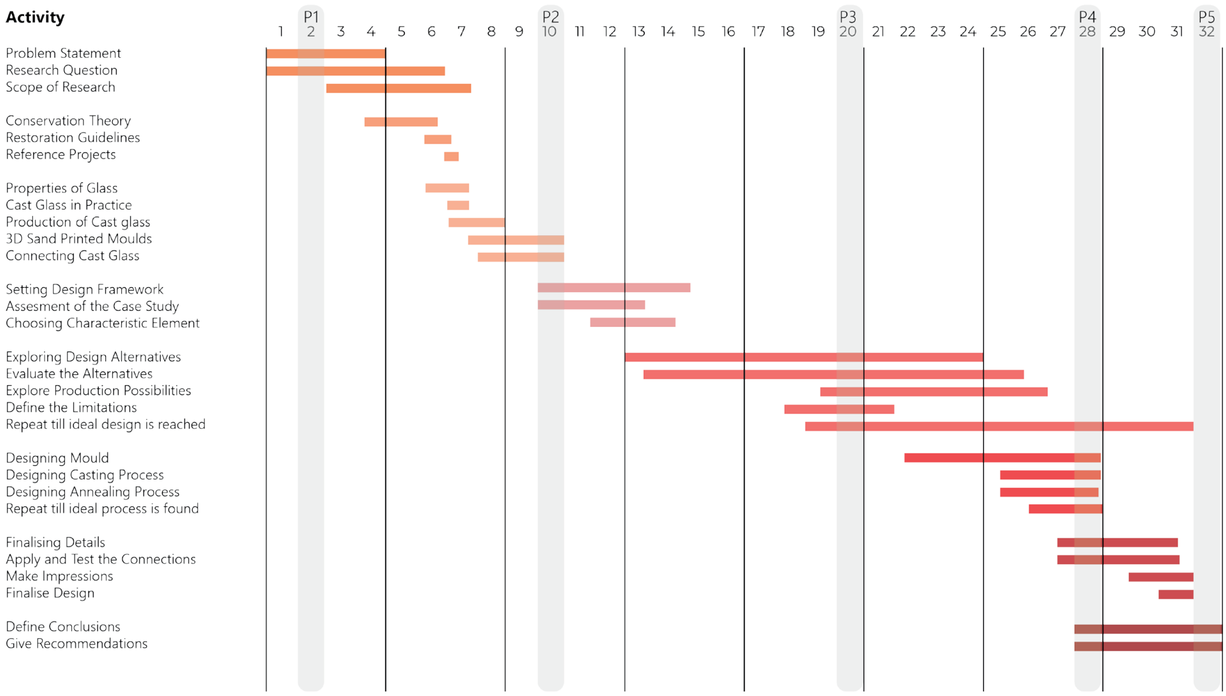


Figure 6: Time Planning

Figure 7: Several columns of the inner eastern collonade have been restored with smooth drums, so without the characteristic flutes. A very intrusive intervention for the monument, (British Museum, 2012)

02.

HERITAGE AND CONSERVATION

2.1 Why do we conserve?

Monuments are from great historical and cultural significance. They connect the ideas and thoughts of people today with experiences of the past. All these monuments combined will give a complete and adequate record of the history and identity of each culture. These buildings can be seen as witnesses of ancient traditions and values, making them irreplaceable and precious evidence from our past. In the 20th century, people have become more aware of the values of these monuments and the stories they tell us. Grown alongside with this consciousness is a common feeling of responsibility to protect and preserve these monuments. It is our duty to preserve the values and authenticity of these buildings for future generations, (Icomos, The Venice Charter, 1964).

There are multiple developments which stimulated this desire of preserving heritage. In the first place because it is part of our collective memory. They are places of cultural significance showing the development and diversity of communities and telling us who we are and how history shaped us in our way of becoming what we are, (Australia Icomos, 2013). Besides their historical value, many monuments also represent national identity, thereby creating an emotional connection to people as well. When this is the case, heritage often creates economic value as well. Tourism is often a strong reason for conversation since it will attract people to historic towns and sites, there creating an economical value for the neighbourhood, like the Roman Piazza Navona, (Orbasli, 2008).

On the other side, the protection of heritage is often seen as an obstruction to development. The debate between conservation and development is still an ongoing battle. The main reason behind these discussions is that monuments are mostly located in the inner cities, where prices have risen enormously over the recent years, making these very attractive areas for developers, (Orbasli, 2008).
This theory is supported by Roha W. Khalaf (2016). He describes the situation in Aleppo, a UNESCO World Heritage city which has severed massively under the Syrian Civil war. A lot of this heritage has been damaged or destroyed over the past years, leaving massive gaps in the urban fabric. This gives investors and business companies the chance to push for new development in the city, instead of restoring and conserving the heavily damaged monuments, (Orbasli, 2008).

Figure 8: Piazza Navona, Rome, source: (Rometips.nl, 2019)

Figure 9: The damaged Umayyad mosque in Aleppo, Syria, source: (Buffenstein, 2016)

These are examples where economic or political influence becomes very aggressive and thereby trying to destroy and erase our history in favour of money or political gain. Regarding this, "the most essential contribution made by the conserving the authenticity is to preserve, clarify and illuminate the collective memory of humanity", (Icomos, 1994). If we lose our collective memory by not conserving monuments we will erase a part of our existence and all economic values along with it. It is thereby vital to conserve our heritage otherwise the cultural value of these places will completely vanish from our cities.

2.2 Values and guidelines

In the charters from Riga, Venice and Burra, as well as in the Nara Document, the main contemporary principles regarding the conservation of heritage are mentioned, (Barou, Transparent Restoration, 2016). However, these principles only form the starting point of a discussion about the conservation. They are guidelines, which should help designers to conserve heritage respectfully and appropriately, (Oikonomopoulou, 2016). The lack of strict regulations is mainly caused by the differences between cultures regarding how the conservation of heritage should be approached. Even within the same culture, these approaches can vary a lot. This makes it impossible to use fixed criteria, but heritage properties should be considered and judged within the cultural context to which they belong, (Article 11, The Nara Document, 1964).

A conservation process will always lead to changes being made to the appearance of the monument or its structure. These changes are accepted when they are necessary to maintain the cultural significance but are unwanted in cases where it would reduce this significance. The degree of change depends always heavily on this cultural significance and which type of intervention is considered to be appropriate. This is only allowed to demolish significant fabric when it is an important part of the conservation and these removed pieces should always be reinstated when circumstances permit, (Australia Icomos, 2013).

Based on Barou (2016) eight combined values from the charters of Venice, Riga and Burra and the Nara Document have been considered as the most important and embracing for this case. These eight values each have been described below.

Authenticity

"Conservation of cultural heritage in all its forms and historical periods is rooted in the values attributed to the heritage. Our ability to understand these values depends, in part, on the degree to which information sources about these values may be understood as credible or truthful. Knowledge and understanding of these sources of information, in relation to original and subsequent characteristics of the cultural heritage, and their meaning, is a requisite basis for assessing all aspects of authenticity." (Article 9, The Nara Document on Authenticity, 1994

When a building is authentic, it means that is original. This does not only apply to architecture, but this term can also be applied to paintings, sculptures and other pieces of art. Over the past century, techniques have been developed, which sometimes can make it very difficult to distinguish a replica from its original. Authenticity is a very important value in showing the history of an object. It shows the evidence and information without being exposed to the influence of other circumstances which might lead to a false or misinterpretation of the truth.

Replacing Missing Parts

"Replacements of missing parts must integrate harmoniously with the whole, but at the same time must be distinguishable from the original so that restoration does not falsify the artistic or historic evidence." (Article 12, The Venice Charter, 1964)

It is important that when missing parts of a structure are to be replaced, the new ones can be clearly distinguished from the original pieces. They should be applied and added in harmony but not erase the stories that are told by the damage the structure has severed over the years. This could lead to a misinterpretation of history, eventually erasing the evidence of what circumstances the building has witnessed.

Conjecture

"The process of restoration is a highly specialized operation. Its aim is to preserve and reveal the aesthetic and historic value of the monument and is based on respect for original material and authentic documents. It must stop at the point where conjecture begins, and in this case, moreover, any extra work which is indispensable must be distinct from the architectural composition and must bear a contemporary stamp." (Article 9, The Venice Charter, 1964)

Although it should be possible to clearly distinguish the old material form the new additions, they still should go hand in hand with each other. It will be the task of the designer to find a balance between these two guidelines and apply them respectfully on the monument.

Respecting earlier contributions

"The valid contributions of all periods to the building of a monument must be respected since unity of style is not the aim of a restoration. When a building includes the superimposed work of different periods, the revealing of the underlying state can only be justified in exceptional circumstances and when what is removed is of little interest and the material which is brought to light is of great historical, archaeological or aesthetic value, and its state of preservation good enough to justify the action." (Article 11, Venice Charter, 1964).

Additions and contributions of earlier times should be treated with respect. They are part of the history of the monument as well, and should not be removed in favour of showing something else in a layer below it. Only in extreme cases, it is allowed to remove parts of a certain layer, but only when this to be unveiled layer is from great historical importance and it will not damage other parts of the monument.

Reversibility

"Changes which reduce cultural significance should be reversible, and be reversed when circumstances permit."(Article 15.2, The Burra Charter, 2013)

The possibility of reversibility is a very important property of an intervention. Sometimes the adaptation does not work out the way it was expected. This could be both structural and aesthetical related problems. When this is the case, it should be possible to reverse the intervention in a relatively easy way. Part of this desire is that new technologies regarding conservation are rapidly evolving these days. These developments might provide better possibilities for conversation than contemporary techniques.

Techniques

"Where traditional techniques prove inadequate, the consolidation of a monument can be achieved by the use of any modern technique for conservation and construction, the efficacy of which has been shown by scientific data and proved by experience." (Article 10, The Venice Charter, 1964)

Just like with the materials, using traditional techniques is preferred over modern ones. Only in cases when these ancient methods prove to be insufficient, new techniques are favoured over traditional ones. However, to prevent the risk of damage, only proven methods are allowed in the conservation.

Minimal Intervention

"The value of cultural heritage is as evidence, tangible or intangible, of past human activity, and that intervention of any kind, even for safeguarding, inevitably affects that evidential quality, and so should be kept to the minimum necessary." (Article 1, The Riga Charter, 2000)

During a conservation process, it should always be the goal to keep the intervention as minimal as possible. The main intention of conservation it to preserve the monument for future generations.

Location

"A monument is inseparable from the history to which it bears witness and from the setting in which it occurs. The moving of all or part of a monument cannot be allowed except where the safeguarding of that monument demands it or where it is justified by the national or international interest of paramount importance." (Article 7, The Venice Charter, 1964)

The physical location of a monument is an essential part of its cultural significance. Removing heritage out of its historical location would negatively impact the identity and authenticity of the object. Only in extreme conditions, when relocation is the only left option of ensuring its survival it is considered as an appropriate option.

2.3 Should we conserve?

Applying these guidelines, alongside with all the other ones in the various charters and other documents, in a conservation process, does not necessarily mean that this intervention is always right and appropriate. Since the beginning of conservation, continuous discussions have been held about whether and to which extend reconstruction is appropriate and allowed, (Stanly-Price, 2009). On one side, there is a strong desire to reconstruct heritage for their national or educational value. Opposing arguments are that ruined buildings can be more evocative of the past than reconstructed ones and that during the restoration authenticity and historical evidence will be lost.

These argumentations lead to two extremes; conserve everything by placing original tissue in a museum to protect it and replace it with replicas, or do not conserve at all and let the monuments int their original state. Although both extremes have support within the world of conservation, the general international opinion regarding conservation lies somewhere in the middle. According to UNESCO's World Heritage Convention in 1972, conservation is only allowed in exceptional circumstances and based on complete and detailed documentation. However, the various charters allow for some interpretation since the definition of reconstruction varies sometimes, (Stanly-Price, 2009).

In this thesis, the position of the author is mainly in line with international guidelines. Given the large variety of monuments and cultures, there is no general system which can declare that a monument should be preserved or not. Each case is unique and should be treated that way. A certain method and intervention can be a very suitable solution for one monument, but when it is applied on a different one, it rarely fits it exactly the same, even when these two monuments look very much alike. Whether a monument should be preserved or not, depends on various aspects, which all have to be evaluated according to local values and guidelines. In some cases, conservation would be a serious consideration while in others, it would be better to leave the monument untouched. However, preserving authenticity should always be the main criterion when making that choice, whether the monument will be conserved or not.

Figure 10: Saint Marc's Bell Tower in Venice, source: (Aless, 2020)

Figure 11: Restored Frauen Kirche, Dresden, source: (Sulfaro, 2018)

2.4 What do we want to preserve?

Before one can use these conservation guidelines, it must be known where to apply them on. According to the Burra Charter, "conservation is all the processes of looking after a place so to retain its cultural significance". This Charter defines this cultural significance as "aesthetic, historic, scientific, social or spiritual value for past, present or future generations. It is embodied in the place itself, its fabric, setting, use, associations, meanings, records related places and related objects", (Australia Icomos, 2013, p. 2).

These definitions raise the question which parts of a monument are part of its cultural significance and which not. From the guidelines in the Burra Charter, (Australia Icomos, 2013), Venice Charter, (Icomos, 1964), Nara Document, (Icomos, 1994) and several others, can be assumed that this significance embodies everything that the monument used to be in its original, undamaged state. Following this assumption would define conservation as the action that should be taken to restore a monument to this original state. However, some of the properties of 'cultural significance' also include the damages a monument has suffered over the years. These damages are an essential part of the historic and scientific value of a building and can thereby be seen as part of the cultural significance of a monument. This contradicts the definition of conservation, containing the desire to bring the monuments back to their undamaged state. ***If missing parts and damages to a structure are part of its cultural significance, should not they be preserved and conserved as well?***

According to Sulfaro (2018), the damage is by definition part of the historical value of a monument. He states that the absence of elements tells a more interesting story than a reconstructed piece can do. "Preserving the traces of a traumatic event can mean also preserving the absence of something that vanished forever", (Sulfaro, p6, 2018). An example the 9/11 Memorial in New York, where two enormous voids have been designed

Figure 12: Ground Zero Memorial, New York, source: (Sulfaro, 2018)

at the location where the Twin Towers have been standing before that disastrous day in September 2001. With these voids, absence has been used to tell a story about an event which never may be forgotten. Sulfaro describes this principle as "a black hole which indicates a negative spatial memory of a trauma", cited from (Boscarino, 1992, p14).

This is an example were leaving a void tells a greater story than a complete reconstruction could ever have done. According to Sulfaro (2018) reconstruction can be seen as a destructive activity itself since it erases memories of an event and removes physical evidence. Although it is seen as a legitimate action, it erases parts of history and can thereby change the course of events, which is a dangerous development. This does not mean that reconstruction is per definition a bad thing, as long as it is done a way which does respect history and not erases it. An example where it has been done inappropriately, according to Sulfaro, is the reconstruction of the city of Warsaw. The reconstruction has been done in such a way that one cannot see what destructions and damage the old city has severed in the second world war, thereby unconsciously, pretending the event never happened. In contrary to this, is the Dresdner Fraunekirche, which was destroyed in a bombing in the second world war as well. However, in this case, the original stones, coloured by the fire and smoke during the bombing, have been used to reconstruct the church. By doing this, it is visible which parts of the church have been destroyed, thereby preserving the historical value of the church.

Following these two examples, the main question seems thereby to be:

How can one, in case of reconstruction, restore the monument structurally and aesthetically, but simultaneously preserve the traces of its destruction as well?

The answer to this question seems to be the key solution in finding the holy grail in the conservation theories. Fining balance between present and past, done in such a way which simultaneously maintains the monuments structural integrity, its appearance and the historical stories it tells us.

2.5 Transparent Restoration

Finding this balance turns out to be very difficult using conventional materials, techniques and approaches. Often using a different material than is originally used is considered inappropriate and wrong, according to the various charters about conservation and authenticity. They require a solution which should preserve the monument for the future, but on the other hand, also desire an intervention which is as minimal as possible and does not affect the existing structure. Add to this desire the wish to preserve the historical damages of a monument as well and it becomes impossible to do this with only existing techniques and materials.

One of the solutions to solve this paradigm is introducing a new material in the field of conservation techniques. A material which is strong enough to structurally reinforce the monument, can change its appearance by simply looking through your eyelashes, thereby showing different stages in the lifetime of the building. Cast structural glass could be one of the solutions which could fulfil all our wishes of what we want to do with our heritage structures.

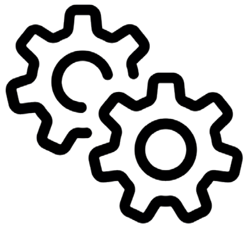
In its liquid state, glass can be poured in almost any imaginable shape, but once it is solid, it becomes a very transparent, strong material. With this shaping potential, it is possible to easily recreate the fragmented area, making the piece of glass fit perfectly on the ancient marble. This would be a much more efficient shape than is currently done at, for instance, the Parthenon, where pieces of marble are accurately cut and trimmed in a very time-consuming process. Also, its aesthetical characteristics make glass a very good alternative for conventional restoration materials. If wanted, glass can be made as transparent as water, becoming almost invisible for an unknowing, unattended eye. It is however also possible to make it translucent, in any colour imaginable. With the correct colour and reflectivity, it can even look just like marble but then made in a new, artificial way. Until the mid-20th century, these properties of glass were almost only used for making windows. But as technology advanced, other applications of glass were being explored. It turned out that, if designed correctly, glass could be used for structural purposes as well.

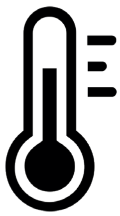
Figure 13: Different types of colour and texture in cast glass elements, source: (Oikonomopoulou, 2019)

2.5.1 Potential using of cast glass for structural restoration of monuments

1. Structural performance

Theoretically, glass is an extremely strong material with a strength amounting 32 Gpa, (Oikonomopoulou, 2019 from Shelby, 2005). In practice, this number will, however, never be reached. The practical strength of glass can vary according to the literature source used. In Oikonomopoulou (2019) the fracture tensile strength of soda-lime glass is given at 30-35 MPa and the compressive strength between 300 and 420 MPa, (Granta Design Limited, 2015). This strength makes glass not only attractive for its aesthetical appearance, but it could also be used for structural purposes, although it should be mainly used in compression, due to its lower tensile strength.



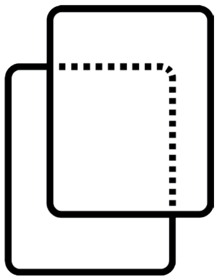


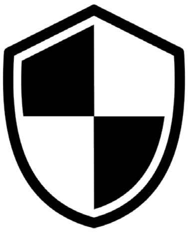
2. Physical properties

One of the main advantages of glass is that it has almost the same thermal expansion coefficient as marble. This allows for a much lower tolerance, and thereby a much more precise and discreet connection between the glass and marble. Moreover, this makes it easier to make the glass and marble collaborate in structural ways as well.

3. Transparency

When transparent elements are used to fill up the missing parts of a structure, it is possible to look into two different periods at the same time. At first, you see the monument in its damaged, present state, but if you look better, the glass parts will fill in the missing parts of the structure and create a kind of silhouette of how the building originally looked like. Because the glass parts are fully transparent, the visible degree of intervention is kept to its minimum. This reduces the impact on the cultural significance and authenticity of the monument.





4. Durability

Glass is a material which endures the conditions in the outdoor environment very well. It is completely airtight, waterproof, and is resistant against acids and UV light. These properties would make glass a very good solution to protect the monuments from the outdoor conditions, such as rain and wind.

5. Innovative

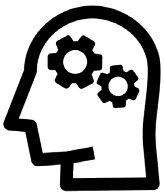
Structural design with glass is slowly gaining support and admiration from within the world of architecture. With this new approach, glass has been reinvented as a building material. However, the limits of this material have, until this moment, not been found yet. This makes it a challenging approach, but the potential results look very promising.

6. Conform the rules

Interpreting the guidelines of the various charters shows that the use of a new material can be considered as appropriate if the situation allows. The guidelines state that traditional methods and materials are preferred during restoration projects, however, if these are insufficient, alternative, modern techniques are allowed. Currently, the restoration techniques in marble temples are very time consuming and expensive. With glass, the same reversibility, stability, appearance, conjecture and authenticity can be reached as with the conventional materials, only in a much faster and cheaper way. In a sense, with cast glass, it is possible to produce an artificial marble, which does not have to be carved in the right shape, but can be cast instead. However, this aesthetical similarity is not even a requirement since new materials don't need to look exactly like the original ones. It is even recommended to make a clear distinction between the new and the old materials. The use of structural glass does not contradict these rules, however, it is also stated that this newly applied technique should be proven and safe. This is the main challenge with cast glass since this application is still very new and in testing phase. It should be proven that it is a safe alternative for existing techniques before it can be used in practice.

2.5.2 Challenges and limitations of using cast glass for structural restoration of monuments

Above, six of the advantages of using cast glass as restoration material are given. However, structural glass has some less favourable properties as well. These are challenges which need to be solved in the design process before the glass can be used as restoration material. Examples of these challenges are:



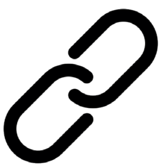
1. Lack of experience

That cast structural glass is a new, innovative material. The lack of experience with it could cause problems in the design and manufacturing process. The buildings on which this new material will be applied, are from great historical value. Damages, caused by inexperience with the material, are not an option and will cause a lot of criticism from all corners of the earth. Being innovative is good, but it should be used in a safe and reliable process.

2. Size of the cast lass piece

One of the most important processes in making cast glass is the annealing phase. In this phase, the molten glass is carefully and very slowly cooled to operating temperatures. This process needs to be done very precisely, to prevent flaws and internal stresses in the glass. The larger the glass object is, the more time and precision it takes to anneal it. It took, for instance, twelve months to anneal a four-ton telescope mirror with a diameter of 2,5 meters, (Oikonomopoulou et al., 2018). This should be taken into account by designing and making the pieces, since they can become quite large, depending on the size of the monument, thereby increasing the annealing time and costs.

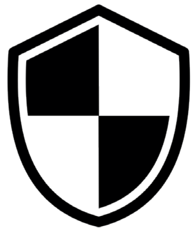
3. Connections

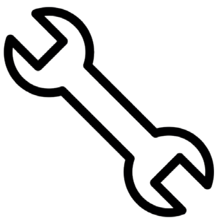


How will these enormous cast glass elements be connected to the existing marble structure? This connection needs to be very strong in the first place, but should also be applied with respect to the existing structure. Which types of forces will occur in these connections and how can be guaranteed that these forces are not being transferred in the fragile existing structure where they can cause local stresses.

4. Safety

Glass and flaws go hand in hand with each other. A flawless piece of glass is extremely strong but impossible to make. However, with a well-controlled production process, the number of flaws can be minimized and the safety increased. Flaws in the glass can cause internal stresses. Too many flaws at one place and these stresses can become too large, causing the glass to fracture and eventually break. To increase the safety of the glass, the number of flaws should be minimised as much as possible.





5. Maintenance

Just like glass in windows, regular maintenance is required to keep the glass in optimal condition. This includes cleaning of the surface and inspections for damages and cracks. If a glass piece breaks, it needs to be replaced as soon as possible, since it loses most of its strength immediately once it is fractured. If this glass piece is part of the structure of a monument, how can it be replaced by a new one, without causing damage to the monument itself?

2.6 Reference Projects

Examples of glass being used in restorations are rare. Only in recent years, techniques have been developed enough to use glass as construction material, but still, it is an unconventional method in the world of conservation. The first time glass occurred as material for conserving monuments, it was only used as protection material, thanks to its air- and watertight properties. In 1954 Italian architect Franco Minissi designed a glass protection system for Timoleonte's Greek Wall in Capo Soprano, Italy. Pieces of float glass were used to pressurize the wall from the outside and preventing them from eroding further, (Vivio, 2015).

This wall, made by the Greeks in 400 BC., was excavated between 1948 and 1954. Soon was found out that the lack of pressure from the earth on the sides of the walls, slowly caused the wall to erode. To keep the wall in compression, glass panels were pressed against the sides of the wall. This was the least intrusive method that could be applied in this case. The glass structure was removed eventually due to bad maintenance and because it was found that the microclimate between the glass and the wall damaged the stones even more, (Vivio, 2015).

Figure 14: Timoleonte's Greek wall, source: (Vivio, 2015)

Figure 15: Theatre of Heraclea Minoa, source: (Vivio, 2015)

Another project of Minissi was the Greek theatre of Heraclea Minoa in Agrigento, Italy. This was the first time that a transparent material has been used to fill up the voids that were left in the degrading process of the building. Minissi used plexiglass covers to protect the vulnerable tuff blocks from eroding further. However, due to failures in construction and occurring microclimatic problems in the space between the plastic and the stone, the plexiglass tiers were eventually removed to prevent more damage to the structure. (Vivio, 2015).

Thanks to his work, Minissi was seen as the first explorer of transparent restoration. His work was not always understood, neither by contemporary critics nor by the modern ones, but with his work, he opened a gate to a new type of restoration. On the next, more of his projects regarding transparent restoration are shown, alongside with other designs from different architects.

All three projects include a type of transparent restoration, but none of them makes use of cast glass elements. In the castle and flour mill, float glass has been used to cover the structure or fill the missing pieces. In the church in Spain, the architect used ETFE, which is transparent plastic. Right now, restoration in cast glass has only been done in some Master Thesis. It is still in an experimental stage. A design for cast glass restoration is shown on the right, where Barou (2016) used a cast glass masonry system to fill up the missing pieces in the Bembo's Bastion, in the south-western Peloponnese.

Figure 16: Impression of the restorated Bembo's Bastion with cast glass elements, source: (Barou, Oikonomopoulou, Bristogianni, Veer, & Nijsse, 2018)

Reference Project

Concept

Figure 17: Horizon Flour Mill, Sparta, Greece, source: (Modati, 2018)

Stacked Float Glass

This flour mill, near the Greek city of Sparta has been damaged a long time ago, but as part of the Arthumanture Topos festival, in 2007, the missing pieces of the mill have been restored in glass. The architect tried to respect the existing structure, but still wanted to give his own signature. The glass top section is built out of laminated layers of float glass, (Modati, 2018).

Figure 18: Castel Juval, Val Senales, Italy, source: (Juval Castle and Reinhold Messner, 2019)

Float Glass Roof

The Juval Castle in northern Italy was built around 1278 and restored in 1913. Momentarily the castle functions as a museum, containing several expositions. The roof of the castle has been restored with float glass, which is supported with an under tied cable construction. This reduces the amount of opaque elements and maximises the transparency of the roof, (Juval Castle and Reinhold Messner, 2019)

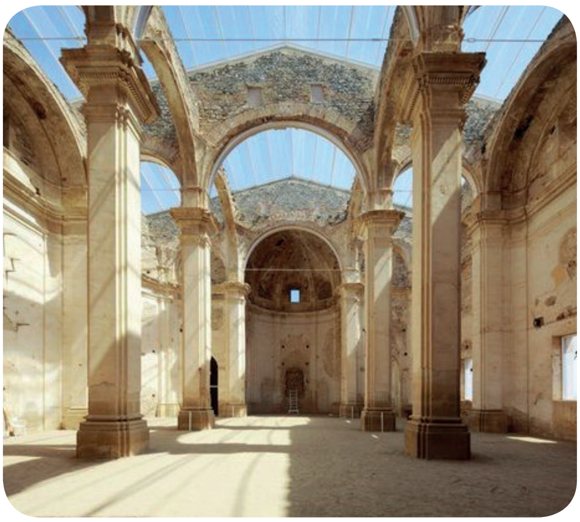


Figure 19: Church of Corbera d'Erbe Terra Alta, Tarragona, Spain, source: (Hevia, 2016)

ETFE Plastic Roof

The main goal of the restoration of this church was to maintain the subtle balance between in- and outdoor spaces. Instead of a normal cathedral, which is dark and closed. The experience visitors had in this church were light and open. It was important that these characteristics were maintained after the restoration. The glass roof protects the vulnerable stone from the weather conditions but the feeling and experience within the church is maintained, (Hevia, 2016)

2.7 Conclusions

Studying different charters and other documents regarding conservation show that there is a lot of room for interpretation. These international guidelines just provide a frame of reference which is applicable in all cultures. This room for interpretation could make glass an interesting new material to apply in reconstructions. It does fit in these guidelines since it can be reversible, respects the authentic material, is distinguishable from the original materials and is not intrusive to the observer. Moreover, existing traditional techniques are not time and cost-effective and in this case, applying new techniques is allowed according to the guidelines.

This is also because glass, as a construction material, is slowly gaining more popularity, as the knowledge and thereby the trust in the material grows. Being a transparent material, glass could be a very suitable option in restoration projects instead of conventional methods. The transparency reduces the visual impact of the intervention to its minimum, thereby distinguishing the old, original parts from new ones in the monument. On top of that, visitors can see the monument in its existing and original state at the same time.
Existing examples of restoration with glass do provide an aesthetical impression of how such an intervention would look like. However, to structurally reinforce with glass, more research into the material and its production process need to be done. All the above-mentioned projects are done with float glass and are non-bearing structures. Casting glass allows for much more possibilities in shaping and detailing and loading, but also brings more complications with it.

In conclusion, glass offers a combination of material properties which is quite rare in architecture: strength and transparency. With the strength of glass, it is possible to use it as a construction material, while the transparency prevents the destruction of historical evidence of the past. This makes it possible to restore the monument to its original state, without erasing the traces that refer to its past. No historical evidence will be removed or hidden, thereby preserving the identity and authenticity of the structure, in both its present and past state.

Figure 20: Front view of the cast glass masonry of the Crystal Houses Facade, source: (MVRDV, 2016)

03.

THE MATERIAL GLASS

3.1 Introduction

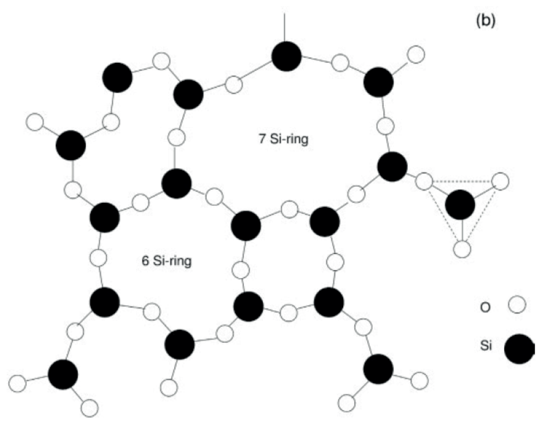
As a natural material, glass has been around for millions of years, fascinating scientists and engineers with its unique material properties. For a long time, glass has been considered as the fourth phase of matter, next to solid, liquid and gas. This was until the liquid-like structure of glass was discovered. This gives the material its unique cooling process, where viscosity is the leading factor in solidifying the material. This mysterious behaviour has not withheld civilizations to explore and use glass in and around their homes, (Le Bouhis, 2008).

The first traces of manmade glass have been found in former Mesopotamia and date back to 3000 years BC, but the production process was rather complicated so the usage was minimal. The first real glassmaking recipe was found on a clay tablet in Assyria, dated at 650 BC. From there the techniques have developed over the years, starting with the Romans, who were able to produce large sheets of cast glass, as well as blown cylinder sheet glass, (Schittich et al., 1999)

For long, the usage of glass in architecture was restricted to windows. One of the main causes of this restricted use is that glass has the reputation of being a fragile and brittle material. However, improving technologies have increased the safety of glass significantly and show the potential of glass as a structural material. In this chapter, the properties of glass will be discussed, along with the different types and construction methods.

3.2 Physical Properties

According to its chemical and physical properties, glass is categorised as a ceramic material. Ceramics are typically inorganic materials, electrically and thermally resistant and the atomic bonds are covalent. These properties distinguish glass from the other three material groups: metals, polymers and composites.
On the atomic level, glass can be seen as an out of equilibrium molecular structure. During the cooling process, the temperature drops too low for the molecules to rearrange themselves in time, causing the glass to 'freeze' instead of crystallising, (Le Bouhis, 2008). This process leaves solid glass with a completely random molecular structure, shown below. This amorphous structure has both advantages and disadvantages. It gives glass, for example, its transparency since the loose ends and holes in the molecular structure allows light waves to travel through the material, giving it its transparent look. However, the lack of a crystalline structure also causes glass's brittle behaviour, making it prone to cracks and other defects



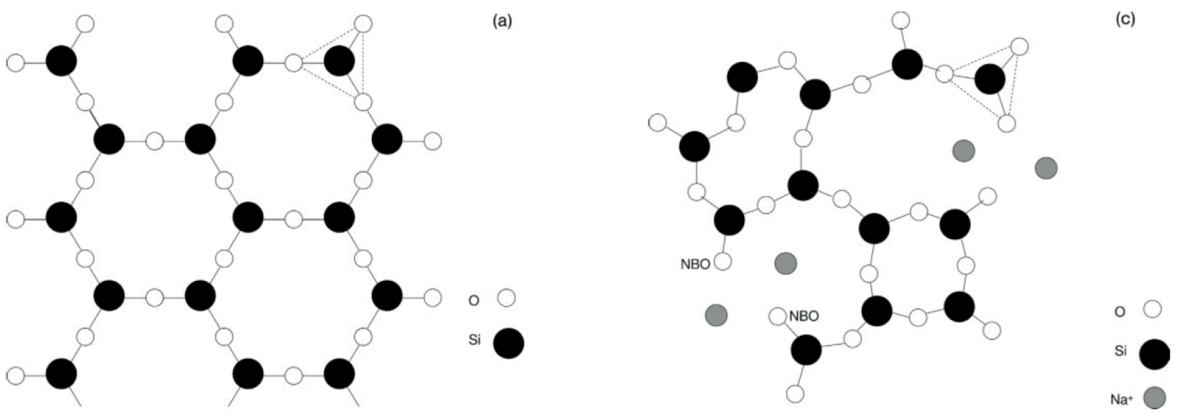


Figure 21: Three molecular stages from a crystalline to a glassy structure, source: (Le Bouhis, 2008)

Optical properties

As said, glass gains its transparency to the amorphous molecular arrangement. It is, however, important to take into account that, despite the transparency, the glass is not invisible. Depending on the shape and type of glass, light can be reflected, absorbed bend or sometimes even completely blocked, which can result in an unexpected aesthetical appearance. This is very much influenced by the angle of refraction between the human eye and the glass surface. The closer this angle comes to perpendicular, the less refraction occurs and more transparent the glass looks.

This transparency is however heavily influenced by the additional materials that are added to the glass. The pieces need to be connected, which is often done with opaque metal joints. Also, the interlayers, which are used between the pieces are not always transparent. This depends on the type and thickness of the layer and the point of view of the observer.

Thermal properties

The behaviour of glass under different temperatures depends heavily on the type of glass that is used. The thermal expansion coefficient differs from 0.55*10-6, for Fused Silica, and 9.1*10-6/°C for lead Silicate glass, (Oikonomopoulou, 2019). The higher the expansion coefficient, the more vulnerable the glass is to thermal shock. Silica-rich and borosilicate glasses have the highest thermal endurance and are thereby the most resistant to sudden temperature differences, (Le Bouhis, 2008). This influences the application possibilities of the glass types enormously, especially when large pieces are involved. The thermal expansion coefficient of the different types of glass and the effects it has on their applications will be discussed later in this chapter.

Durability

Glass is resistant against most types of acids, besides hydrofluoric and phosphoric acid. Also, most alkalis and sulphates can damage the surface of the glass and should be removed as soon as possible, (G.James Group Australia, 2000). Since glass is also water and UV resistant, the maintenance intensity is very low. However, since it is a transparent material, it needs to be cleaned quite often to keep it transparent.

Figure 22 & 23, The soda lime glass blocks from the Crystal Houses are very transparent from a perpendicular view, but looking from an angle, the reflection of the glass becomes more visible, source: (Oikonomopoulou, 2019) top, (MVRDV, 2016) bottom.

3.3 Mechanical properties

The strength of glass

The aforementioned covalent and ionic bonds between the molecules make glass a very strong material. They give glass a very high theoretical yield strength of 17 GPa, which is about fifty times more than high-quality steel. The practical strength of the glass is however much lower, (Lehman, n.d. and Le Bouhis, 2008).

The strength of a piece of glass is highly influenced by the flaws in the material. A perfectly, flawless piece of glass could reach the strength of the aforementioned 17 GPa, but this is practically impossible to make. Flaws in glass are just as inevitable as creep in concrete. There are a lot of different flaws which can cause a loss in strength. The most occurring ones are scratches, inclusions, bubbles and inhomogeneities, (Lehman, n.d.). Not every defect has the same effect on the performance of the glass, which makes it hard to predict its actual strength, moreover, locally the strength of the glass can vary as well. To approach it, the 'weakest link theory' is used, which means that the most severe flaw in the glass determines its strength, (Le Bouhis, 2008). Glass is usually weaker near the edges than in the middle of the object, since the risk on defects is larger there. Also is the risk of failure due to tensile bigger than to compression stress.

The Brittleness of Glass

So glass owns its high mechanical strength to the covalent bonds between the molecules, but these same bonds also give it its biggest weakness. Covalent bonds are the strongest type of atomic bonds, (Le Bouhis, 2008), but once they break they do not reform easily, (Veer, 2007).

This brittle behaviour has kept engineers and architects from using glass as structural material. Science was not developed enough to predict the strength of glass and because of the brittleness, glass does not show any sign of failure before it actually fails. Unlike steel, there is no plastic deformation before it breaks. Once the maximum strength is exceeded the glass cracks and immediately loses its strength, there is no time to take action to reinforce the structure. Once a steel beam fails, it starts to deform plastically, but still holds its strength. So there is time to support the beam and prevent it from breaking.

3.4 Types of Glass

The silica glasses are composed of a three-dimensional network of silica and oxygen atoms. The main ingredient is silica dioxide (SiO2) although the single molecular unit is not distinguishable in the larger structure. In the network one silica atom is connected to four oxygen atoms, creating a tetrahedron shape (SiO4). All four oxygen atoms in the shape are again connected to another silica atom, thereby creating another tetrahedron and a three-dimensional network. In pure silica glass, the ratio between silica and oxygen atoms is exactly 1 to 2 and the atomic bonds are covalent. In such a network all oxygen atoms are connected to two silica atoms. When other atoms are present in the glass, such as sodium or aluminium, they create an ionic bond with the oxygen. By replacing some of the silica with other atoms, different molecular compositions can be created, resulting in different types of Glass, (McLellan & Shand, 1984). Based on their additives, the different types of glass can be categorised in six different groups which will be show below: (Oikonomopoulou, 2019).

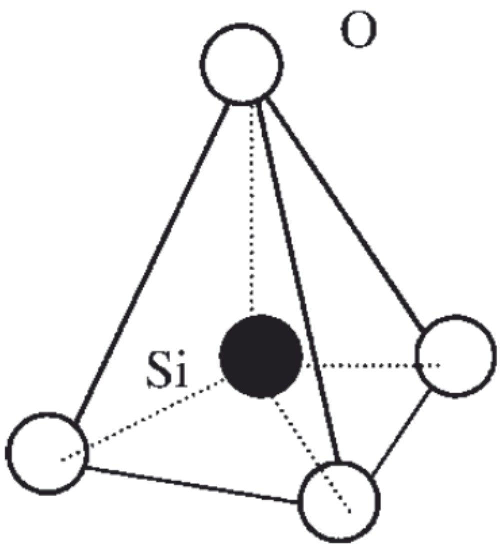
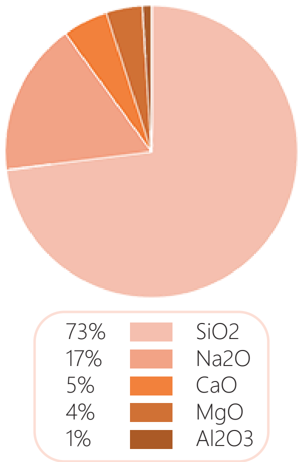


Figure 24: The molecular structure of one tetrahedron, with one silica and four oxygen atoms, source: (Le Bouhis, 2008)

SODA-LIME



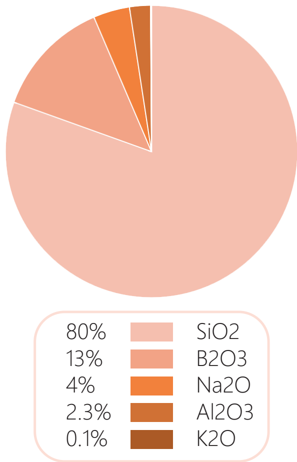
Characteristics

Least expensive
Poor thermal resistance
Poor chemical resistance
Durable

Applications

Windows
Bottles
Facade Glass

BOROSILICATE



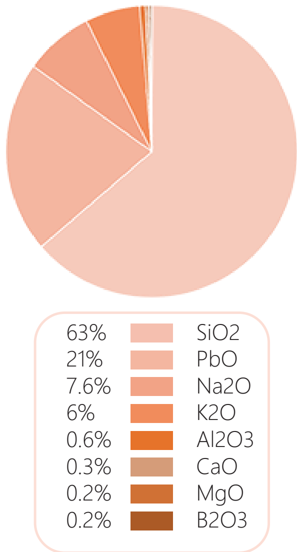
Characteristics

Good in thermal shock
Good chemical resistance
More expensive than soda-lime

Applications

Labaratories
Ovens
Lightbulbs
Telescope

LEAD SILICATE



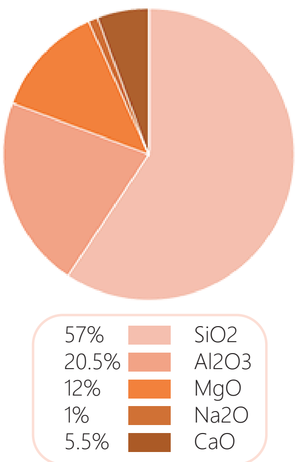
Characteristics

Second least expensive
Relatively soft
Easy to cold work
Poor thermal properties
Good electrical insulation

Applications

Artistic ware
Neon-tubes
TV screens
X-ray panels

ALUMINOSILICATE



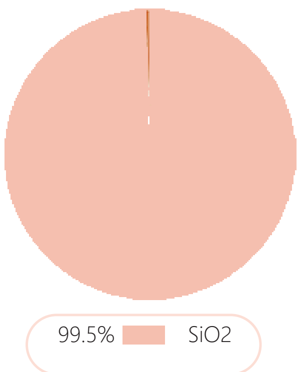
Characteristics

Good in thermal shock
Good chemical resistance
High manufacturing costs

Applications

Phone screens
Fibre glass
Combustion tubes

FUSED SILICA



Characteristics

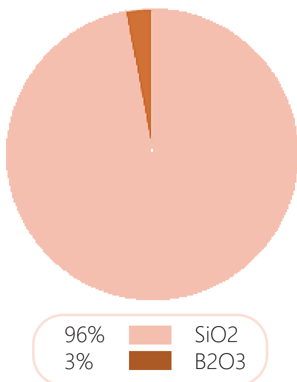
Highest thermal shock resistance
Difficult to work with
High production costs

Applications

Outer windows in space craft

Telescopes

96% SILICA



Characteristics

Good in thermal shock
Good chemical resistance
Meticulous manufacturing process

Applications

Outer windows in space craft

Furnace sight glassees

Figure 25: Overview of the different types of glass, based on Oikonomopoulou, 2019

	SODA-LIME	BOROSILICATE	LEAD SILICATE	ALUMINOSILICATE	FUSED-SILICA	96%-SILICA
MEAN MELTING POINT [°C]	1350 - 1400	1450 - 1550	1200 - 1300	1500 - 1600	>>2000	>>2000
SOFTENING POINT [°C]	730	780	626	915	1667	1500
ANNEALING POINT [°C]	548	525	435	715	1140	910
STRAIN POINT [°C]	505	480	395	670	1070	820
DENSITY [kg/m3]	2460	2230	2850	2530	2200	2180
TH. EXPANSION COEFF [E-6/°C]	8.5	3.4	9.1	4.2	0.55	0.8
YOUNG'S MODULUS [GPa]	69	63	6.2	87	69	67

Figure 26: Properties of the six different types of glass, (Oikonomopoulou, 2019)

The different chemical compositions in the glass affect the physical and mechanical behaviour of the glass, thereby changing the type of application it can be used for. Figure 26, by Oikonomopoulou (2019), shows the main properties for the different types of glass. What stands out is that the main influence on these properties is the amount of silica dioxide (SiO_2) in the mixture. More silica means higher working temperatures since the non-disrupted tetrahedron structure keeps the atoms longer connected in the molecular structure. Other characteristics that seem to be dependent on the amount of silica are the density of the last and its thermal expansion coefficient.

To determine the best type of glass for this specific function, the advantages and disadvantages of all the glass types will be assessed by the following categories: Physical properties, which include the working temperatures and thermal expansion, mechanical properties, including strength and stiffness, and the costs. For the mechanical physical behaviour of the material, the similarities with marble have been an important factor in the assessment.
Based on all these criteria, borosilicate glass seems to be the best option. The working temperatures are acceptable, although they are slightly higher than the other hybrids. The problem is, however, the thermal expansion coefficient. Borosilicate glass has a relatively low thermal expansion coefficient compared to soda-lime and the difference in thermal expansion with marble is quite large. It is an essential and hard criterion is that the glass can structurally cooperate with the marble. So the thermal expansion coefficient of the two materials must be as similar as possible. Large differences would lead to high tolerances, which make this cooperation difficult. This is also the reason why titanium is used in the connections during marble restoration projects. The expansion coefficient of titanium and marble are very similar and soda-lime glass would fit nicely in this, as can be seen in the table above. Given this, soda-lime glass would be the most suitable glass type to use, despite all the other advantages borosilicate glass has.

	SODA-LIME	BOROSILICATE	MARBLE	TITANIUM
MEAN MELTING POINT [°C]	1350 - 1400	1450 - 1550		
SOFTENING POINT [°C]	730	780		
ANNEALING POINT [°C]	548	525		
STRAIN POINT [°C]	505	480		
DENSITY [kg/m3]	2460	2230	~2600	4500
TH. EXPANSION COEFF [E-6/°C]	8.5	3.4	~5.5 - 14.1	8.9
YOUNG'S MODULUS [GPa]	69	63	40.1	116

Figure 27: Comparison between the properties of soda-lime and borosilicate glass on one side, and titanium and marble onthe other, source: (Skoulikidis et al., 1993), (Granta Design Limited, 2015)

3.5 Production types of glass

Speaking of glass types can hint towards two directions. The first one, the types of recipes, has been discussed above, the other one is the type of glass in a manufacturing way of speaking. The origin of glass manufacturing goes back till 3000 BC and since then these techniques have been improved over time, based on our understanding of glass as a material. The Romans were able to make flat glass panels, and in the 14th century the crown glass method was discovered, (G.James Group Australia, 2000). Nowadays, there are four different types of glass production, float glass, extruded glass, cast glass and 3d printed glass, (Oikonomopoulou, 2019). All of these will be briefly discussed below.

Float glass

The first and most produced type of glass is float glass. This process has been developed by the Pilkington brothers in 1959. The name is derived from the process where molten glass is poured into a bath of tin. Since the glass is lighter than the metal, it floats and creates a flat sheet of glass, (Veer, 2007). Advantages of this process are that it is relatively cheap, widely applicable and produces optical quality glass, (Oikonomopoulou, 2019). The standardised manufacturing produces sheets of glass with a width of 3.2 and a typical length of 6 meters, although the maximum length can be increased if wanted. The thickness of the glass can vary between 0,3 up to 25 mm, (Pilkington, n.d.). The two-dimensionality of float glass makes it very applicable for windows and façade elements, although it can be used for three-dimensional glass structures as well. A good example is the Apple Cube in New York, which is completely made from float glass panels, mechanically and adhesively connected.

Extruded glass

Extruded metals and plastics were already very common at the time when the first glass extrusions were produced. At that time, blown, cast, pressed and rolled glass were the standard production methods. However, as the use of glass diversified, the demand for new types of glass increased, resulting in a new type of glass production: extrusion, (Roeder, 1970).
There are two types of extrusion, direct and indirect. In both cases hot glass is pressed through a die, creating a long glass profile with a continuous cross-section. With direct extrusion the glass is pressed through the die by a pressing disc, thereby creating the rod. In indirect extrusion, the die moves through to container, in the opposite direction of the extrusion. This process requires a lower pressure, but because hollow sections are more difficult

Figure 28: Glass structure of the Apple Cube in New York, source: (Mafi, 2019)

Figure 29: Example of an Extuded Glass structure in the form of a truss bridge, source: (Snijder et al., 2018).

to make, direct extrusion is the more common process, (Roeder, 1970). Because of the pressure that is applied on the glass, extrusion allows for a higher viscosity and thereby a colder working temperature. Because of this lower temperature, the used tools are usually made from heat-resisting steel and nickel-based alloys. When higher silica glasses are used the temperature becomes higher and graphite tools are used instead of the metal ones. Extruded glass can be used to make three-dimensional objects like trusses or the swing shown above, which is made at the Delft University of Technology.

3D Printed Glass

The techniques of 3d printing have developed rapidly since the start of the 21st century. 3d printed structures of concrete and plastics are not uncommon anymore in the field of architecture. However, 3d printing glass is something next level, compared to these other materials. The main concern with 3d printing of glass is the annealing process. The casting process is similar to kiln casting, using a chamber where the glass is heated to about 1040°C. From here the glass is printed in the correct shape, build in a second chamber where the temperatures are just high enough to make the layers of glass adhere to each other. Simultaneously the glass is slowly cooled down to room temperature. This process is however still in development at MIT in Boston, (Klein, 2015 and MIT Media Lab, 2018)

The potential of this process lies within the ability to make very complex 3d shapes, in a

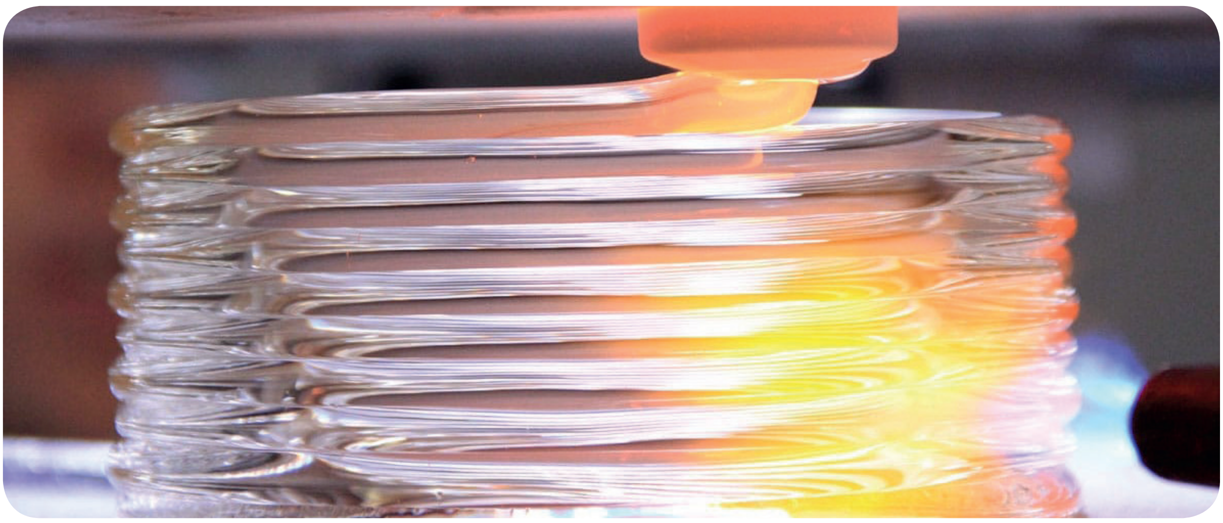


Figure 30: How the layers of glass are placed on top of each other, source: (Llowlab, 2015)

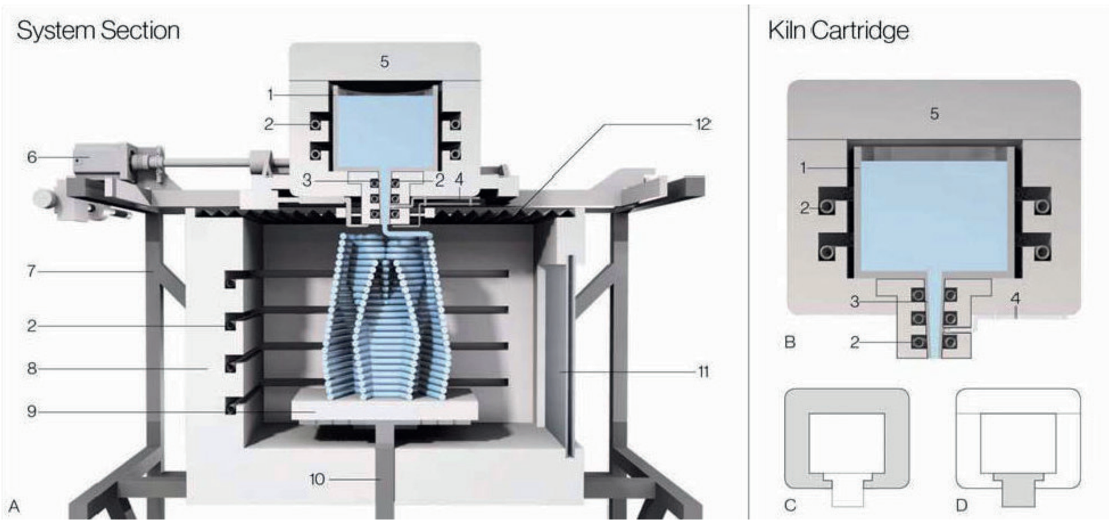


Figure 31: Cross section of a 3d glass printing system, source: (Klein J. , n.d.)

relatively easy way. Compared to casting, no mould making is involved which could speed up the process. The annealing process is, however, a very restricting factor in this process. It is only possible to 3d print glass in a highly controlled annealing chamber, to let it cool down in a very slow and controlled process. Momentarily, the sizes of these chambers determine the maximum sizes of a 3d printed glass object. Moreover, 3d printing glass structure is a process we just start exploring, which the first specimen only being built in 2015, and it is still unknown how the glass behaves structurally.

Cast glass

The fourth and final type of glass production is casting. It is the oldest glass-making technique, but due to the popularity of float glass, the use of casting in the built environment has decreased a lot, but it is still popular in the fields of arts and astronomy, (Oikonompoulou, 2019). To cast glass, it has to be heated until its melting temperature. This can be done in two ways: hot forming and kiln casting. These two processes will be explained later in this chapter, but the main difference is that in kiln casting, reproduced glass blocks are re-molten, while with hot forming the raw ingredients of the glass are used. Once the viscosity of the glass is low enough, it can be poured into the mould, (McLellan & Shand, 1984).

With these moulds, the glass can be cast in any size or shape, which is one of the main advantages of cast glass. This mould needs to be designed well and type can be different for each cast glass application. The different moulds and their advantages and disadvantages can be found in Chapter 4. Once the mould is filled, the glass can be annealed and brought back to room temperature.

Figure 32: The molten glass is manually casted in the mould, source: (Oikonomopoulou, 2019)

3.6 Why cast glass for this application?

From the four alternatives, casting glass shows by far the most potential for this specific design application. It is the only production method which can make three-dimensional objects with a substantial thickness. Maybe in the future, it becomes possible to use the 3d printed glass as well, but for now, this technique is not developed enough to compete with the casting process. Of course, is it possible to build in 3d with both float and extruded glass, but these structures will always be build-up from multiple parts. The connections between these parts, whether they are laminated, adhesively or mechanically connected, will always reduce the transparency of the glass object, compared to one single piece of cast glass. Moreover, the level of detail required to make the glass fit perfectly on the fragmented marble surface cannot be reached with float or extruded glass. This is only possible with casting glass in a very well designed and produced mould. Regarding these assumptions, a cast glass design will be the best solution for recreating a missing piece of marble.

3.7 Casting

As briefly discussed before the casting process of glass can be done in two ways: primary and secondary casting, (Oikonomopoulou, 2019). In primary casting, the raw ingredients of glass are mixed and heated up. Once it has reached its liquid state, it is poured into the mould. This temperature depends on the viscosity of the glass. This material property indicates how smoothly a material flows. For instance, water has a very low viscosity, while honey has a much higher one. With secondary casting, the pieces of glass are re-molten and then poured into the desired shapes.

Hot forming - Quenching

Hot forming or quenching is the main process of primary casting. Here the raw ingredients are mixed at high temperatures till they reach their liquid state and it becomes possible to mix them. The materials must be evenly distributed over the mixture, making the chemical composition equal at all places. When this is done the molten glass is poured into the mould, which is usually made of steel or graphite. Melt-quenching is often used in processes with larger production volumes. Large amounts of raw materials, in the right composition, can be mixed simultaneously and poured over a larger period, as long at the temperature remains above its liquifying point.

Kiln casting

Kiln casting is a secondary production process. Pieces of glass that are made in an earlier phase of the process, are re-molten and poured into

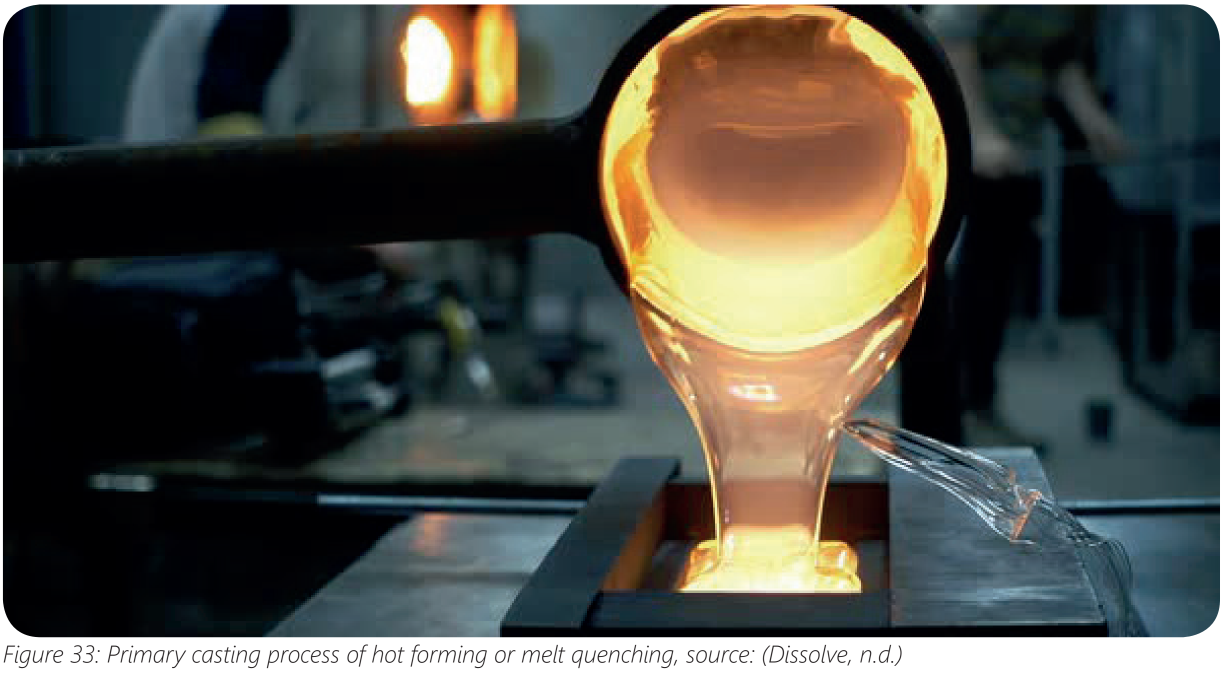


Figure 33: Primary casting process of hot forming or melt quenching, source: (Dissolve, n.d.)

the right shape. With this type of casting, only one kiln is required, which is used for both pouring and annealing the glass, (Bristogianni, Oikonomopoulou, Veer, Snijder, & Nijsse, 2017). The temperatures and the heating time, are thereby defined by the properties of the mould. This could make kiln casting unsuitable for some types of glass with a higher melting point. Especially since kiln casting is often combined with the use of a disposable mould, which cannot always withstand the higher temperatures which are needed for some glass types. This makes it not a very useful technique in mass production processes. It is more often used in prototyping or very small production sizes.

3.8 Annealing

Annealing is the most important phase in the cast glass production process. Making a slight error here, and all the work done in the earlier stages can be regarded as wasted and useless. The purpose of annealing is stated as the process of cooling a material to remove internal stresses, created during the cooling above the annealing point, (McLellan & Shand, 1984). This process is one of the most limiting factors in cast glass design. The annealing process of cast glass element can take up to months for large pieces and the smallest mistake can cause the whole project to fail.

The annealing process is similar for both types of casting. When the viscosity of the glass becomes low enough, due to the rising temperature, it is possible to pour it in the mould. Once the mould is filled, the annealing process begins. As with any cooling process, the outside of an object cools down more rapidly than the inside, resulting in temperature differences in the structure. This results in the contraction of the exterior surfaces towards the hotter interior, causing the build-up of internal stresses, due to strain differences, (Sawyer, 2009)

According to McLellan and Shand (1984), there are three main factors which influence the magnitude of the residual stresses in the glass.

The rate of cooling within the transformation range of temperatures,

Figure 34: The secondary process of kiln casting, source: (Oikonomopoulou, 2019)

The thermal expansion coefficient of the glass and

The thickness of the used section.

The thermal expansion coefficient is a material property which cannot be altered. An option is to choose a different type of glass, with a lower expansion value, but sometimes that is not a possibility, due to other changing material factors. It is also hard to change the thickness of the cross-section since this is usually a well-thought design decision. It would help if annealing is taken into account when cast glass components are designed, but once the production process has started, further changes are ruled out. This leaves the rate of cooling as the best option to minimize the residual stresses in the glass and is the reason why the annealing process is so important. Since a piece of glass is mechanically speaking in balance, there will be both compression and tensile stresses in the glass. The amount of occurring stress is hard to predict, but once the tensile stress exceeds the maximum the glass can withstand, the piece will fracture immediately and will be unable to use.

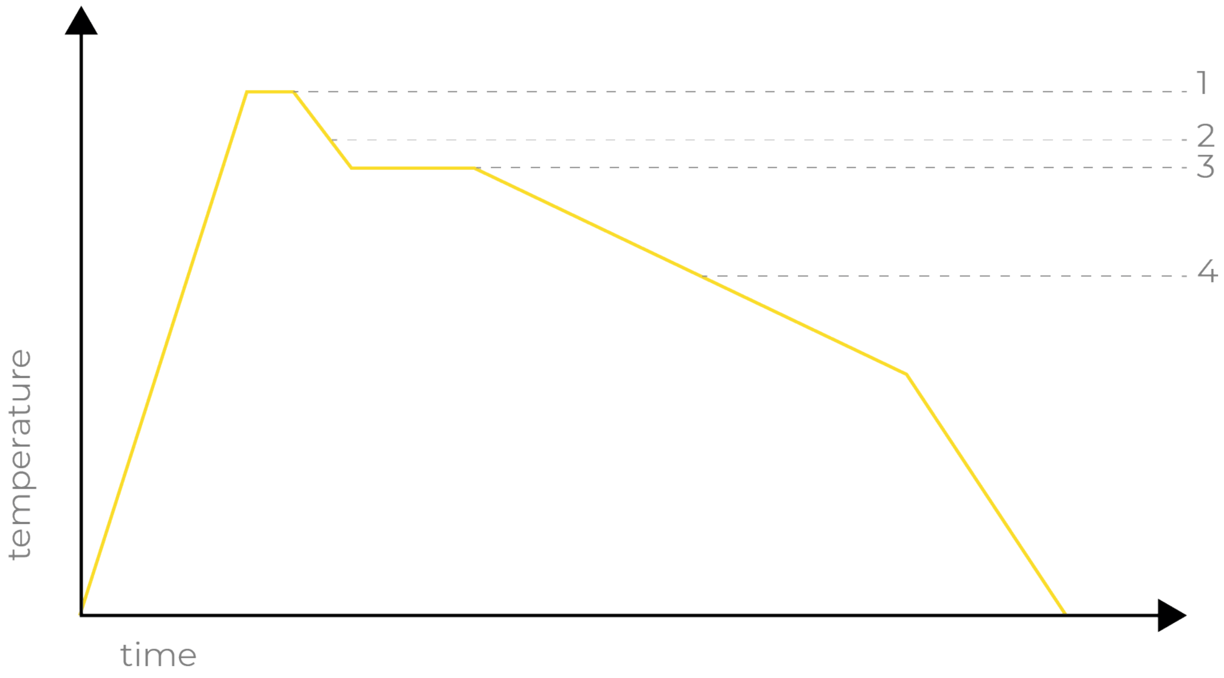


*Figure 35: Different cooling stages of the annealing process, **1**: working temperature; **2**: softening temperature; **3**: annealing temperature; **4**: strain point*

During the annealing process, the glass goes through different phases, shown in the figure above. In the casting process, the glass will be heated to a temperature above its annealing point. At this working temperature [1], the viscosity of the glass is low, making it almost fully liquid and easy to pour. At this temperature any internal stresses will be released within minutes, (McLellan & Shand, 1984).

Soon after the mould is filled it is rapidly cooled to just below its softening point [2]. This is the point from which the glass is solid enough to retain its shape under the pressure of its own weight but simultaneously viscous enough to release the internal stresses, (Oikonomopoulou, 2019).

From this point, the cooling rate will be much lower. During the cooling process, a thermal gradient will appear between the hot core of the object and the cooler surface. This temperature difference will result in the build-up of stresses. The amount of stress at any point in the glass is proportional to the difference between the local temperature and the average temperature in the section, (McLellan & Shand, 1984). Thus the bigger the temperature difference, caused by rapid cooling, the more stress is build-up in the glass. Ideally, the maximum temperature difference in the glass is lower than 5°C, (Sawyer, 2009). This is the reason why the cooling process is so delicate and time-consuming. Till the annealing temperature [3] is reached, the glass is capable of plastic deformation, allowing for a relatively quick release of stress, which is built up during the cooling. In this annealing range, the glass transits from a plastic to an elastic material, (Sawyer, 2009).

At the annealing temperature, the viscosity is still low enough to allow for molecular rearrangement. It is recommended to maintain this temperature for adequate time because here, stress relief can occur within a couple of minutes, (Sawyer, 2009). One the glass is cooled further this will slowly get harder and more time-consuming. Once the glass reaches its strain temperature [4], it can take hours to relief residual stresses. Below the strain point, the viscosity becomes too high and strains are unable to relax. Any present stresses in this phase are thus considered permanent, (Oikonomopoulou, 2019). When the temperature of the object has dropped below the strain point, the cooling rate can speed up, although the risk of breakage due to thermal shock should be taken into account.

Controlling the annealing process

The process of cooling down the glass is affected by many variables, from which the size of the object is the most influential one,

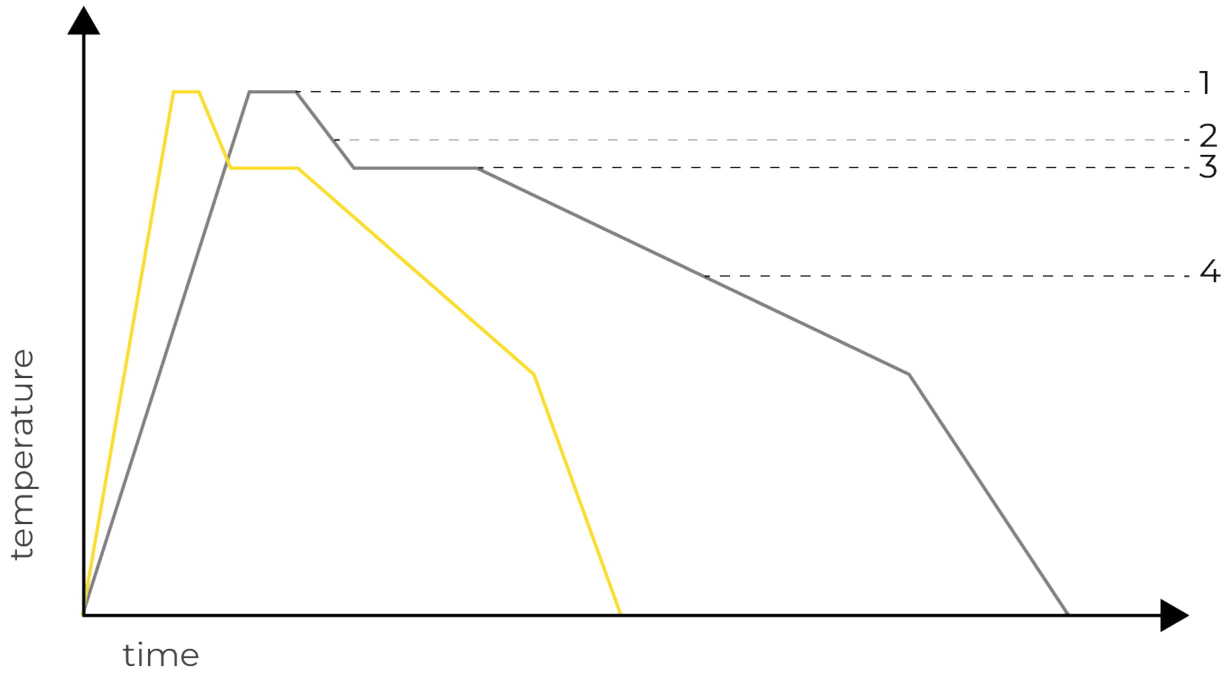


Figure 36: Influence of the mass of the glass object on the annealing time.

(Schott AG, 2019). However, there are more parameters which affect the time and quality of the annealing process, most of them very well controllable. Some variables are design related, as the shape and volume to surface area ratio. It is, for instance, better when an object does not have sharp edges or corners. A smooth, preverbally round or ellipsoid object, has the best annealing properties and the amount of surfaces exposed to cooling affects the process as well, (Oikonomopoulou, 2019).

Also, small differences in the equipment can lead to deviations in the expected temperatures. Examples are the mass and geometry of the furnace and type and design of the mould. When a casting is completely enclosed in a mould, the cooling process is more homogeneous, since the mould itself acts like a thermal barrier, which reduces heat loss. A casting in an open mould has one or more surfaces which cool down more rapidly than the other ones, thereby increasing the temperature difference, (Bray, 2001)

3.9 Application of cast glass and its limitations

Within architecture, structural cast glass elements are still quite rarely used. Examples are the Crystal Houses, Atocha Memorial, Crown Fountain and the Optical House. In these projects, solid cast glass blocks with a weight between 2 and 8.4 kilos have been used as a masonry structure, some supported by a sub-construction, some are fully self-supporting, (Oikonomopoulou, 2019). The time-consuming annealing process has prevented the used of larger cast glass pieces in architecture since the production would become too expensive.

Art is a field in which large cast glass elements are more common. There are various examples where large castings have been used in expositions. Some of them do however show signs of improper annealing, although in most cases there is little information about how this process was executed, (Oikonomopoulou, Bistrogianni, Barou, Veer, & Nijsse, 2018). These sculptures are likely made in a more experimental way, using trial and error. In most cases these art pieces do not have structural applications, so cracks and other flaws in the glass do not decrease the performance of the object, in the worst case, they only reduce the aesthetics of the sculpture.

Nowadays, the largest monolithic cast glass structures are used in the mirrors of space telescopes. The first ones were made from a completely solid disc. The largest one was 2.5 meters in diameter, containing 4 tons of glass, and took 12 months to anneal. But as the demand for larger telescope mirrors increased,

Figure 37: Optical House in Hiroshima, Japan, source: (Archdaily, 2017)

new techniques need to be found to reduce the production time and costs. This technique was found out by Corning, in the design of the Hale telescope at Mount Palomar. With a 5 meter diameter, it would be too large to anneal it as a solid piece. Instead, a honeycomb structure was designed for the glass. This hexagonal pattern, that reduced the weight of the mirror enormously, combined with a newly designed, less expanding type of glass the annealing time was reduced to 10 months. Two months shorter than the previous largest mirror, despite being four times as heavy. However, the post-processing of the mirror took more than 10 years, so there was still a lot of room for improvement, (Oikonomopoulou, Bistrogianni, Barou, Veer, & Nijsse, 2018).

Figure 38: An exposition of solid cast glass sculptures by Roni Horn, source: (Oikonomopoulou, 2019).

This improvement came in the form of spin casting, a new technique, which can create a parabolic shaped mirror, by using a rotating mould. This significantly reduced the annealing and post-processing time of the mirror. This technique is applied in the production process of the largest contemporary monolithic cast glass structure: the Giant Magellan black. This giant has a diameter of 8,4 meters and a total weight of 16 tons. This results in a 90% weight reduction, thanks to the thinner ribs of the mirror, (Oikonomopoulou, Bistrogianni, Barou, Veer, & Nijsse, 2018)

So concluding, two main parameters can be tuned to reduce the annealing time of large cast glass pieces. The first one is shape optimisation, like the hexagonal ribs in the giant telescope mirrors. Less weight means less stored heat, that needs to be released in the annealing. As the telescopes show, with a clever shape optimisation, the largest made telescope mirror has a four times shorter annealing time than the largest solid blank, despite it is 4 times heavier. The second variable is the type of glass. In the Giant Magellan blank E6 borosilicate glass is used. This glass has lower working temperatures, thus a lower amount of stored heat, and expands significantly less than Pyrex glass, which was used in the Mount Palomar telescope, allowing for a faster cooling process. This shows that clever thinking can reduce the production time and thereby also the costs enormously and opens new possibilities for the application of large cast glass elements.

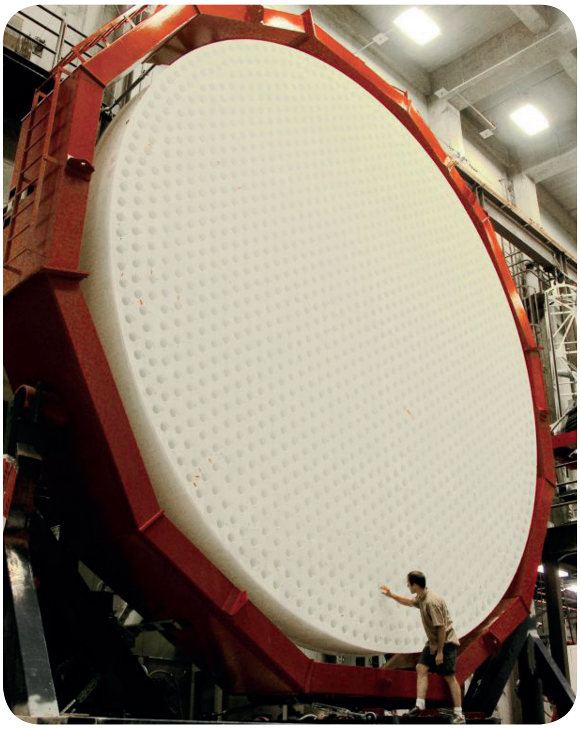


Figure 39: Giant Magellan Telescope mirror, source: (Smithsonian Insider, 2012)

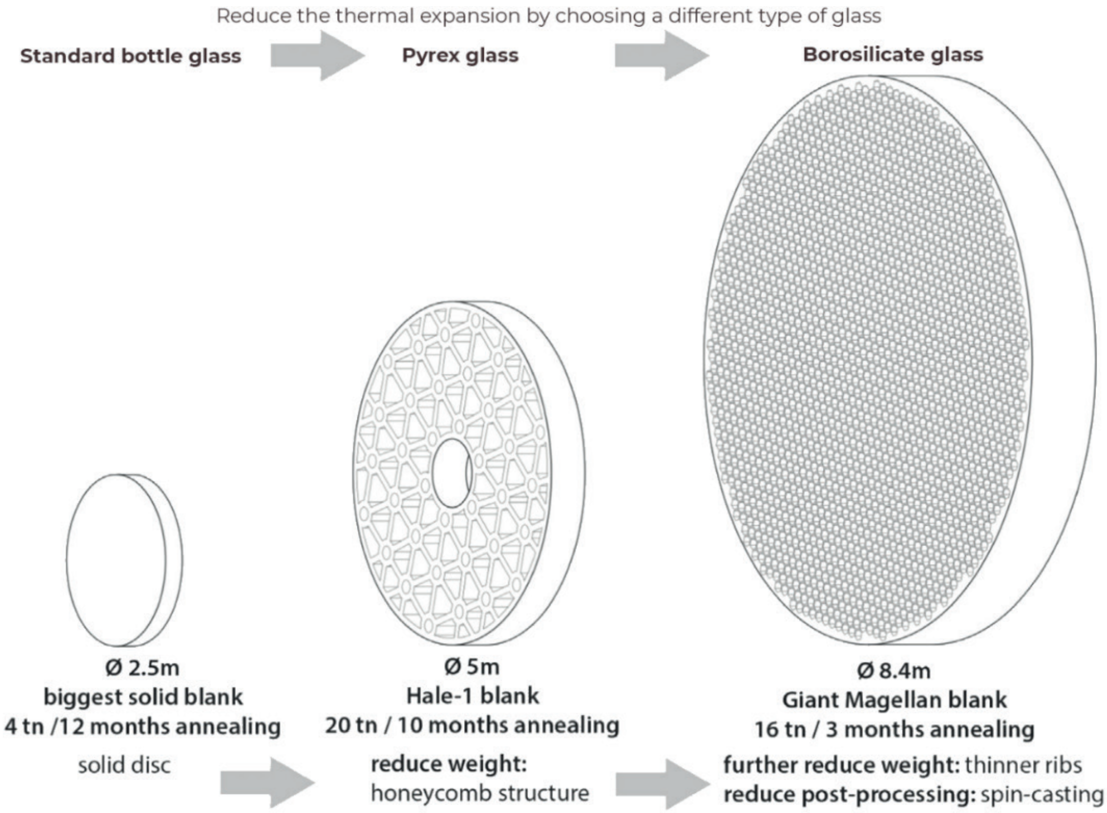


Figure 40: Evolution of the sizing and shaping of large telescope mirrors, source: (Oikonomopoulou, Bistrogianni, Barou, Veer, & Nijsse, 2018).

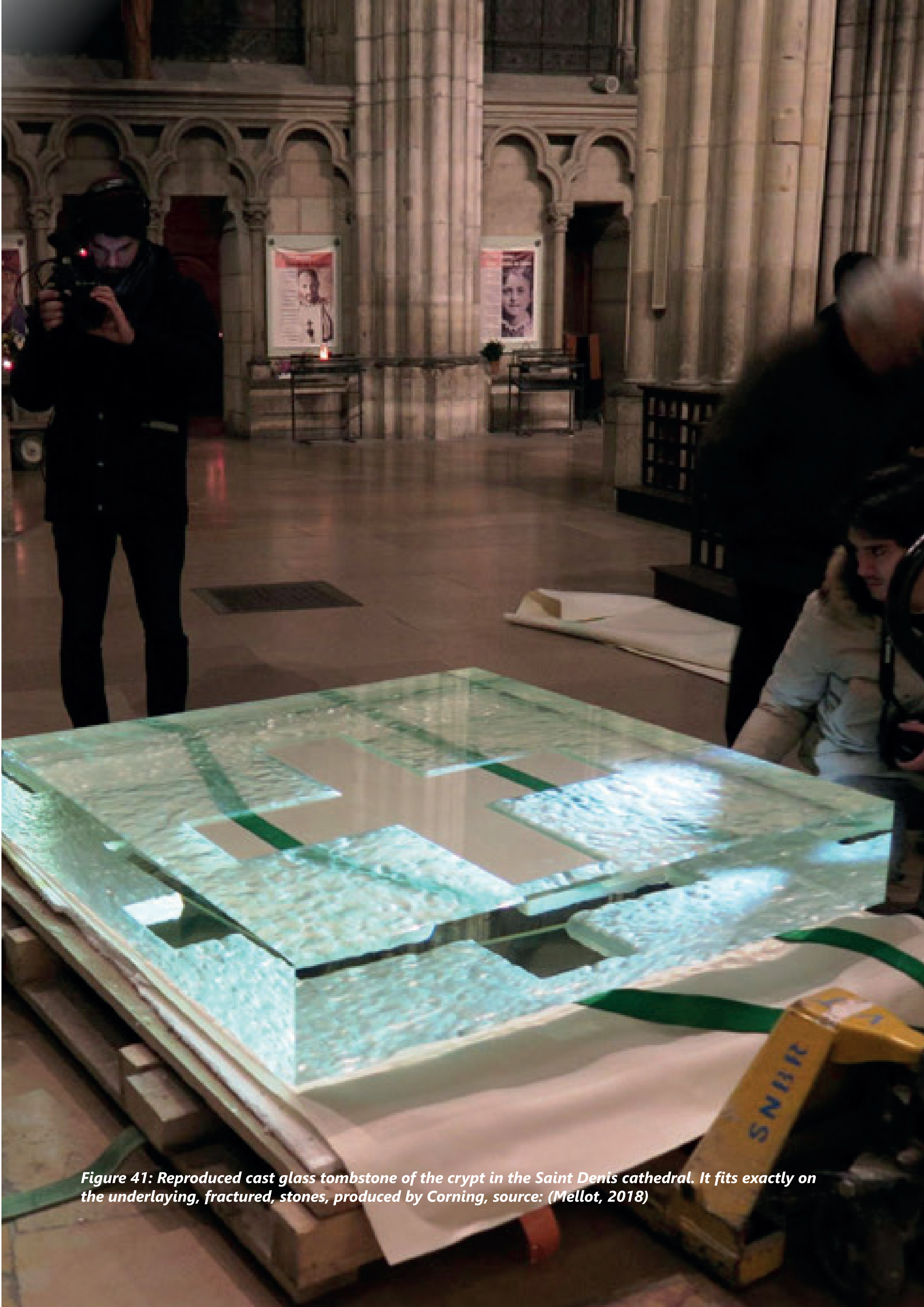


Figure 41: Reproduced cast glass tombstone of the crypt in the Saint Denis cathedral. It fits exactly on the underlaying, fractured, stones, produced by Corning, source: (Mellot, 2018)

04.

REPRODUCING A MARBLE ELEMENT BY CASTING

4.1 Introduction

In this chapter, the production steps, between having a fractured piece of marble and a fitting counter shape of glass will be discussed. The techniques regarding casting glass and annealing are discussed in the previous chapter, so these will not be discussed here. When applicable, there are several options given on how the process could be approached and which techniques are available.

4.2 3D scanning

To generate the geometry of the missing pieces of the monument, the structure needs to be digitalised, using 3D scanning technologies. With these scanners, the existing state of the structure can be examined and a new replacing geometry can be made. There are several types of 3D Scanning, which can be divided into two groups

4.2.1 Contact

Contact scanners collect data through a physical touch of the object. A 3D probe touches many points which are collected digitally and thereafter translated into a 3D model. Contact scanners are very precise and come in various types but it is recommended to not use them on organic or vulnerable objects. The contact between the scanner and the object is the slightest of touches but still could cause some damage to a fragile object. This is why non-contact scanners are preferred for scanning art and other objects with historical value, (Mongeon, 2016)

4.2.2 Noncontact

Instead of using physical contact, these scanners make use of electromagnetic radiation to determine the distance between a point of reference and the recorded surface. A very well-known application of these scanners are x-rays but outside of the medical world, scanners use light waves with a lower frequency. There are several scanners available, each one has different properties and is thereby suitable for different applications. These non-contact scanners come in two different types: passive

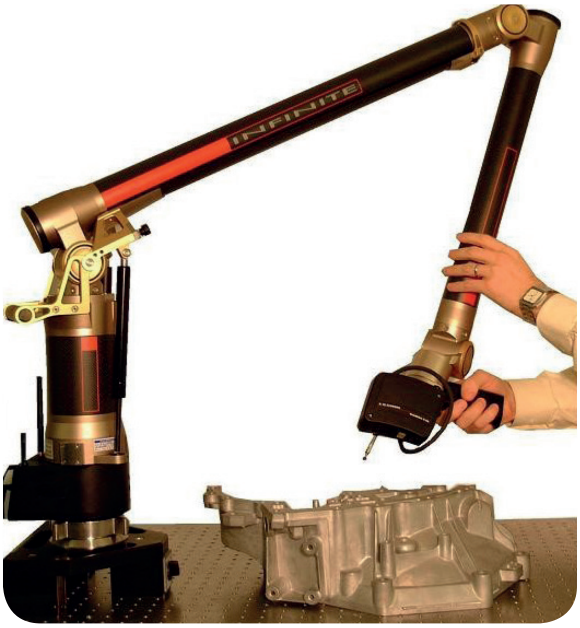


Figure 42: Example of a manual contact scanner, source: (Langnau, 2015)

and active. The difference between these two is that an active scanner sends out a ray of light and captures it again while passive scanner captures the light emitted by an external source, (Mongeon, 2016)

Nowadays, almost all active scanners operate on three different range principles, triangulation, pulse or phase comparison. The main differences between these three calculation methods are the level of accuracy they can reach and the maximum distance from the measured object. Up next, each of the three options will be discussed and evaluated, based on their properties and advantages and disadvantages regarding the scanning of heritage, (Historic England, 2018).

Principle

Triangulation

Triangulation is a form of active scanning, based on the cosine calculation method. The distance between the laser and the camera is fixed. To calculate the distance between the camera and the object, the angle of the laser, relative to the principal directions of the global coordinate system, is measured. With this angle and the distance between the laser and camera, the distance to the object can be calculated. To determine the position of the reflection point, the distance will be linked to direction, based on the angle of impact of the laser beam on the camera.

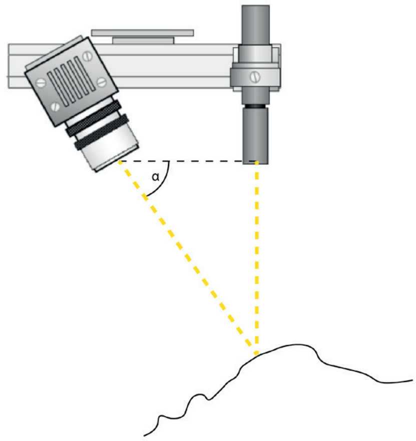


Figure 43: Scanning principle of triangulation

Pulse-Phase Comparisson

Pulse-phase scanners are the most straightforward scanners on the market. They emit a pulse of light, and measures the time till the wave has returned in the camera. A simple calculation of the speed of light multiplied by the time gives the distance to an object Over the past years, the scanning process has become much quicker, thanks to the development in technologies. Despite that the next pulse cannot be emitted before the previous one has returned, the latest cameras can reach a frequency of one million points per second.

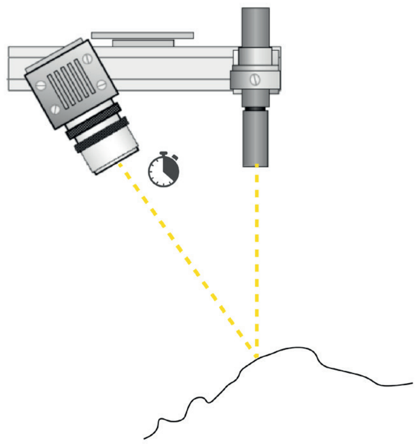


Figure 44: Scanning principle of Pulse-Phase Comparisson

Phase Comparisson

Pulse-phase scanners are the most straightforward scanners on the market. They emit a pulse of light, and measures the time till the wave has returned in the camera. A simple calculation of the speed of light multiplied by the time gives the distance to an object Over the past years, the scanning process has become much quicker, thanks to the development in technologies. Despite that the next pulse cannot be emitted before the previous one has returned, the latest cameras can reach a frequency of one million points per second. (Historic England, 2018)

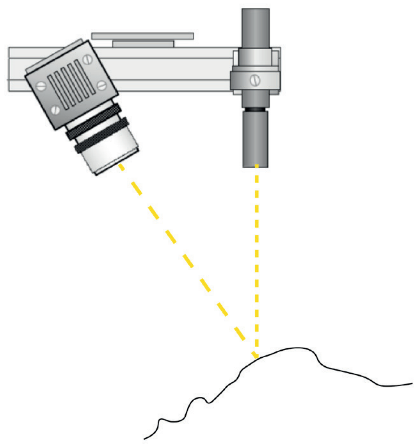


Figure 45: Scanning principle of Phase Comparisson

Triangulation is often used for detailed scanning of archaeological features because it is more accurate than the other two principles. Based on the method one uses, the accuracy of the scan varies between 0.05 and 30 mm, depending on the distance between the sensors and the object. This makes triangulation a very suitable method for close-range scanning, where a high level of detail is required. A downside of this method is that is sensible for ambient light. It works better in a dark room, where there is no distortion from other light sources. This could make it difficult to use this method in outside conditions, (Historic England, 2018).

Pulse-Phase comparison is often used for long-distance measurings, like geomorphological and glacier-monitoring applications. It is less likely that it is used for scanning cultural heritage objects of buildings, although accuracies between 1 and 6 mm do allow for this application as well. Compared to the triangulation method, the pulse-phase principle is made to cover larger distances, thereby sending out light waves with much higher energy. This makes them less vulnerable for ambient light distortion and thereby better applicable in outside conditions, (Historic England, 2018).

Phase-comparison cameras send out a continuous wave, instead of the phase-pulse method, which emits short bulbs of light. This results in much higher data capture and thereby high-resolution scans. This makes phase-comparison scanners very suitable for recording heritage objects. However, the high density could also cause problems since low details parts of a scan could be recorded to heavily. This eventually could create problems in the computer processing phase, since it requires much more computational power to generate all the points, from which some are unnecessary, (Historic England, 2018).

Passive scanners

The technique of passive scanning has been around since the 1920s when it was used to make maps from the earth. For a long time, technology did not allow for further development but has taken advantage of the rise of digital image processing, which makes it very easy to generate digital models, (Chandler & Buckley, 2019). Passive scanners use a different process to digitalise the three-dimensional object. The most important difference between the two is that passive methods do not emit radiation themselves. They capture the ambient radiation which is deflected by the object and turn that data into a 3d model, using software and algorithms, (Ebrahim, 2015). Most cameras detect visible light, however, other types of radiation, such as infrared or ultraviolet can also be used. The primary advantage of passive methods is that they can be very cheap. Most cases do not need sophisticated hardware, mostly a simple digital camera is enough. There are several passive scanning techniques and methods. The most well-known are explained below.

The development of scanning methods, together with a clever marketing strategy has mad active scanning the most obvious choice for close-range 3D scanning. Despite that these techniques are widely applied there are still some disadvantages which remain. They are largely related to practicality and cost of the scanning equipment. The costs of a decent scanner varies between $30,000 and $80,000, however, as technology develops, prices are expected to drop, (Chandler & Buckley, 2019). These high costs have given away for other methods to access the market and compete with the costly active scanning technologies, the passive scanning methods. However, for this design application, a high-quality scan is a hard criterion, so the surface of the fractured marble will be scanned actively. The most promising method would then be the triangulation. With this scanning technique, the highest accuracy can be reached and it can be used on very close distances, and is less prone to ambient light, so the scanning can be done on-site.

Stereoscopic

This scanning method uses two video cameras, which are placed slightly apart from each other but looking at the same point. The two viewports are compared with each other and with an algorithm, the slightest differences are detected. Based on this, the distance between each point can be calculated in 3D. This works the same as having binocular sight. Just like the aforementioned cameras, our eyes are slightly apart from each other and aim in the same direction. Thereafter, our brain compares the view from one eye to the other, thereby noticing minimal differences, which are translated into depth in our sight.

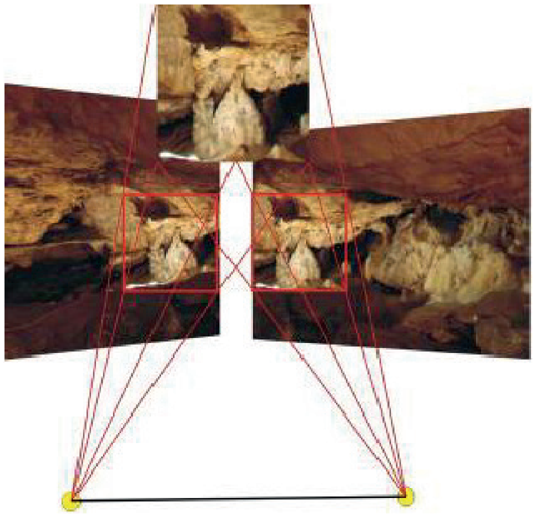


Figure 46: Stereoscopic scanning principle, source: (Rodriguez-Gonzalves, et al., 2011)

Photometric

Instead of using two cameras, photometric scanning uses only one. Multiple images are made under varying lighting conditions. With software can be determined how the light reflects from each point in the object. With this data, the orientation of each piece is calculated, combining them will lead to a complete solid shape, (Ebrahim, 2015).

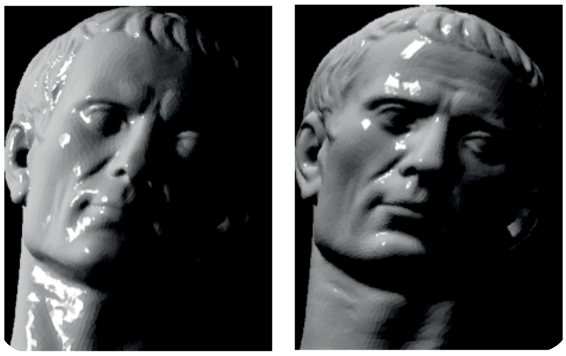


Figure 47: Photometric scanning principle, source: (en.wikipedia.org, 2019)

Silhouette

Silhouette scanning the outlines of an object are detected by the camera. A well-contrasted background is used to highlight the shape of the object. These silhouette pictures are taken from all angles and then combined into one three-dimensional object by intersecting the images.

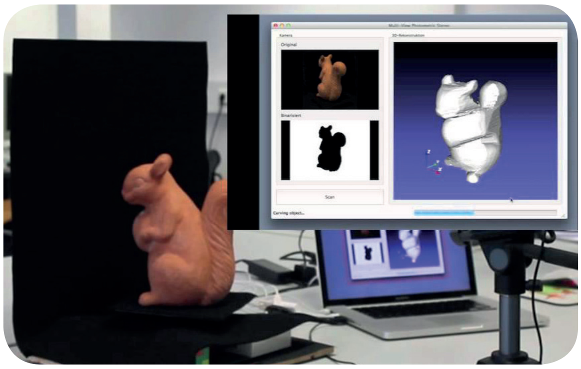


Figure 48: Silhouette scanning principle, source: (Wolf, 2013)

Photogrammetry

The word photogrammetry is a combination of photography and geometry and explains exactly how the process works. Several photos are taken from all around the object. A computer searches for common points in these pictures and with these points, a 3d shape is made. It is a very accessible method since you only need a camera and proper software. The quality of the scan is heavily dependent on the quality of the camera that is used. A better camera leads obviously to better scans, but also a constant distance and angle to object improves the quality (Ebrahim, 2015).

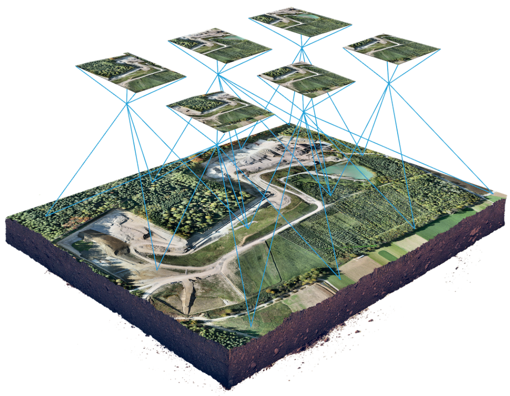


Figure 49: Photogrammetry scanning principle, source: (Wingtra, 2019)

4.3 Model Reconstruction

When the scan is completed, the computer will generate the data and produce a point cloud. This is the same for both active and passive scanners. The density of the point cloud depends on the quality of the scanner and is also related to scanning time. It takes more time to generate a higher resolution of points. A good scanner can produce more points at the same time but is thereby obviously more expensive. The desired point density depends on the use and is thus different for each scan.

The produced point clouds could be used instantly for measurement and visualisation, but for most applications, the points need to be transferred into 3D models. There are three general types of 3D models, where the points can be imported: Polygon mesh models, Surface models and Solid CAD models. The most suitable type depends on the industry in which the scan will be used. Each meshing type is slightly different and has advantages and disadvantages. The most important ones will be discussed below, (Ebrahim, 2015).

The first type is the Polygon Mesh, in these models, curved objects are tessellated into smaller flat surfaces to approach the actual shape. The smaller the surfaces are, the closer the model comes to reality. This makes it very hard to edit the geometry after the mesh is generated from the scan. Another downside of this is that it makes the model relatively heavy, compared to the alternatives. It is, however, suitable for many types of software, including widespread use ones like AutoCAD and Rhino.

Surface models are a more sophisticated type of meshing. This type makes use of NURBS which do allow for curvatures. It is thereby not necessary to split them up in smaller surfaces. This makes these models much lighter than Polygon meshes. The surfaces in these models are editable, but only in a sculptural way, like a clay model. This allows for more dynamic and organic shapes and is thereby also suitable for artistic purposes.The last type is the Solid CAD model. From an engineering perspective, this the best representation of a digitized shape. It can be parametric and is thereby very easy to edit. This has made CAD the standard language in the manufacturing industry, (Ebrahim, 2015).

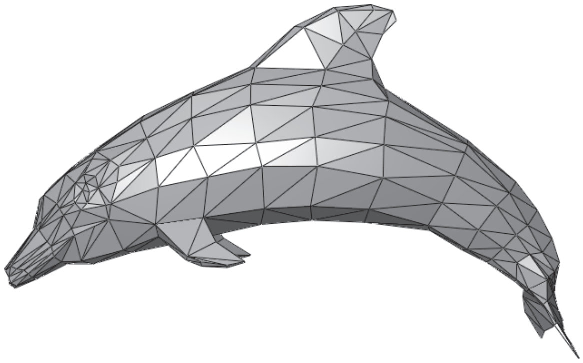


Figure 50: Polygon mesh, source: (en.wikipedia.org, 2019)

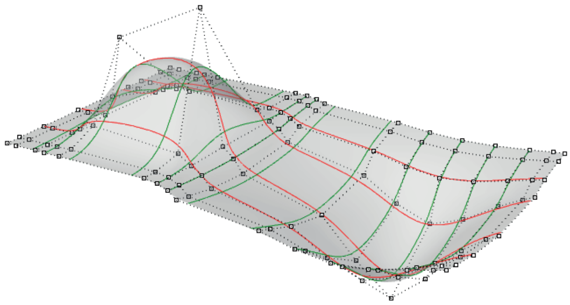


Figure 51: Nurbs surface, Source: (Issa, 2019)

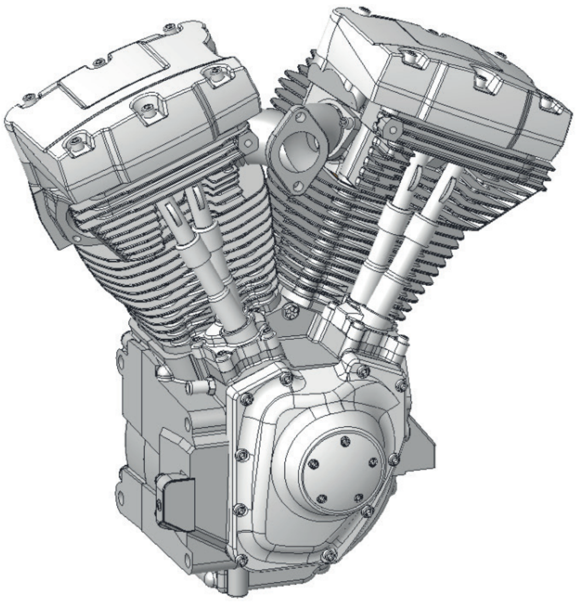


Figure 52: 3D CAD model, Source: (DBBP Shop, 2019)

4.4 Mould Making

To turn this digital three-dimensional model into cast glass pieces, the shape needs to be inverted and thereafter translated into a mould. There are a lot of different types of mould, each one has its own properties, advantages and disadvantages. Choosing the best mould is a delicate procedure and differs for each application. The primary factors in this decision are the production volume and the level of accuracy that is desired in the glass, (Oikonomopoulou, 2019).

Regarding these criteria, moulds can be divided into two categories: disposable and permanent moulds. Disposable moulds are cheaper than permanent ones and are thereby more cost-effective with lower batch sizes or prototypes. Permanent moulds can be used multiple times, but come with higher production costs. The higher the production volume becomes the less economical the use of disposable moulds becomes, this goes on till the amount is reached when making a permanent mould has become more cost-effective. The table below shows the comparison in production and usage between the disposable and permanent moulds.

Permanent moulds.

Permanent moulds can be made from two materials: (stainless) steel and graphite. With these materials, a higher accuracy and detail lever can be reached, compared to the disposable moulds. Besides the standard fixed moulds, a similar process as with disposable ones, these materials allow for pressed and adjustable moulds as well. With pressed moulds, an even higher casting quality can be achieved. Adjustable moulds are especially efficient in applications where one dimension of the casting is variable. This is only applicable to steel moulds and has a negative effect on accuracy and detailing.

With steel and graphite moulds, minimal to none post-processing is needed to reach transparency. Only if the desired accuracy cannot be reached by casting, the elements need to be polished To remove the glass smoothly from the mould, a coating is required on the inside. It is possible to remove the mould before the annealing process is finished. This reduces the accuracy but allows for a quicker production process since the mould can be reused much faster.

	DISPOSABLE MOULDS			PERMANENT MOULDS	
REUSABILITY	SINGLE - USE			MULTIPLE - USE	
MATERIAL	SILICA PLASTER	ALLUMINA SILICA	3D PRINTED SAND MOULD	STAINLESS STEEL	GRAPHITE
ADJUSTABILITY	NON-AJUSTABLE			AJUSTABLE - FIXED PRESSED	
COSTS	LOW	HIGH	LOW	MODERATE	HIGH
TOP TEMPERATURE	900 - 1000	1600 - 1650	?	1260	?
ANNEALING METHOD	MOULD NOT REMOVED DURING ANNEALING			POSSIBLE	REMOVED
RELEASE METHOD	IMMERSE IN WATER	WATER PRESSURE	WATER PRESSURE	RELEASE COATING NECESSARY	
ACCURACY	LOW/MODERATE	HIGH	MODERATE	MODERATE / HIGH / VERY HIGH	
FINISHING SURFACE	TRANSLUCENT			GLOSSY WITH SURFACE CHILLS	

Figure 53: Properties of the different mould types, based on (Oikonomopoulou, 2019)

These permanent moulds do allow for both types of casting, although quenching is usually the most logical option. Permanent moulds are almost only used with large production levels and since melt-quenching is more time-efficient than kiln casting, these two are often used together in the production process, (Oikonomopoulou, 2019).

Disposable moulds

Disposable moulds are made from a much cheaper and easier to process material and come usually in two types: Silica plaster and Alumina-silica fibre. The main difference between them is the quality of the casting and the operating temperature. Due to the higher temperatures Alumina-silica fibre can withstand, the glass can be poured in more easily. A higher temperature leads obviously to a more fluid mixture. This allows for a better filling of the mould, with a lower chance of flaws and thereby a higher quality casting. Both mould materials will give the glass a translucent look as the mould material tends to stick to the glass. This results in a rough translucent surface, so post-processing is vital if a smooth glossy surface is desired.

Silica plaster moulds are made by investment casting, where the positive shape of an object is used to create the negative one. The mould itself is thereby cast as well, using a test specimen. With alumina-silica fibre moulds a different process is used. These moulds are usually grinded into the right shape. Once the glass is poured into the moulds, it will stay there till it is completely solid. It is not possible to remove the mould before the solidification has ended. The moulds are eventually removed with water. With the silica plaster, it is enough to drown them in the water, alumina-silica requires more force to be removed.

Figure 54: High precision, permanent steel moulds for the Crystal Houses project, (Oikonomopoulou, 2019)

Both materials have a very brittle structure. This makes them more vulnerable than steel or graphite moulds. It is thereby recommended to not use the quenching method to pour the glass. Usually, kiln casting is applied with these moulds, (Oikonomopoulou, 2019).

Figure 55: Disposable Silica Plaster Mould, source: (Oikonomopoulou, 2019)

A new promising type of disposable mould is the 3D printed sand mould. Under glass artists and for metal casting, sand moulds are already a commonly used technique, like in Figure 56, where aluminium profiles are cast in a sand mould made from only wood and sand. Combining this ancient technique of casting with 3D printing, complex shapes can be sand-casted very easily. This technique has been used in several cases by Arup and 3Dealise to make complex shaped steel nodes, like the one that is shown in Figure 57. However, due to the low accuracy level has prevented the usage of sand moulds in the production of building elements. However, when this accuracy can be increased, the use of 3d printed sand moulds could take the production process of cast glass to the next level, (Oikonomopoulou, Bistrogianni, Barou, Veer, & Nijsse, 2018).

With 3d printed sand mould, the casting process is as similar as for any other type of mould. However, these moulds are quickly made and the used materials can be easily reused, thereby reducing the production costs and increasing the sustainability of the moulds, (Niehe, 2017). The typical material that is used in the sand moulds is Silica sand and has three different grain sizes, varying from 140 to 250 micrometres. This sand is applied layer by layer, while a printing head applies the binder, based on the geometry in the CAD file. This process is repeated until the final shape is completed, as can be seen in Figure 58. After this, the excessive sand is removed and can be reused in future prints. The layer thickness of the print varies between the 0.3 and 0.4 mm, (Voxeljet, 2018)

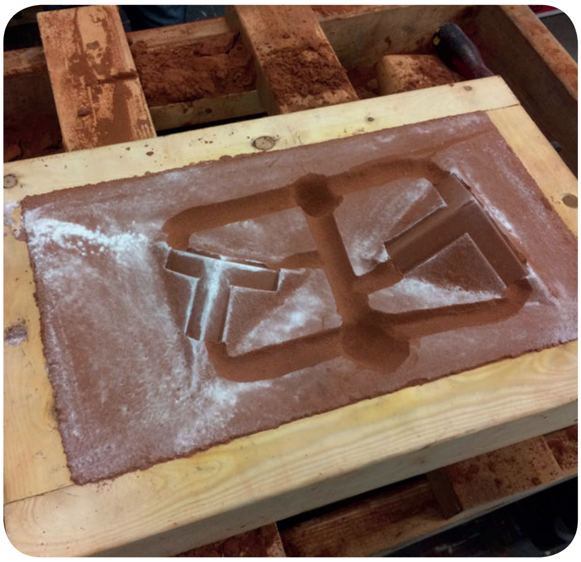


Figure 56: Hand-made sand mould for aluminum casting, source: (fab.cba.mit.edu, 2013)

Figure 57: 3d printed sand mould to cast a steel node, source: Davidfotografie from (Niehe, 2017)

3D printing process

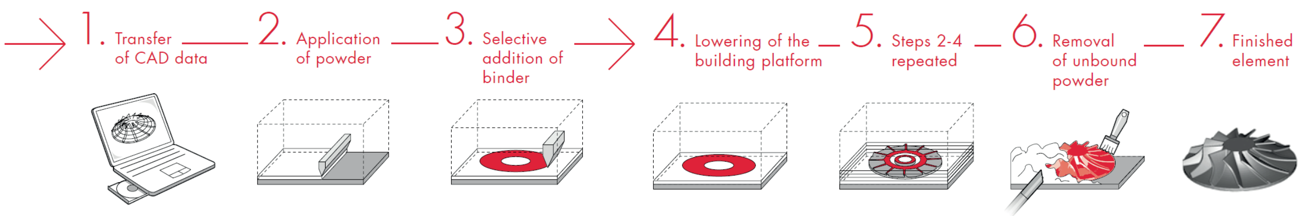


Figure 58: Sand mould production process, source: (Voxeljet, 2018)

Damen (2019) and Singh (2019) both did research produced prototypes of cast glass in 3D printed sand moulds. The results of these theses is shown below, with on top a part of a topologically optimised glass column, (Singh, 2019), and below a topologically optimised glass node, (Damen, 2019). In both prototypes complex glass shapes have been cast in sand moulds, showing the potential of this casting method for further research and development.

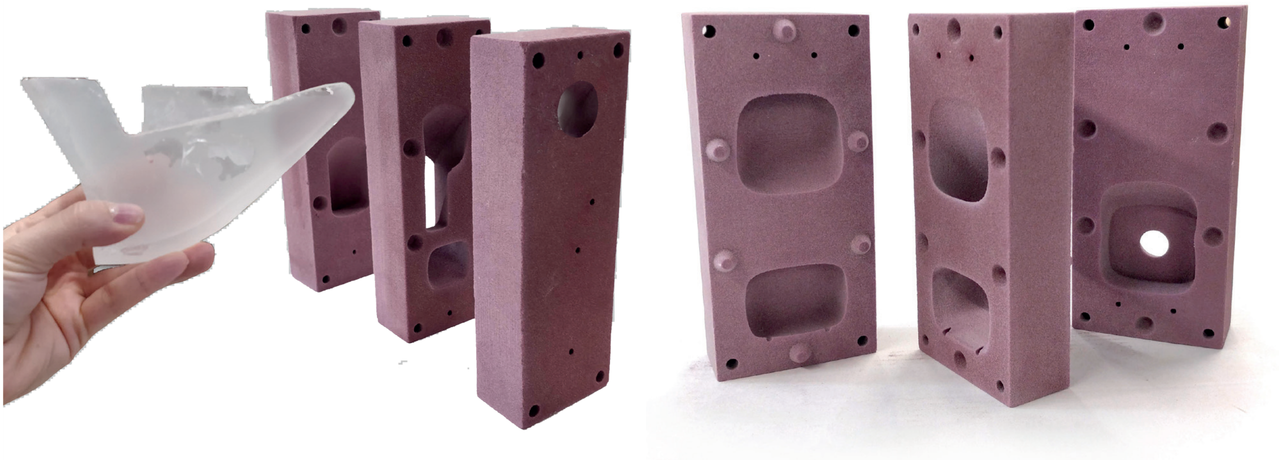


Figure 59: Glass prototype cast in a 3D printed sand mould, source: (Singh, 2019)

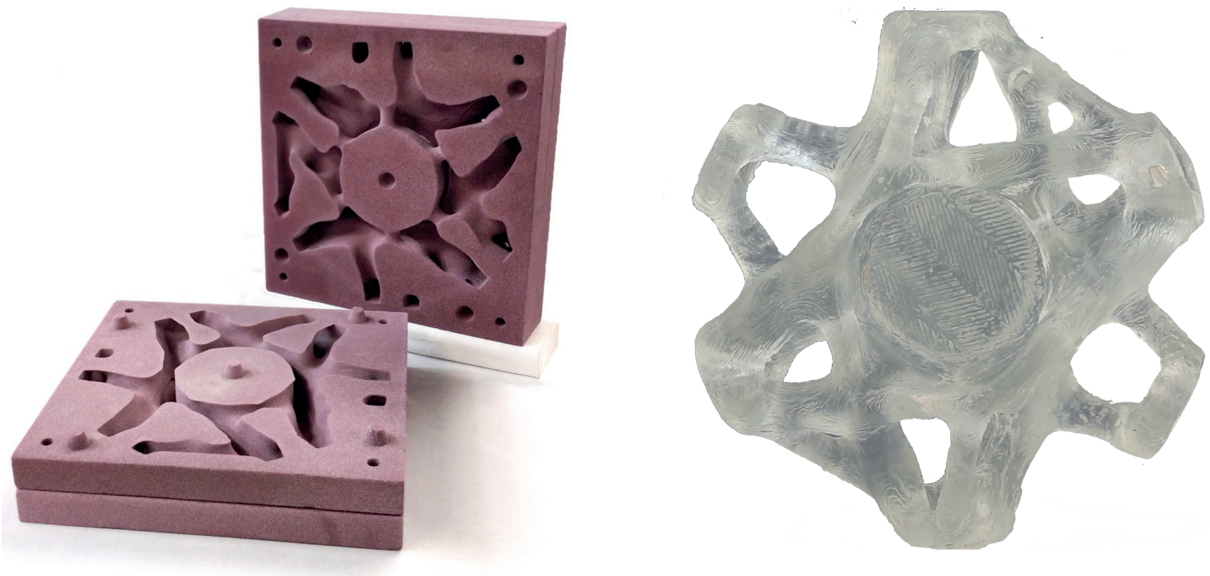


Figure 60: Glass node, cast in a 3D printed sand mould, source: (Damen, 2019)

4.5 Connect cast glass components

Once the annealing and post-processing are finished, the glass can be used as a building material. The final step of the production process is connecting the glass or to another building material. At this moment there are three types of glass connections, each having their advantages and disadvantages, all discussed below, (Oikonomopoulou, Bistrogianni, Barou, Veer, & Nijsse, 2018) and (Oikonomopoulou, 2019).

Adhesive connection

To maximize the transparency of a glass structure, adhesive connections will likely be the best way to reach it. Adhesives, such as acrylates or epoxies, acts like glue and permanently bonds two layers of glass to each other. This makes the adhesive connection a very strong one since the load transfer is homogeneous. With the right thickness and material, the bonded glass elements can structurally cooperate, creating one single rigid behaving structure. These strong bonds do however have an important downside and that is that they are completely irreversible. This makes it hard to replace damaged adhesively bonded parts and recycling is also nearly impossible. Another point worth concerning is the labour intensity of the process. Applying the adhesive is a very delicate and precise task. The layer is often only several millimetres thick, so it cannot accommodate dimensional tolerances in the geometry of the glass, like mortar can in a masonry wall. This makes it difficult to do this on-site, although it is still possible, as is proven in the Crystal Houses project in Amsterdam and Atocha Memorial in Madrid.

Mechanical connection

Mechanical connections are more diverse than the adhesive connections. One option is to use a metal substructure to connect and provide stability and stiffness to the glass elements. These type of structures are used in the Optical House in Hiroshima and Chicago's Crown Fountain, (Oikonomopoulou, Bistrogianni, Barou, Veer, & Nijsse, 2018). In the Optical House, the glass bricks are punctured and threaded by pre-tensioned steel cables. These cables give the system the lateral stability, while the glass is self-supporting. In the Crown Fountain façade, the glass bricks are preassembled and connected to a stainless steel structure, which takes up both the vertical and horizontal loads.

Another type of mechanical connections is the metal joint. This type is already very common in float glass structures since they can easily be inserted during the lamination process. In cast glass, this application is still in the research phase, but inserted metal elements could eventually be a potential connection method for cast glass as well.

Figure 61: Adhesively bonded glass bricks in the Crystal Houses project, source: (MVRDV, 2016)

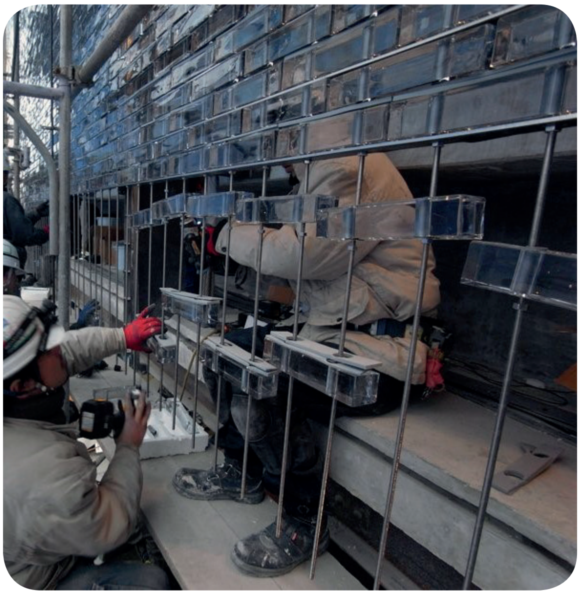


Figure 62: Assembly of the glass blocks to the mechanical support system in the Optical House, source: (NAP & Hiroshi Nakamura)

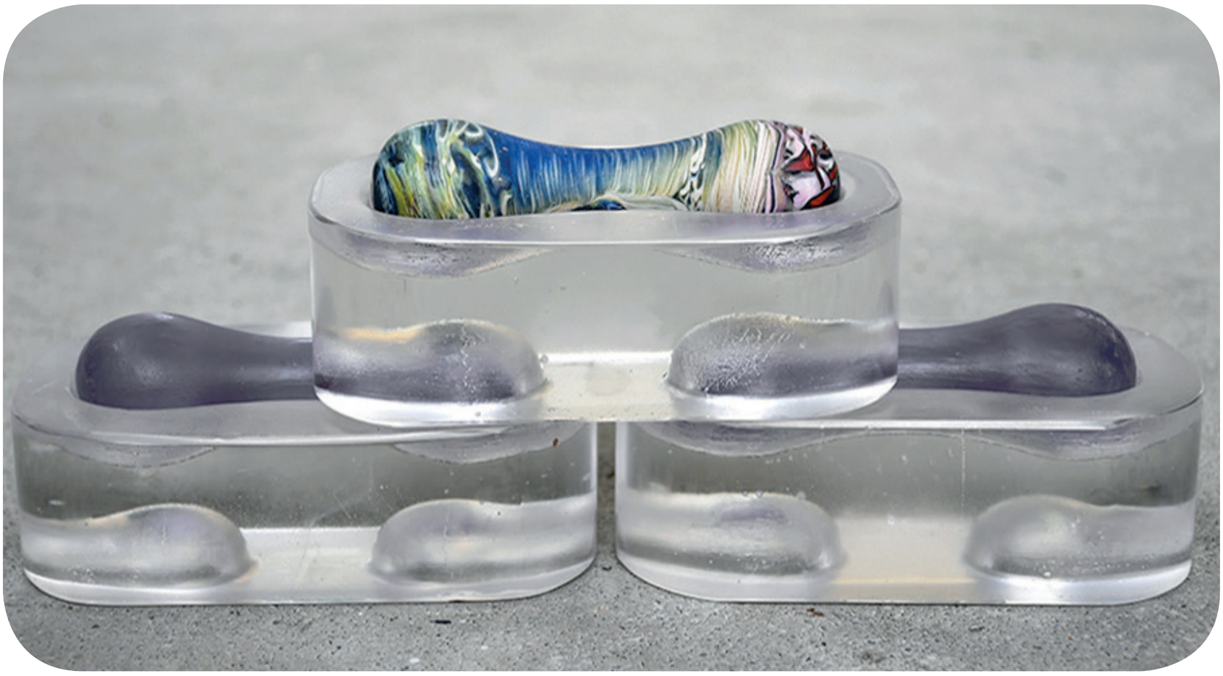


Figure 63: Interlocking cast glass components, source: (Oikonomopoulou, Bistrogianni, Barou, Veer, & Nijsse, 2018)

The main advantage of mechanically connected glass is that it can be completely reversible and often easy to assemble. This advantage is however compromised by a reduction in transparency. The metal substructure or joints are visible opaque elements in the structure and are thereby almost always visible. Another disadvantage is that some metal connections can create peak stresses in the glass where it comes in contact with the metal, potentially causing damage to the glass.

Interlocking system

The third and final connecting type is the interlocking component system. In this system, the strength and stability are given by the self-weight of the structure, while the interlocking geometry provides stiffness in the lateral directions. This structure, which is still in a research stage, does not require adhesive or mechanical connections, creating a potentially completely demountable structure. This increases the circularity and since the glass blocks are not contaminated with adhesives or coatings, they are much better recyclable as well. Between the interlocking blocks, a dry and colourless layer is placed. This layer maximizes the transparency and prevents impact damage caused by the glass to glass contact. Moreover, this dry interlayer reduces the labour intensity significantly and allow for easier on-site construction.

MECHANICAL CONNECTION	ADHESIVE CONNECTION	INTERLOCKING GEOMETRY
DRY ASSEMBLY	ADHESIVELY BONDED	DRY ASSEMBLY
INTERLAYER ALLOWS FOR SIZE DEVIATIONS	HIGH ACCURACY IN UNIT SIZE	INTERLAYER ALLOWS FOR SIZE DEVIATIONS
EASY ASSEMBLY	LABOUR INTENSIVE ASSEMBLY	EASY ASSEMBLY
COMPROMISED TRANSPARENCY	HIGH TRANSPARENCY	HIGH TRANSPARENCY
REVERSIBLE	NON-REVERSIBLE	REVERSIBLE

Figure 64: Summary of the three glass connecting methods, source: (Oikonomopoulou, 2019)

4.6 Altar of Saint-Denis Cathedral

A very good reference project for this thesis is the altar in the St. Denis Cathedral in Paris. All aforementioned production steps and techniques have been applied in the restoration of France's most visited monuments. With glass artist Vladimir Zbynovsky in charge, a 1,4 t glass block was perfectly fitted on a rough-surfaced supporting stone, using 3d scanning technologies, (Corning, n.d.)

Figure 65: Cast glass refurbishment to the Choir of the Saint Denis Cathedral, source: (Corning, n.d.).

The casting process of this piece of art was executed in a rather unusual way. It turned out that it was not possible to cast the glass directly into the delicate mould with the rock surface, Figure 66 (left). It would cause the mould break in pieces and the risk on local crystallisation and bubble entrapment would be too high. Another possibility was to use a press mould, where the 3d scanned shape was used to compress the glass, Figure 66 (right). This however proofed to be too dangerous to try. The enormous dimensions of the object, 1.42 * 1.42 * 0.28 meter would cause uncontrollable spilling of glass overflows which made it dangerous to work with. The risk of flying spats of molten glass with temperatures higher than 1200°C was too high[1].

Since these conventional techniques turned out to be inadequate and unusable, a new approach was needed to make this unique piece of glass. It was achieved by making it in two phases. First, a rectangular block was cast in a simple metal mould. Once the glass was properly annealed, shown in Figure 67, which took about a month, it was re-heated until its softening temperature. Simultaneously a plaster mould with the desired fragmented surface geometry was pressed on the top surface of the glass block. As the temperature rose, the mould would slowly be pressed into the softening glass. At 690°C, the glass was soft enough and this temperature was maintained for a month to ensure good imprinting of the pattern. Thereafter, the imprinted glass was cooled down again in another month, (Oikonomopoulou, 2019).

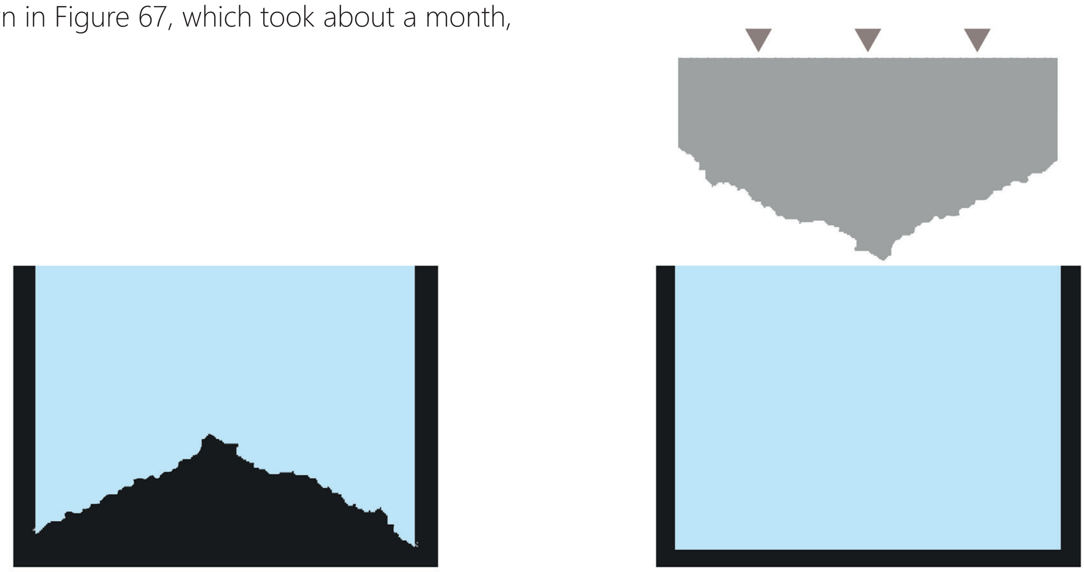


Figure 66: Simplistic scheme of the principles of Direct casting (left) and a Press mould (right)

[1] This information is based on personal communication between F. Oikonomopoulou and T. Dannoux form Corning Inc.

This process gives a lot of insight into how missing pieces of marble columns could be made out of glass, and especially how not. The dimensions of a Parthenon column are quite similar to those of the Denis Altar project, so the restrictions of that case study are an important input for this design. The most important assumption drawn is that direct casting an object of this size in a disposable mould is not possible. It is too dangerous or the risk of flaws in the glass or the mould is too high. The two-phase process does, however, show great potential, since cheaper disposable moulds can be used and a high level of accuracy can be reached by pressing the rough surface of the stone in the glass like a stamp.

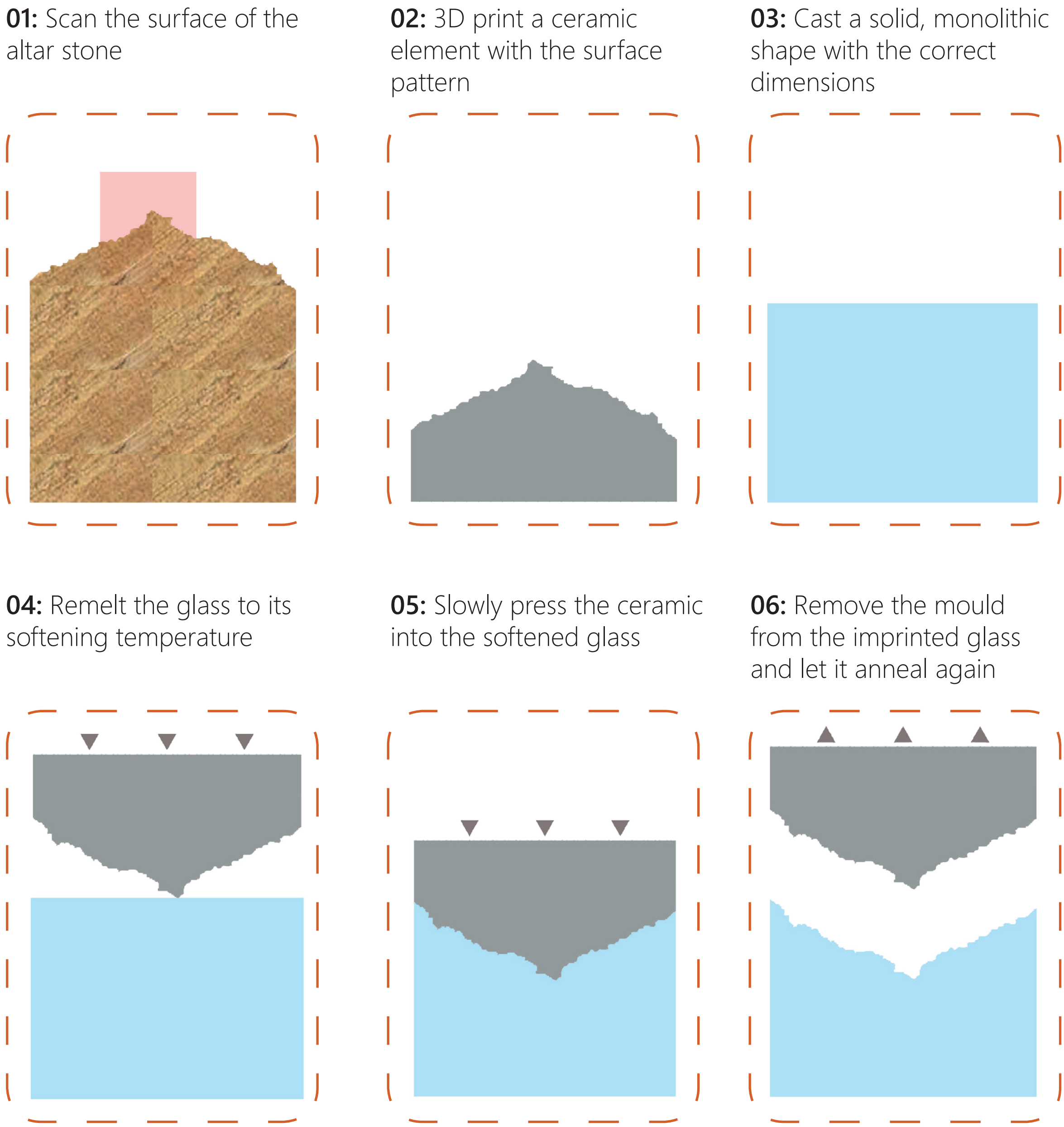


Figure 67: Production steps of the fitting cast glass element on the St. Denis Altar

4.7 Conclusions

With all the involved production steps explored, conclusions can be drawn from the found results. These conclusions will be the starting input for the following design phase. Some of them are hard criteria while others are softer and more subjective.

As mentioned in Chapter 3, the type of glass that will be used will be soda-lime. The main criterion for this choice was the similarity in thermal expansion between Pentelic marble, and soda-lime. To cast the glass into the desired shape, 3D printed sand moulds will be used. With these moulds, it is easier to make complex shapes with high precision, which is required to make the glass fitting on a fractured piece of marble. Other advantages of 3D printed sand moulds, is that they are easy to produce, reusable which makes the production process faster and cheaper than other mould types.

As is shown in the production process of the altar in the St-Denis Cathedral, the casting and annealing of the final shape is rather complicated and goes in two phases. First, the geometry will be cast with the right dimensions after it will be annealed. Once it is cooled down, it is reheated again to the softening temperature of the glass and the geometry of the broken surface is pressed into the glass before it is annealed again.

The type of connections heavily depends on the shape of the glass object. It can already be stated that adhesive connections will be excluded. With adhesives, the different glass parts cannot be disassembled any more. With the desire for circularity and recycling and the requirement for reversibility in the restoration process, adhesives are not a usable connection method. This leaves two options, each one with a lot of different alternatives. When the structure is split up in multiple parts, the interlocking geometries could be a very promising connection type. This also how the ancient Greeks built temples with marble, as will be explained in Chapter 5. The other option is to use mechanical connections, however, this requires interventions in the marble and is thereby riskier. Moreover, the use of embedded mechanical connections is not very common so far.

These decisions will be the starting point in the design phase. Before that, research into the chosen case-study will give more assumptions regarding the structural system and combined with the values in the conservation guidelines, a set of guidelines will be made which will be the base of the design research in Chapter 6.

Figure 68: View on the eastern collonade of the Parthenon in Athens, source: (British Museum, 2012)

05.

ASSESSMENT OF THE CASE STUDY

5.1 Introduction

Based on the guidelines in Chapter 4 a design proposal can be made for a case study. However, as mentioned before, the goal of this thesis is not to make a design for a specific monument, but a design which can be applied on any marble monument with similar constructive and aesthetical problems. Nevertheless, to test and apply this designed production method a proper case study is required. Given its extensive documentation, the Greek Parthenon has been chosen as case study for this project. After a request, the authorities that lead the reconstruction works on the Parthenon, gave access to a high-resolution 3D scan of one of the Parthenon columns. With this scan, which belongs to one of the columns in the west-collonade of the temple, it is possible to turn the proposed design to a realistic 3D model of an original column. The availability of this 3D scan was the deciding factor in the choice for the Parthenon as a case study.

In this Chapter will be explained how a column of the Parthenon has been constructed, how it is connected to the other parts and in which way it contributes to the integrity of the superstructure as a whole. Also, environmental conditions, like weather and geotectonic activity will be discussed. Finally, the type of materials that are used in the construction of the Parthenon, both the original ones as the modern ones that are used in the restoration process, will be highlighted

Figure 70: Side view from the recieved 3D scan of the Parthenon.

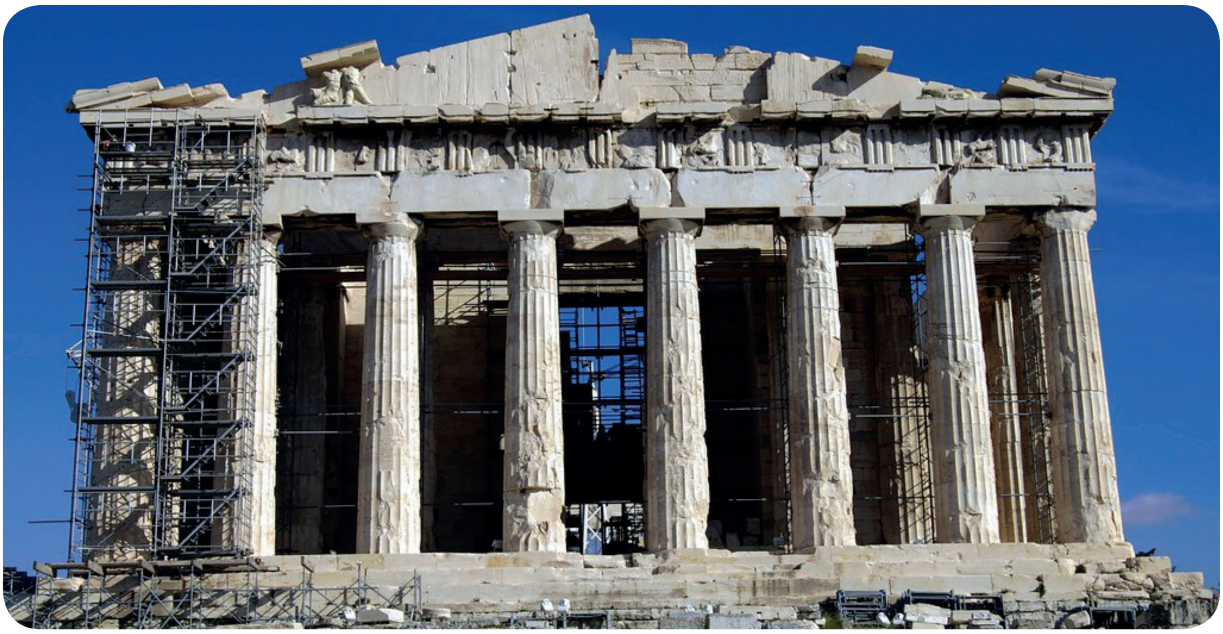


Figure 69: West elevation of the Parthenon. The 3D scan is made from the fourth column from the left, Source: (Notay, 2009)

5.2 Location and Climate

The Acropolis is located in the centre of the Attica peninsula, about five kilometres from the Aegean coast. This location gives it a typical Mediterranean climate with hot dry summers and warm humid winters. The mean temperature in the hottest month, which is July, is around 27°C, while in January the average temperature is 9°C. Given the proximity to the sea, the humidity is relatively high, averaging between 50 and 70%, but the wind direction is mainly off-shore, coming from the north. More detailed annual weather conditions in Athens can be found in Appendix A

The main design challenge in this area is however not the local climate, but the geo-tectonic activity. Greece is located just between two active tectonic areas. Most of the seismic activity occurs near these vault lines, but sometimes earthquakes strike more inland as well. Like in July 2019, when a 5.1 Magnitude earthquake hit at just 22 kilometres north of Athens. This was the first major earthquake in the Greek capital since 1999, which had a magnitude of 6.0 (BBC News, 2019) So both the islands and all the mainland of Greece are prone to earthquakes, however, most of them are relatively small. It is estimated that in this area a magnitude 8 or higher earthquake occurs once every thousand years. For comparison, Japan has severed five of those >8 earthquakes only in the past 75 years. (Hays, 2009)

Thus the intensity of the earthquakes in Greece is not very high compared to other seismic active zones like Japan and Chile, but they still can cause a lot of damage to buildings and other structures, like displacement of the drums in the Parthenon columns, in Figure 72. The impact of earthquakes on the Parthenon is, however, reduced by the Acropolis itself. The solid rock, on which the temple is built, reduces the effect of an earthquake significantly. Other historic temples often do not have this natural protection against earthquakes and are thereby more vulnerable than the Parthenon. It is thus important to build earthquake resistant structures. Since most possible cases for cast glass restoration have a similar climate and seismic activity, the actions taken in this thesis should also be applied in other comparable project locations.

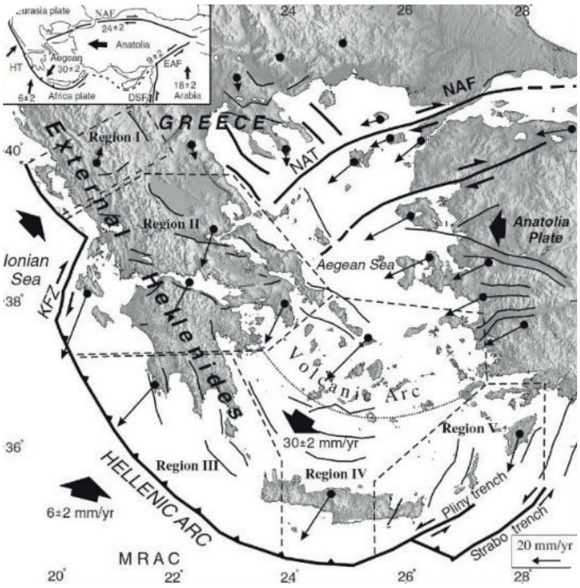


Figure 71: Seismic and geotectonic situation in Greece, source: (Patton, 2018)

Figure 72: Displacement of drums in the Parthenon columns are often caused by seismic activity, source: (Lambrinou, 2010)

5.3 Construction of a Parthenon column

The Parthenon columns are built in the Doric style, the first of the three classical orders in Greek architecture. This Doric column is the simplest of the three orders since it has no further ornaments attached. Its shape makes the Doric column also more robust, compared the Ionic and Corinthian order which tend to have a more slender shape with a smaller cross-section. Despite that these Ionic and Corinthian columns have proven to be strong and stable enough, the larger cross-section of the Doric columns in the Parthenon is an advantage for the strength and stability of the structure.

A typical section of a Parthenon colonnade can be split up in three parts. The Doric order is characterised by a column which rests directly on the stylobate, instead of having a base, like the other orders. This stylobate is a kind of podium, on which the temple is constructed. In most temples, this podium is flat, however, in the Parthenon a slight curvature in implemented in this stylobate. The architect added this slope to compensate for the perspective view, making the temple look larger to the human eye.

On top of the stylobate, the 46 columns of the Parthenon colonnades are placed in an 8*17 grid. Each of those columns is constructed from a total of ten stacked, disc-shaped elements, called drums and is topped off with a capital. The carvings on these drums are called flutes and give the column its typical Greek look. The stability of the column is only provided by the gravitational force of its mass and the architrave, frieze and cornice it carries. No binder or mortar is used to connect the drums, they are only kept together by friction between the marble surfaces. The only element which connects the drums is a small wooden joint, called an Empolion. However, this joint does not have a structural function, its only task is to align the two drums perfectly on each other in construction or case of lateral displacements, such as an earthquake, (Glassman, 2008).

An empolion has three components, two 'empolia' and one 'polos'. These empolions were placed in the centre of each drum surface. The bottom one of the two empolion was placed in an out carved hole which thereafter was filled up with molten lead to connect the empolion to the marble. Subsequently, the polos and the other empolion were positioned with a dry connection based on friction. When the empolion is in place, it helps to position the next drum neatly on top of the one below and thereafter the process begins again, (Karakitsou & Konteas, 2013)

The shape of the empolion is vital for the stability of the column. In case of an earthquake or another lateral force in the column, the empolion functions as a re-alignment tool. When the columns are rockling due to an

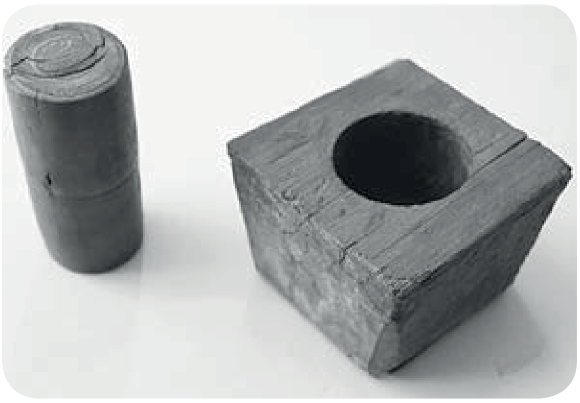


Figure 73: Close-up view of an ancient Empolion connection, source: (Karakitsou & Konteas, 2013)

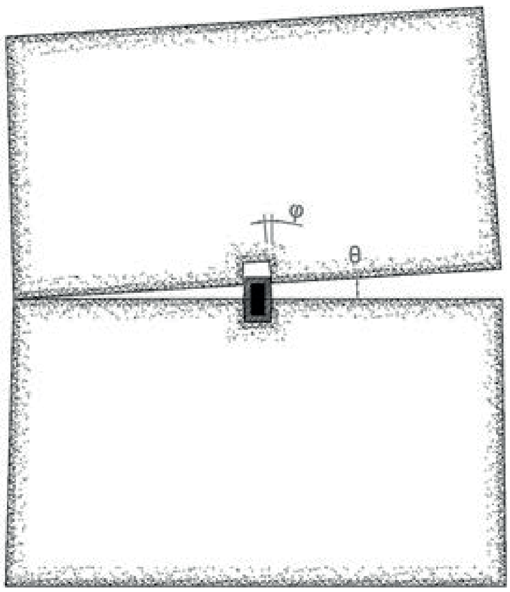


Figure 74: The empolion allows the drums to bank slighly and also guides them back to their original position, source: (Karakitsou & Konteas, 2013)

Figure 76: An orginal, damaged, empolion of the Parthenon. The damage is probably caused by an earthquake, source: (Karakitsou & Konteas, 2013)

earthquake, the inclination of the empolions surfaces allows the horizontal joint between the two drums to open at an angle like is shown on the right. If the drum falls back, the empolion will guide it back to its original position, limiting the horizontal displacement between the two drums. This increases the stability of the column and structure enormously. Only if the banking is too steep, the wooden joint will be crushed by the marble, like is shown on the images below, (Karakitsou & Konteas, 2013).

The reason why these wooden empolia have survived for more than two millennia is hidden within the design of the drums themselves. To prevent an organic material like wood from decaying, it should be conserved in a complete air and watertight environment. So the air between two drums should be completely closed off from the outdoor climate, otherwise, the system that provides stability to the columns would have decayed within decades. To manage this, the contact area between the two pieces of marble should be made so smooth that they fit perfectly on each other. However, instead of polishing the whole surface of the drum, the Greeks only smoothened the edges, while they carved out the middle slightly to create a small airtight space in the centre of the column. A perfect place to conserve a piece of wood. The image above shows a drum which was used in the temple of Artemis in Sardis, which is nowadays western Turkey. The gap for the empolion is clearly visible in the middle of the drum and it is surrounded by a rough surface. The outer surface is much smoother and provides the airtightness for the inner cavity, (Karakitsou & Konteas, 2013).

Figure 75: In the middle of this drum in Sardis, Turkey, the carving for the empolion is clearly visible, source: (Cartwright, 2013)

5.4 Materials

The columns of the Parthenon have been constructed with white Pentelic Marble from the Dionysus quarries in Attica, 5 kilometres north of Athens. This specific type of marble has very low porosity and is extremely resistant to acids and sulphates. It has a specific weight of 2,730 kg/m3 and a thermal expansion coefficient of 9*10-6/°C. The mechanical properties of this Pentelic marble are as follows: **Compressive strength 77.8 MPa, bending strength 18.0 Mpa, shear strength 12,7 Mpa and Youngs Modulus 42.1 Gpa, (Skoulikidis, Vassiliou, Tsakona, & Kritikou, 1993).**

In the original construction, the only other materials that were used in a column were wood from the empolion, usually from olive trees, and lead, to join the wood with the marble. However, in recent restorations, other materials are used to reinforce or repair damaged pieces of marble. The joint clamps or rods are usually made from titanium, (Bouras, Ioannidou, & Jenkins, 2012). The advantage of this material is that it is very strong, but the reason why it is used is that it has the same thermal expansion coefficient as the Pentelic marble. Between the old and new pieces of marble, a mortar is used as filament. This mortar is carefully composited for this application because the chemicals in the mixture may not result in the decay of the marble, (Aggelakopoulou, 2013)

5.5 Types of interventions

Over the years the Parthenon has severed many destructive events, mostly caused by human actions like bombings, fires and raids. These damages have resulted in a scattering of marble elements over the entire Acropolis. The reconstruction of the Parthenon looks like a 70000 pieces three-dimensional jigsaw puzzle, where each piece of marble is unique and only fits at one single place, (Glassman, 2008). It is the task of archaeologists and architects to find the connecting pieces of marble and thereby slowly reconstructing the temple. However, during the turbulent history of the Acropolis, some pieces of marble went missing, were stolen or damaged too much to be reused. In that case, replacing tissue is used to complete the puzzle. The columns of the Parthenon columns show three unique types of damage:

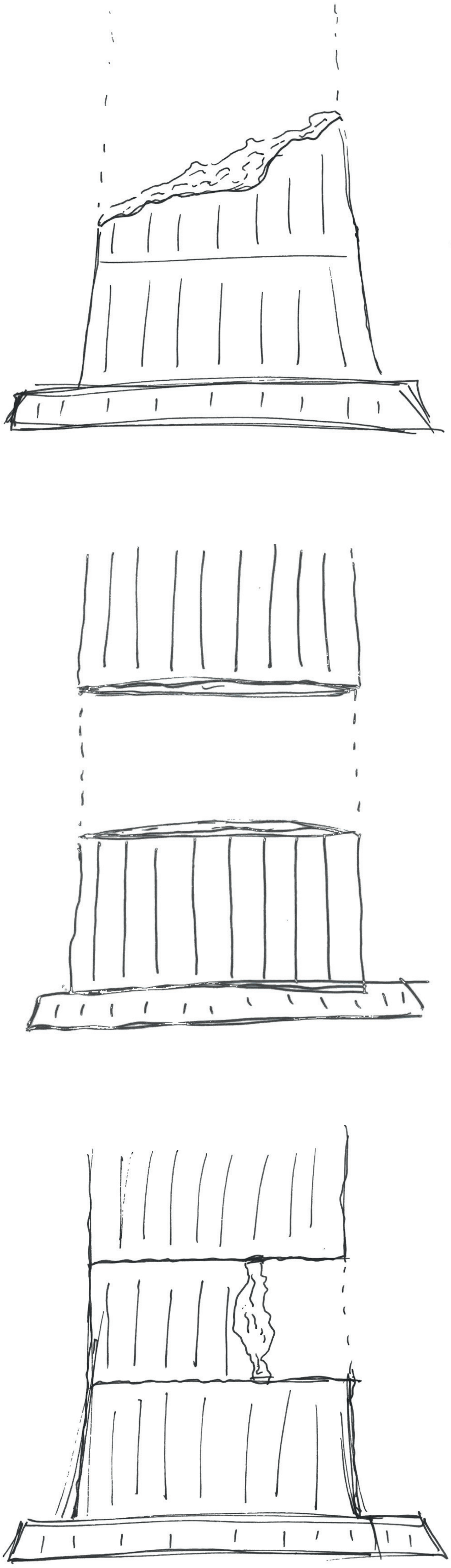


Figure 77: Typical types of damage the Parthenon has severed over the pas millinia

The first two types are quite similar but are different in approach. In both cases, a drum is fractured and the missing pieces cannot be found or are too damaged to be reused. When it is cracked in a horizontal direction the weight of the overlaying drums is completely carried by the reproduced piece, often resulting in shear force in the connection. In case of a vertical fragmentation, the flow of forces is much more straight forwards, since they are only vertical. In the third case, a complete drum is missing, or too damaged or fragmented to be reused. In that case, the whole drum will be reproduced. In practice, the second type of damage has a lower priority of reconstruction than the other two, assuming that the missing element does not cause instability of the structure. In this thesis, the focus lies thereby on the two other types of damage, case 1 and 3, since those are essential in the reconstruction process of the entire Parthenon. If these damages are not repaired, the column and thereby the whole superstructure cannot be reconstructed.

The 3D scan model, sent by the authorities of the Parthenon reconstruction project, does not show these type of damages. To use this scan for the design, these damages are made manually in the digital model. In this theoretical restoration case, several drums are missing or too damaged to be reused. The goal of this thesis is to reconstruct these missing pieces from glass and re-complete the column again. The digitally fractured column is shown below and this will be the starting point for the design phase.

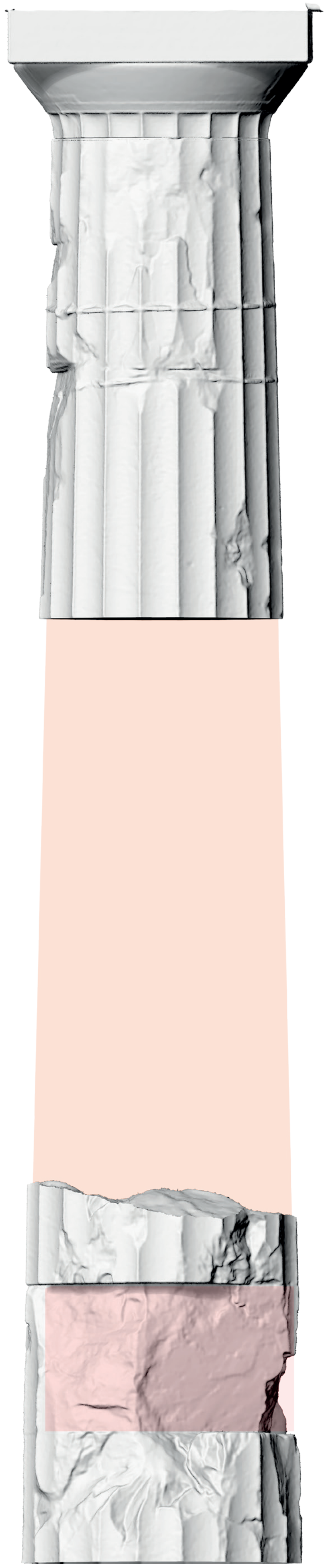


Figure 78: Manually created design case. The column is digitally fractured. Drum 3 is broken with only half of it retrieved. Drum 4, 5 and 6 are missing had have to be reconstructed.

5.6 Current restoration process

The current restoration project of the Parthenon has been lasting for more than forty years. In those 4 decades, the restoration team tried to complete a three-dimensional 70,000 piece jigsaw puzzle with a total weight of 100,000 tons. During these restorations, damages caused by wars, fires raid and improper and incorrect earlier restorations have been tried to repair. During the process, it has always been the goal to restore the monument to its original state but simultaneously respects the ruin it has become over time. To achieve this, restoration worked relied till a certain degree on traditional Greek techniques since they proved to be more accurate than modern ones.

Before the reconstruction began, first all improper previous restoration had to be removed. In earlier interventions, mainly under command of the Greek architect Nikaloas Balanos, drums and other marble elements were placed in wrong positions. Moreover, the iron connections used by Balanos corroded due to a lack of protection, causing damage to the ancient marble. Once these damages have been repaired, all the remaining elements have been catalogued and their original pieces have been found. It was quickly found out that several pieces of marble were missing from the catalogue because they have been looted, destructed or simply vanished without a trace. To reconstruct these pieces the restoration workers grabbed back to ancient traditions and equipment.

To acquire new marble pieces, the restoration workers turned back to the same quarry the ancient Athenians used. However, the Pentelicon quarry yearly provides only three pieces that are large enough to be used in the Parthenon, delaying the process heavily (Discovery UK, 2017). Once a piece of sufficient size has been retrieved, it will be manually carved into the desired shape, by using a pantograph and a cast plaster replica. This ancient masonry tool is used to accurately record to original shape till it can be transferred, point by point, into the new marble. This process is extremely time-consuming and can only be done by master stone makers since the required accuracy comes down to only a tenth of a millimetre. When the pieces are shaped they are finished by grinding sand over the marble surface with a metal plate. With this technique, an accuracy of a twentieth millimetre can be achieved and it is used to remove the smallest imperfections from the connecting surface, (Glassman, 2008)

Figure 79: A master stonemaker is manually carving a new piece of Pentelic marble, using a pantograph and a cast plaster replica, source: (Glassman, 2008)

Figure 80: The final sanding process is still done as in ancient times. With this metal plate, which is grinded over the sand, an accuracy of one twentieth of a millimeter can be reached, source: (Glassman, 2008)

Once the marble elements are shaped, they can be fitted onto a broken or irregularly shaped ancient one. To make sure that the two pieces fit perfectly, red clay is applied on the surface of the new piece. Everywhere the clay is scraped away the two pieces make contact, indicating where the piece needs to be finetuned. This process is often repeated a dozen times before the two pieces fit perfectly. To eventually join the two pieces, mortar and, if required for structural purposes, titanium bars are used. The use of these bars should, however, be minimised as much as possible since it is very intrusive towards the monument, (Glassman, 2008)

Looking into this process shows two main constrains which make it expensive and time-consuming. At first, there is the accesibility of the Pentelic marble. Marble pieces of sufficient size are extremely hard to retrieve. Even with modern techniques to cut pieces of marble, only two or three pieces a year can be used for the Parthenon. This can not only result in delays if no sufficient blocks can be retrieved for a longer period, but this scarceness makes the marble also extremely expensive, resulting in higher restoration costs.

The second constrain of this process is the required accuracy of the new pieces of marble. This accuracy cannot be reached by modern electronic tools, so the marble has to be carved manually by stone makers. This is a very hard and time-consuming process and can only be done by master stone makers. But even for them, the process is still very hard and the required accuracy is difficult to achieve.

With glass, it is possible to make marble looking elements artificially. It can be cast in such a way that it looks and feels like just like original marble, but it is easier and cheaper to make. Instead of marble, glass is not a very scarce material and it can be easily made in big sizes. So it is not necessary to wait till a marble piece of sufficient size is retrieved from the quarry. Moreover, since the glass is cast, it is much easier to achieve a complex shape than is currently done with marble. With 3D scanning, the exact surface of an ancient broken stone can be digitalised and turned into an artificially produced mould. This process is much less labour intensive than manually carving the marble blocks and continuously testing if it fits on the original stone. This, in combination with the availability of glass, makes 'artificial marble', made from cast glass, a promising alternative to the expensive and time-consuming conventional techniques.

Figure 81: Eastern view of the Acropolis, source: (Earth Trekkers, 2020)

06.

DESIGN RESEARCH

6.1 Introduction

With all the involved fields explored, conclusions can be drawn from the found results. These conclusions will be the starting input for the following design phase. Some of them are hard criteria while others are softer and more subjective. In this chapter, several design alternatives are proposed. Each alternative can also be found in Appendix C where they are shown on a bigger scale.

6.2 Design Criteria

One of the most important value during conservation is that an intervention should be as least **intrusive** as possible. It should ensure the structural integrity and aesthetical quality of the monument, but not draw attention itself and work in harmony with the existing structure. A second value is that during the restoration, any type of intervention should be **reversible** in later stages. From these principles, the main design criteria are derived. These criteria are used in the assessment of the proposed design alternatives and are as follows: **Compatibility, Visual Impact and Annealing**. These aspects are still quite broad, but they can be made more specific depending on the to be assessed design alternative. The three criteria will be further explained below.

When a new structure is added to an ancient existing one, **compatibility** can refer to several aspects. First, there is aesthetical compatibility, which includes the appearance and shape of the new structure related to the old one and how the two pieces go together. Subsequently, there is structural and mechanical compatibility. Since the key of this restoration lies in the joining of these materials and make them structurally behave and unison, the design of the glass pieces should be mechanically compatible to be joined to the existing marble pieces. The third and final type of compatibility is related to the production and assembly process of cast glass.

The second main criterion is the **visual impact.** Instead of what one might think is logical, minimal visual impact is not the same as maximum transparency. It is, of course, possible to go full transparent with glass, but even then, a cast glass object will not look transparent from oblique angles, since the critical angle of glass is only 42°. The visual impact does not only apply for the glass but in the connections, visual impact is also an important criterion.

The third and final main criteria is the possibility to **anneal** the glass pieces. As mentioned in Chapter 3, annealing is the most essential and critical phase in glass production. It thereby has to be done in a very delicate and precautious way. Several aspects could ease the annealing process and thereby the time as well. Sharp angles and large masses are typically hard to anneal and are thereby much more time consuming, assuming that it is even possible to anneal them properly.

6.3 General Concept

The concept of using structural cast glass elements in buildings is not new. However, until now the only application is in masonry structures, from which several are discussed in previous chapters. This only requires relatively small elements, which are easy to produce. However, for this application, replacing a large marble piece of a column the size of the cast glass components need to be upscaled significantly. This requires a total new approach of constructing with glass, bringing in problems that were not there in the cast glass masonry structure.

6.4 Aesthetical appearance

When asking people to mention a thing about glass, transparency is often one of the first words that they will come up with. However, this general idea of glass being transparent is strongly related to the application of glass in the built environment. Of course, glass is a transparent material, but that depends on more than only this chemical composition. The main purpose of using glass in the built environment is to be transparent, so it is made to be as transparent as possible: flat and thin, like in windows. This specific use feeds the public idea that glass is always transparent. This does not, however always have to be the case.

6.4.1 Physical behaviour of light

When glass is shaped in thicker, and more curved elements, the glass will not look as transparent as in a flat thin sheet in a window frame, despite that the transparency, physically speaking, is still the same. This is caused by several natural phenomena which occur when radiation strikes with an object. When a light wave collides with an object its radiation will be reflected, absorbed and transmitted, depending on the material, its surface quality, the angle of impact and the energy of the wave.

Physically speaking the grade of transparency equals the amount of light transmitted by an object. However, a high transmittance does not automatically mean that an object looks transparent. Transmittance is only the amount of light that not reflected or absorbed by an object. It does not say how this light is emitted by the object. To determine whether a body looks transparent, other optical phenomena come into play, like the ones shown below, (Barou, 2016).

Transmitted light can be emitted from an object in two ways; **direct and diffuse.** The difference between lies in how the wave travels through an object. With direct transmittance, the light wave is barely obstructed by the molecular structure of the object while in diffuse transmittance the light is continuously colliding with the molecules of the body. With each collision, the light wave is scattered more and more. Eventually causing

Figure 82: Most common optical phenomena, source: (Barou, 2016)

it to emit in all directions, instead of one like is the case with direct transmission. The more the light is scattered in an object, the less transparent it looks.

The same phenomena occur in the **reflection** of light, which can again happen in a diffuse way or via direct reflection, depending on the smoothness of the reflecting surface. A good example of this phenomenon is the mirroring of water. During quiet waters, the surface is so smooth that it reflects almost like a mirror. However, if the water is turbulent due through strong winds or waves, the light reflection will be much more diffuse and the mirror image will not be so clear. The same accounts for a glass surface. If it is polished it will reflect the light, if the surface is matte, it will be diffused.

The third important phenomenon to take into account is **refraction**. This the change in direction which occurs when light travels from one medium through another and is a very common phenomenon in nature. The amount of refraction depends on the angle of incidence and the energy of the light wave. The more oblique the angle of incidence is, the stronger the refraction effect will be. If the angle of impact is 0, so perpendicular to the glass surface, no refraction will occur and the direction of the wave remains straight.

6.4.2 Influence of the geometry

The effect of these natural phenomena on the appearance of glass objects depends heavily on its shape. If a surface is flat and smooth it will give a reflection similar to that of a mirror. However, if a surface is smooth and curved the reflection will look more like the one you see in a spoon or a distorting mirror. The light is not diffused but the mirror image will be warped.

The geometry of a Greek column will cause the same since the flutes on a drum will create the same reflection as a spoon does, but now there are twenty of them next to each other, all ten meters high. In the image above, this problem is illustrated. Several parallel light waves collide with the geometry of the drum and each wave is reflected in a different direction. This is not the same as diffuse light, because there is still a pattern in the light, but the result will likely be the same as in a distorting mirror, which could be very disturbing for the observer.

The same problem occurs with refraction. Since each light wave hits the drum on a slightly different angle, they will all have different refraction angles, as is shown on the right. These waves travel further through the glass before emitting on the other side of the drum. This results in two waves, which enter the glass very close to each other, ending up several centimetres apart and having different directions when they are emitted from the object. This especially accounts for the light waves that hit the drum around the points on the flutes. These two waves travel in a completely other direction and will both be emitted in a completely different part of the column, despite that they enter it only millimetres from each other.

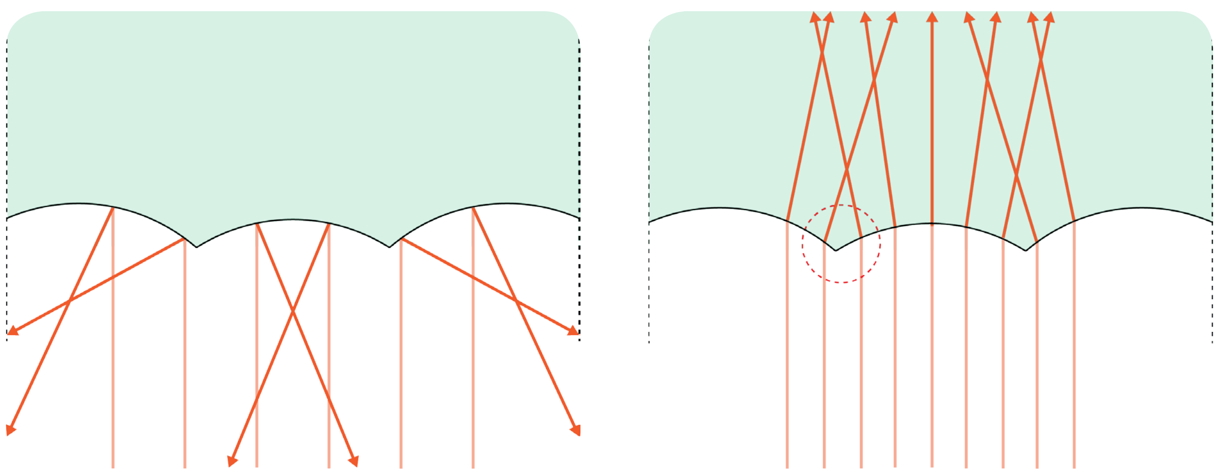


Figure 83: Principles of light refraction (right) and light reflection (left) on the geometry of a Greek column

Both reflection and refraction problems will occur several times in the body. Given that the glass element will be split up in several pieces, separated by interlayers, a single ray of light will give several reflections and will refract several times. All of this will distort the light and the view for the observer will not be as transparent for instance in the Crystal Houses project.

Figure 84: The transparency of the Crystal Houses facade cannot be reached with the given geometry of the column, source: (Oikonomopoulou, 2019)

6.4.3 Transparency

The reflections and refractions will cause severe light distortions in the glass elements, which could be very annoying for the observer and intrusive towards the monument. This effect will even be magnified by the fact that multiple glass elements will be used to fill the missing piece. Each time two glass bodies touch each other the same problem with refracting and reflecting will occur, which increases the light distortion even more.

According to this, a full transparent element is not the least intrusive choice of glass for this restoration project. A more translucent type of glass, which allows no direct transmittance but emits the light diffusively is thereby a more preferable option.

Choosing this type of glass is not only favourable for the light distortion, but it also helps in reducing the visibility of the connections, interlayers and other elements in the glass. If the glass is translucent they will not be clearly visible anymore. It is still likely that their contours are distinguishable but they will not draw the attention as much as they would do with fully transparent glass. The third advantage of translucent glass is that it reduces the risk of local heat storage within the glass. If light waves are not scattered when they travel through the glass some of them might bundle somewhere in the object. This light bundling is similar to what happens with light under a magnifying glass and could theoretically result in local temperature difference, and eventually fractures in the glass.

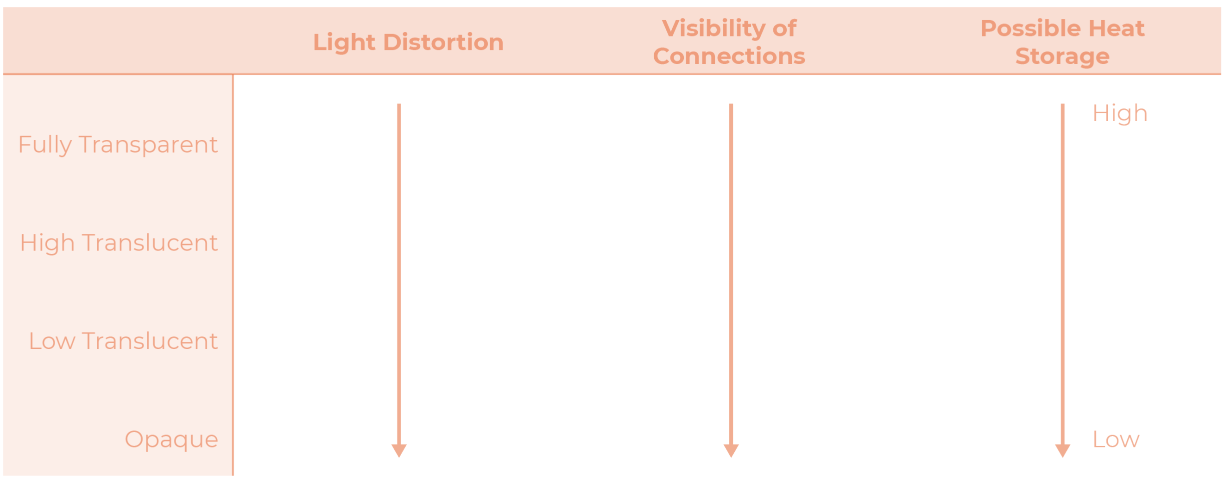


Figure 85: Design consequences of a reduced glass transparency

6.4.4 Surface texture

That the glass will be made translucent instead of transparent does not affect the surface of the elements. A translucent glass element can still have a reflective surface but as shown in the previous paragraph, the geometry of the Greek column makes it very difficult to make a reflecting surface. That is why a more rough-textured and only slightly reflective surface is preferred over a smooth glossy one. Below, two test specimens from Barou (2016) are shown. The left one has a translucent and rough surface, while the right one is more transparent and reflective.

A combination of translucent glass with a slightly rough and matte surface as shown in the left image could approach the look and texture of marble, while it is still distinguishable due to its light-transmitting properties. To determine the exact grade of translucency and roughness of the surface, more specific research is required. This decision to make the glass look translucent with a rough surface has several implications on the further design of the cast glass element. Since it will not be fully transparent, it will be easier to hide connections and contact areas for the observer. The effects this decision has on the design process will be further discussed below.

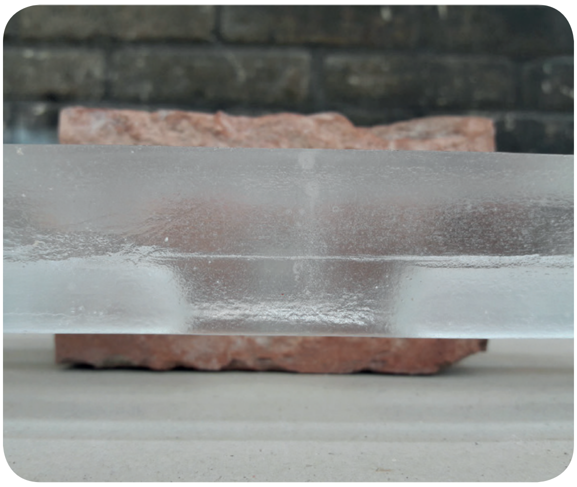


Figure 86 & 87: Two cast glass specimens, one translucent with a rough surface (top) and transparent with a glossy surface (bottom), source: (Barou, Transparent Restoration, 2016)

6.5 Fragmentation

Now it is known how the glass element will have to look, it is possible to start designing the missing marble element. The first step will be to determine the shape and size of the replacing element. With marble, it is possible to make enormous blocks in one piece by simply cutting them in the desired, monolithic shape. With glass, there are various reasons why is desired to split this geometry up in several pieces.

Figure 88: Structurally optimised glass node, source: (Damen, 2019).

6.5.1 The importance of fragmenting

The first reason is providing stability. As described in Chapter 5, the stability and earthquake resistance of the Parthenon is partly created by the allowance of the drums moving separately from each other. This dampens the lateral forces and prevents them from moving to the top of the superstructure, where they can cause more damage. If the replacing glass pieces stretch over multiple drums, this effect is reduced, making the column more prone to horizontal forces like earthquakes.

Secondly, the fragmentation of the missing element makes the glass much easier to anneal since the mass is reduced. If a single drum would be made from a monolithic glass piece it would have a mass of 7.3 Tons. For comparison, the largest solid, monolithic telescope mirror weighs 4 tons and took twelve months to anneal. This glass drum is almost twice as heavy, making the annealing time even longer. If the drum would be split up in several pieces, which could be annealed simultaneously, the total production time and cost could be reduced significantly.

Another option to reduce the annealing time, instead of fragmenting, would be to topologically optimise the geometry, resulting in a single piece drum with cavities inside. In Damen (2019) an example of topological optimised glass element is given. This glass node is structurally optimised, thereby reducing the total mass and section thickness, resulting in a much lower annealing time while still maintaining its structural and mechanical strength. Moreover, having a single piece glass drum would significantly simplify the assembly process and no connections are needed to join the fragments, reducing the visual impact of the intervention.

Based this, a single, mass optimised, piece of glass would be a good alternative, but the main is safety. If a single drum is made from one single piece of glass and it breaks, it loses most, if not all, of its strength. When the entire column is supported by this one piece of glass there is no back up if that single piece fails. To prevent this, there need to be at least three pieces in each drum, so that if one of them fails, it still has 67% of its strength. So fragmentation is definitely required, despite all the advantages an optimised single piece glass drum has.

6.5.2 Fragments in the original column

When the missing geometry will be split, it is important to do this in an appropriate way which is as least intrusive for the monument as possible. A split will be a visible element in the glass because, first, at the point where two surfaces meet the light will reflect and, second,

Figure 89: Fragmentation of an original Greek column.

the pieces need to be joint together, which will require connection elements and an interlayer. The decision to make the glass look translucent will reduce the visibility of these elements but it is still important to position these splits in the least intrusive place. To do this, the fragmentation will be based on the original design of the column. Each column in the Parthenon is composed of ten drums, each around one meter high and topped with a capital. This rhythm will be continued with the inserted glass elements. If a missing section extends over multiple drums, the split between the glass elements will be made on the same position where the joint between the marble drums used to be. This results in glass pieces that will never be higher than one drum. This ensures the stability of the column, which is based on that drum height.

6.5.3 Alternatives

Now, when the size of a glass component is maximum the size of one drum, the pieces still weigh around 7 Tons, which is way too much. So within that drum shape, more fragmentation is necessary. Splitting this element into pieces, it is again important to base this on the geometry of the drum. A Parthenon column has twenty flutes carved in the marble, making the shape twenty times circular symmetric. It is only possible to split the drum into equal pieces if it is fragmented by a number in which twenty can be divided; 2 – 4 – 5 – 10 – 20.

For only structural reasons, this is not a hard criterion. Using only equal pieces does not increase the stability of the whole drum a lot. So a splitting in three would also be an option, but the two-piece solution is excluded. If one of the two breaks, the strength is reduced by 50%. A small eccentricity of the column could then make it collapse. A drum made out of ten or twenty pieces is on the other side not chosen for practical reasons. Since all pieces need to be connected, it would be extremely complicated join so many pieces to each other, especially because this number of pieces do not provide more safety than a four or five-piece structure would do.

This leaves three possibilities: splitting the drum in three, four or five pieces, as shown in the table above. Out of these three, the four-piece is the least stable option. There are two pairs of parallel split lines, which make it possible for the pieces to move alongside these faces. This would put more force on the joints that keep the pieces together. When the geometry is split into three or five pieces, there are no parallel lines which mean that the pieces could not move alongside the contact surface.

The remaining alternatives are both structurally safe and stable, but each has its advantages and disadvantages. If the drum is split in three, the mass of each piece is higher than if it would be split in five, requiring a longer annealing time. However, the lower number of elements that need to be joint together makes it easier to assemble. It is assumed that these consequences cancel each other out, so the final decision is made based on the compatibility with the existing geometry. Both solutions could be perfectly used to solve the problem. However, when the drum would be split in three, it would result in unequal pieces. Given the elegance of the Parthenon and the fact that every measurement is carefully calculated, it is in the opinion of the author that you cannot end up with three pieces if they are not equal. This why the drum will be split into five, identical, pieces and not in three.

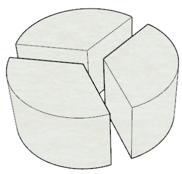
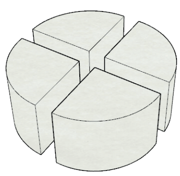
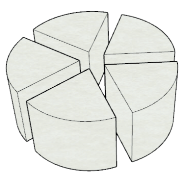
	Concept	Evaluation
3 Pieces		⊖ Compatibility ⊖ Solid Mass ⊕ Stability ⊕ Assembly
4 Pieces		⊕ Compatibility ⊕⊖ Solid Mass ⊖ Stability ⊕⊖ Assembly
5 Pieces		⊕ Compatibility ⊕ Solid Mass ⊕ Stability ⊖ Assembly

Figure 90: Evaluation of the three most promising alternatives

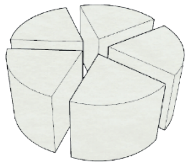
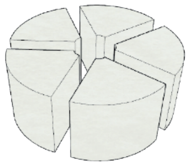
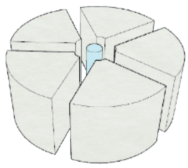
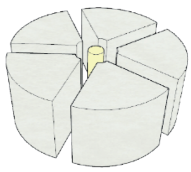
	Concept	Evaluation
No Core		⊖ Compatibility ⊖ Annealing ⊖ Tolerances ⊕ Visibility
Hollow Core		⊖ Compatibility ⊕ Annealing ⊕ Tolerances ⊕⊖ Visibility
Glass Core		⊕⊖ Compatibility ⊕ Annealing ⊕⊖ Tolerances ⊕ Visibility
Marble Core		⊕ Compatibility ⊕ Annealing ⊕⊖ Tolerances ⊖ Visibility

Figure 91: Evaluation of the four alternatives for the core

6.5.4 Core Solution

The result of each glass drum being split into five pieces is that they will come together in the middle of the drum. This raises the question of what happens at that point where all five pieces meet. The first alternative is that the pieces end up in points like pie pieces, fitting neatly on each other. Secondly, there is the option of a hollow cylindrical shape in the middle of the drum. The pieces do not end up in points but in a rounded edge. The third and fourth option has the same cylindrical shape in the middle, but now it is filled up with or glass, or Pentelic marble. The table below shows an overview of these four design alternatives, including an evaluation of according to the design criteria.

A quick evaluation immediately cancels out the option without a core. If the five pieces end up in a point, the angle of 72° would be very hard to anneal. That leaves three options available, all having a cylindrical core and 90° angles. From these remaining alternatives, the ones with a solid core look the most promising ones. This is based on how the original marble drums were connected. The empolion is always embedded in the middle of the drum, if the core is hollow there is no element to attach the empolion to. It would be much easier to make that connection if the core would be glass or marble. These materials are the only serious options to use in the core. Theoretically, titanium would also be a valid option, given the similar thermal expansion coefficient as soda-lime glass and Pentelic marble, but titanium is very expensive and the properties that make it so valuable are not necessary here.

The biggest difference between a glass and marble core is visibility. This is however strongly dependant to the grade of translucency of the glass. The more milky the glass is, the less impact a marble core has on the appearance of the column. Another difference between glass and marble is the compatibility with the connections. This core element will be where two drums are connected, via the empolion. This empolion needs to be embedded in the core of the drum. From a processing perspective, this would be much easier in a marble core than in a glass one. In marble, this gap can be carved out, while in glass it needs to be annealed, including sharp angles and point. This would increase the annealing time of the core significantly.

6.6 Connections

With the missing geometry split into fragments, the design is both safer and better producible. The next step is to design the connections between these pieces. With the given fragmentation there will be four different connections required in the design proposal. These are connections between glass and glass and between glass and marble.

Each connection has different requirements regarding stability and mechanical behaviour, so they all have a unique approach. The key to designing these connections is not to alter the structural behaviour of the column itself. The Parthenon has been standing there for almost 2,500 years so the connections, designed by the Greeks, have done their job very well. Changing the connection principle could affect the total stability of the structure and is thereby not favoured and not allowed according to conservation guidelines. An overview of the different connections can be seen in Figure 92.

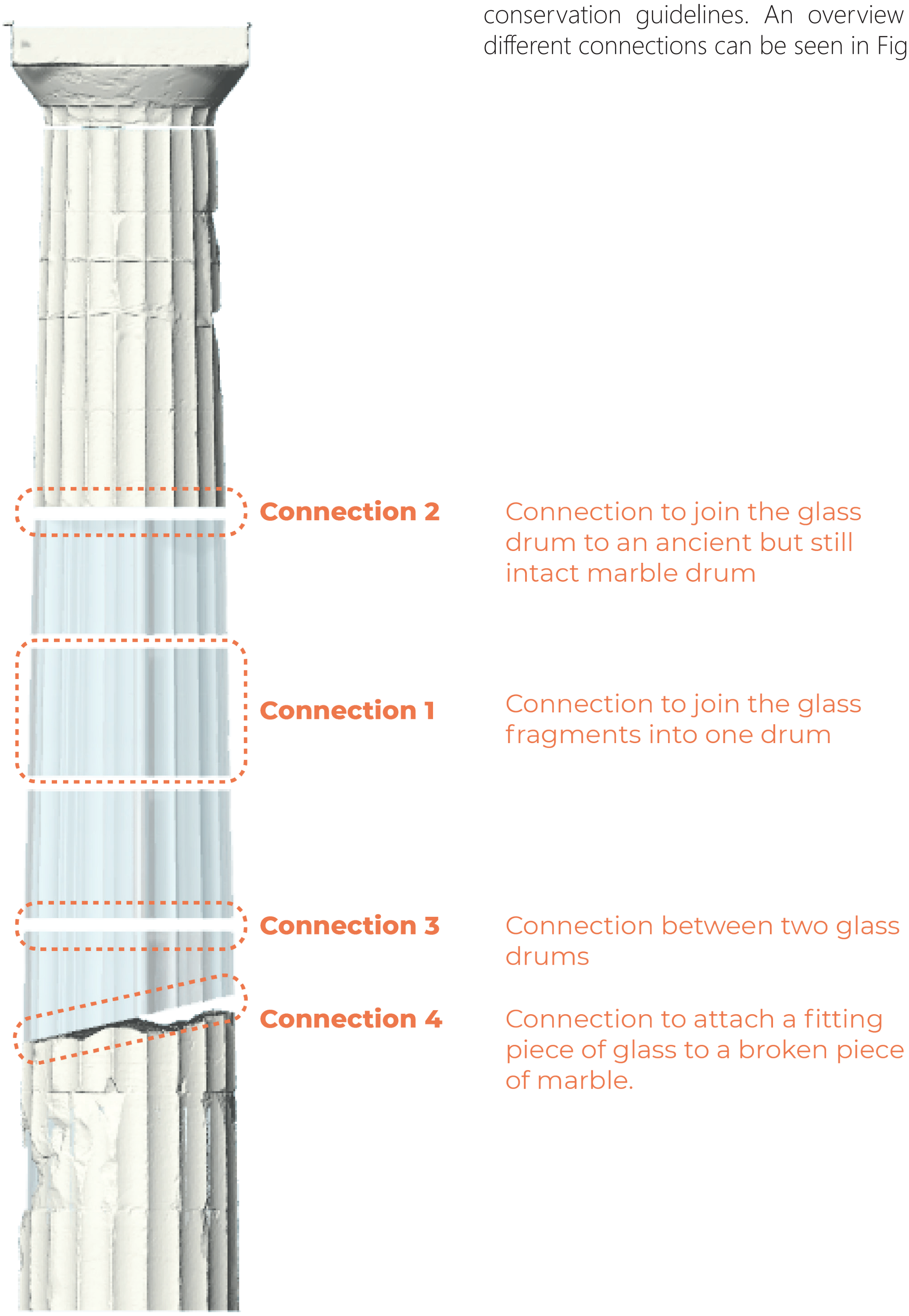


Figure 92: Overview of the different connections that are required to join the glass fragements

6.6.1 Connection 1

The first connection that will be designed is the one that joins the six drum fragments together. As decided in paragraph 5.5, each drum will be composed of five identical pie pieces with one core element in the middle. This gives a total of ten contact surfaces, five between the pie pieces themselves, and all the pieces are connected to the marble core in the middle As mentioned, it is important to respect the mechanical behaviour of the original structure when designing new pieces to it. This new drum should provide the same structural stability and mechanical behaviour to the superstructure as a marble drum would do. So the design strategy for the connections between the glass is to make the separate pieces behave as a monolithic element as much as possible. A marble drum is a monolithic eight-ton element. Both the mass and being monolithic provides its strength and stability to the structure, so if this is replaced by a glass element, these properties should be kept as much as possible.

This requires the connections between the six elements to be very tight and strong. The pieces are not allowed to move from or towards each other. During normal conditions, this will not be a problem, since the enormous mass of the superstructure provides enough normal force in the column to prevent lateral movement of the drums. However, in case of an earthquake, these forces have proven to be large enough to shift entire marble drums.

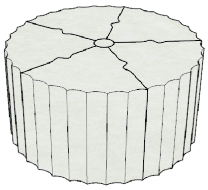
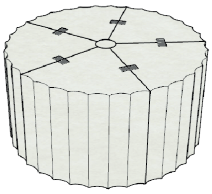
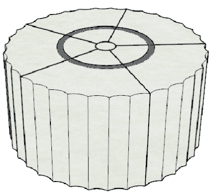
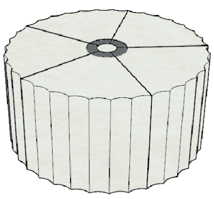
	Concept	Evaluation
Interlocking		⊕ Compatibility ⊕ Annealing ⊖ Stability ⊕ Peak Stresses ⊕ Visibility
Embedded Joints		⊖ Compatibility ⊖ Annealing ⊕⊖ Stability ⊖ Peak Stresses ⊕⊖ Visibility
Compression Ring		⊕⊖ Compatibility ⊕⊖ Annealing ⊕ Stability ⊕⊖ Peak Stresses ⊖ Visibility
Titanium Core		⊖ Compatibility ⊕⊖ Annealing ⊕⊖ Stability ⊖ Peak Stresses ⊕⊖ Visibility

Figure 93: Overview and evaluation of the different connection principles

Three of the four alternatives are based on joints between the pieces, thereby clamping the core in the middle. The fourth one is based on a connection between the core and the pieces, so not between the pieces themselves. The most promising and favoured one is the interlocking geometry connection. This connection does not need metal joints, which makes the connection less visible. It is also much easier to anneal then the other three options. The metal joints need to be embedded in the glass which requires a much more complicated geometry with more sharp angles. Another downside of the metal joints is that it will result in local peak stresses. Especially in the second and fourth option, this will likely cause problems. With a compression ring, these forces will be spread over a much larger surface area, which reduces these peaks, but the local stresses will still be higher than in an interlocking connection. The only criteria in which interlocking connections score slightly less is the stability. This is not a problem, but since the connection is made with glass, which has a lower young's modulus than titanium, it is slightly less stiff. This is however not seen as a large problem and does not weigh up against the advantages of an interlocking connection as compared to the three titanium-based connections.

Interlocking geometry

To determine which interlocking geometry is the most suitable for this application, it is needed to know its requirements and restrictions. The first criteria are that the interlocking pieces have minimal sharp or pointy edges. It is preferred to have a smooth interlocking surface to prevent a large increase in annealing time. A second criterion is that it should be easy to assemble the pieces to make one drum. To protect the glass and the interlayer between the glass pieces, the movement that brings the element into place needs to be as simple as possible, so in a single direction so the contact between the elements is minimised. The final criterion tells in which directions the geometry is locked and still allowed to move. As mentioned above, it is critical to prevent any movement in lateral directions. Four different proposals are shown in the table below, based on two parameters, a single or double curved surface and a full or half sinusoid shape.

The advantage of a double-curved surface is that it not only locks in the horizontal directions but also in the Z direction, thereby approaching the monolithic property of the original marble. A downside of this is, however, that a keystone

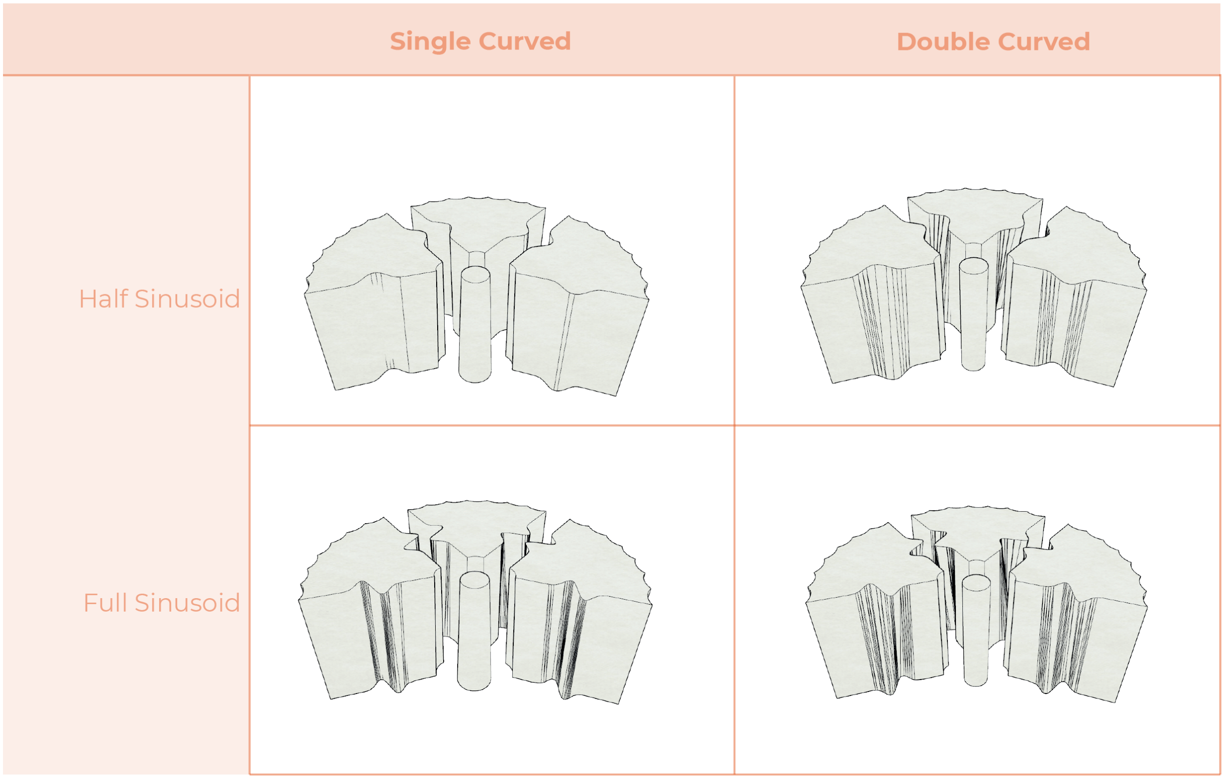


Figure 94: Four alternatives for an interlocking geometry

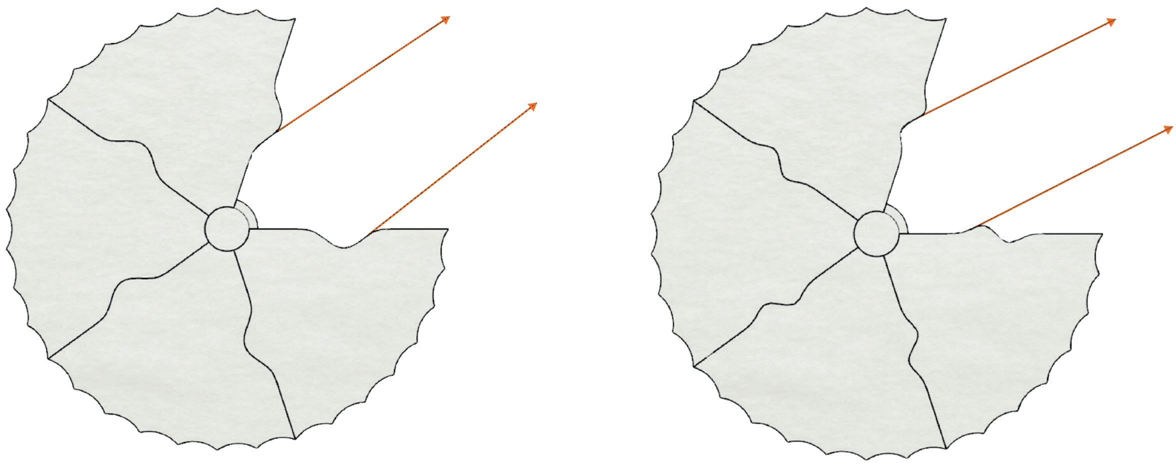


Figure 95: Difference in the amplitude of the curve between a half and full sinusoid shape, based on their tangent lines

is required to lock everything together. The fifth and final piece cannot be placed if it has the same geometry as the other four. So this requires a different geometry of at least two of the five pieces. So a single curved element is preferred here. This does not lock the geometry in the vertical directions, but now it is possible to have five equal pieces, which are moved vertically into position. A much easier process than a double-curved surface. In this case, the core can act as a keystone. This core is slightly wedged, as it gets slimmer towards the top of the column, as can be seen in Figure 96.

So the interlocking geometry will be single curved but will have a full sinusoid shape. This will allow for a smaller amplitude of the curve as can be seen below. To interlock, the tangents of the curves need to cross somewhere in this XY plane. Only then the geometry interlocks and keeps the elements into place. So the amplitude of the curves need to be large enough to interlock but also be as low as possible to reduce the impact on the annealing process, this is easier in a full sinusoid shape.
Both options will have interlocking properties but in the right option, the amplitude of the curve is much lower than in the left option. This lower amplitude means less distortion of the shape and is thereby easier to anneal. This is why this full sinusoid shape is chosen above the half sinusoid variant.

This will lead to the following design for the glass drums. The five pieces are all identic and are clamping the core which has a slightly conic shape. This conic shape will prevent the pieces to slide down in case a drum starts rockling during an earthquake. The width of this core depends on the vertical position in the column since it is in ratio with its diameter.

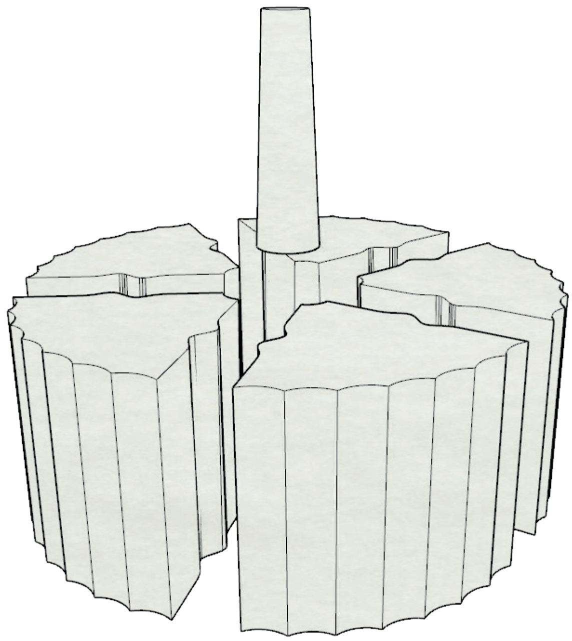


Figure 96: Exploded view of the interlocking desgin of the glass drum

6.6.2 Connection 2 and 3

With the glass pieces joined into a drum the final three connections can be designed, starting with the two that are very much alike: the connections between a marble drum and a glass drum or between two glass drums. This vertical connection between drums is not new since it is designed by the ancient Greeks and used in many classical temples. The principle of this connection is very simple but effective, which is the reason why it will be the base for Connection 2 and 3.

As discussed in Chapter 5, the connection between the drums is made with an embedded empolion, which only use is to (re)-align the drums properly. This technique is currently still used in the reconstruction process of the Parthenon. Only now, the wood is replaced by titanium, since its thermal expansion coefficient matches with that of Pentelic marble. To recreate this connection but now involving glass elements, we first need to know all the characteristics of the ancient connection with the wooden empolion. Below the drum from Sardis is shown again. A rough and coarse surface is surrounding the embedding for the empolion. On the outside of the section, the surface is more smooth and looks polished. This smooth surface is where the drum makes contact with the one above or below and where all the load is transferred. At the rougher surface, the drums make no contact and if they are placed on top of each other, this space becomes an airtight cavity. In the middle, the empolion interrupts this cavity. It makes contact with both drums, but no load is transferred here.

The same type of connection will be made between a marble drum and a glass drum. As is shown in Figure 98. On the top, the marble drum has the embedding for the empolion, which is carved around 2500 years ago, a rougher area around this embedding and on the edge of the surface a smoother area where the load will be transferred. Also around the empolion, in the centre of the surface, there is a small contact area. This ensures stability of the glass drum, as the pieces now have two supports.

Figure 97: Cross-section of a column in Sardis, Turkey, source: (Cartwright, 2013)

The empolion will have the same shape as the original wooden joint, but this time it is made from titanium. The other end of the empolion will be embedded in the marble core of the newly made drum. This embedding will be carved out manually like it is done in modern reconstruction works as well. At the places where the glass and marble make contact, an interlayer will be added to prevent damages to both vulnerable materials. The type of interlayer and the corresponding argumentation will be discussed later in this Chapter.

This connection will also be used between two glass drums, Figure 99. The only difference with the image above is that the top drum is now made from glass and not from marble. The contact area between the drums is slightly different than in the ancient connection. The marble cores in the glass drums are touching each other around the empolion. The other area where the drums make contact is around the edges, just like the old marble drums. This is enough to carry the load of the structure and reduces the post-processing time of the glass. At these contact areas, the glass needs to be polished, which is a time-consuming process. By only using the outer areas, the middle part does not need much post-treatment, reducing the production time and costs.

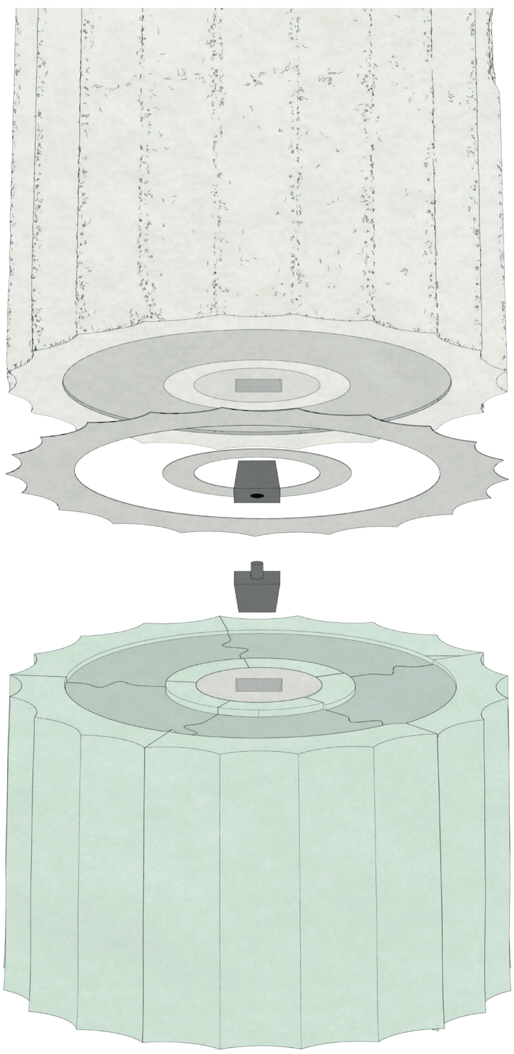


Figure 98: Exploded view Connection 2

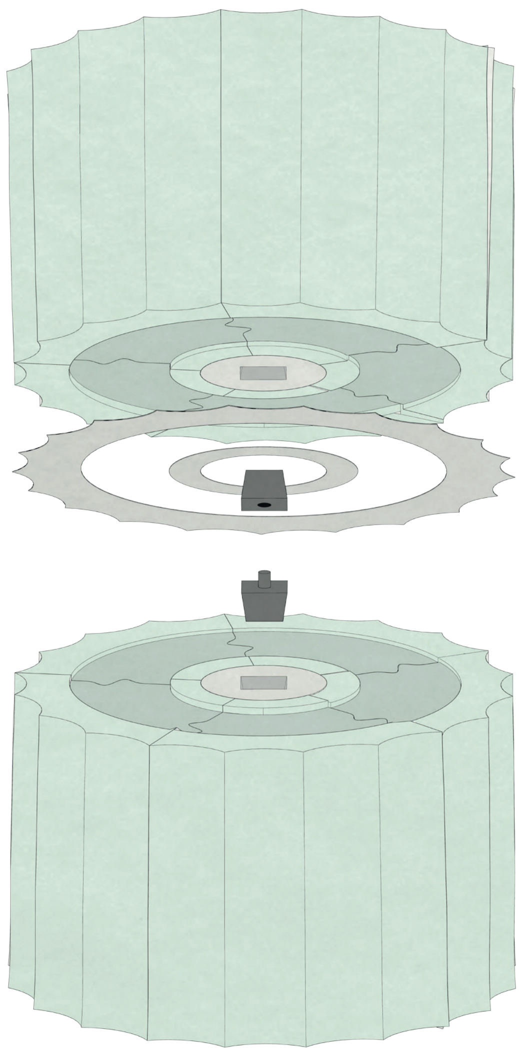


Figure 99: Exploded impression Connection 3

6.6.3 Connection 4

The fourth and final type of connection is the one that joins the broken marble drum to a fitting glass replacement. This connection is fundamentally different from the other three since this will be a permanent connection and cannot be easily reversed. This connection is nowadays made with two marble pieces: an original, 2500-year-old, and a new one which replaces a missing or damaged element. Looking into those connections tell a lot about what is currently allowed and how stability and unity between the distinct pieces are reached.
Figure 100 shows how a replaced piece of a frieze is attached to an original one. The metal rods are made from titanium and are drilled into the original marble. This is a rather intrusive intervention but nowadays it is the applied method during the restoration works on the Acropolis. The titanium is strong enough to carry the shear forces in the frieze. By applying twelve bars the forces that are transferred into the marble are split over a larger surface, which reduces the local stress in the stone, (Bouras, Ioannidou, & Jenkins, 2012).

At the point where the surfaces meet, a layer of mortar is applied to connect both stones, as can be seen on the image below. However, this layer of mortar has several more applications than only be a connecting element. At first, it protects the stones from severing contact damage and secondly, it allows for some slight tolerances between the surfaces. The mortar is not allowed to be stronger than marble, so when the structure proves to not strong enough, the mortar layer will be the first one that will break and not the precious marble. This gives restoration workers time to reinforce the structure and prevent damage on the marble, (Aggelakopoulou, 2013)

The images shown here are made from a frieze and a piece of wall, but the principle of joining two pieces is similar in a column. These principles will be the base for designing the connection between the broken marble and the cast glass element. Four alternatives are given in on the next page.

Figure 101: Where the old and new marble pieces touch each other, a layer of mortar is applied: (Barou, n.d.)

Figure 100: Reconstruction of a Frieze in the Parthenon, source: (Bouras, Ioannidou, & Jenkins, 2012)

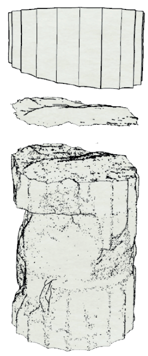
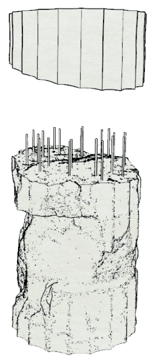
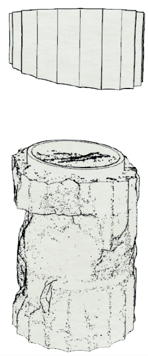
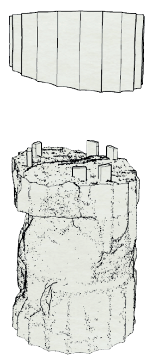
	Concept	Evaluation
Mortar		⊕ Intrusiveness ⊕ Compatibility ⊖ Stability ⊕ Peak Stresses ⊕ Visibility
Titanium Bars		⊖⊕ Intrusiveness ⊖ Compatibility ⊕ Stability ⊖ Peak Stresses ⊖ Visibility
Interlocking Ring		⊖ Intrusiveness ⊖⊕ Compatibility ⊕ Stability ⊕ Peak Stresses ⊖ Visibility
Interlocking Teeth		⊖⊕ Intrusiveness ⊖⊕ Compatibility ⊕ Stability ⊖⊕ Peak Stresses ⊖⊕ Visibility

Figure 103: Overview of the different alternatives for the fourth connection

The first connection the only structural element is a mortar layer. For almost all the criteria this is the preferred solution. It is the least intrusive to the marble, least visible and most compatible solution for assembly. The downside is, however, that mortar creeps and thereby the risk on instability is high. This effect is magnified by the fact that the broken surface is never flat. Most of the times it will be broken under an angle. This angle will cause the gravitational force to split up in normal force and shear force, Figure 102. So if the mortar is the only material that joins the pieces, the creep effect will cause the top piece to slowly slide down, till it eventually collapses.

So non-creeping elements are needed to take up that shear force. The first alternative is the technique that is used in Figure 100. It is however very intrusive and hard to make the holes in the glass. Also, the bars will be clearly visible from the outside, despite that the glass is made translucent.

The other two options are quite similar. Both interlocking ring and teeth are less intrusive to the marble and less visible than the titanium bars. The ring is more stable since more interlocking elements are used in the connection. This, however, does make it much more intrusive than the teeth alternative. This why the Interlocking Teeth design is chosen above the ring-shaped element. Both are compatible with conservation guidelines and glass manufacturing, both are stable connections, which do not creep. The only aspect which is better in the Interlocking ring is the risk of peak stress. It is however expected that the teeth do spread the forces sufficiently over the adjacent geometries.

The interlocking geometry will only take up the lateral forces in the connection. If it also bears the vertical dead load of the whole superstructure, the reaction forces will be so large that it will result in fractures in both marble and glass. So the vertical load will be transferred via the mortar layer that is also applied between the two elements, just like is done in Figure 81. This mortar layer will make the load transfer as homogeneous as possible, thereby reducing the peak stresses in both glass and marble. The composition of this mortar will be discussed further in this paragraph.
Shaping the Teeth

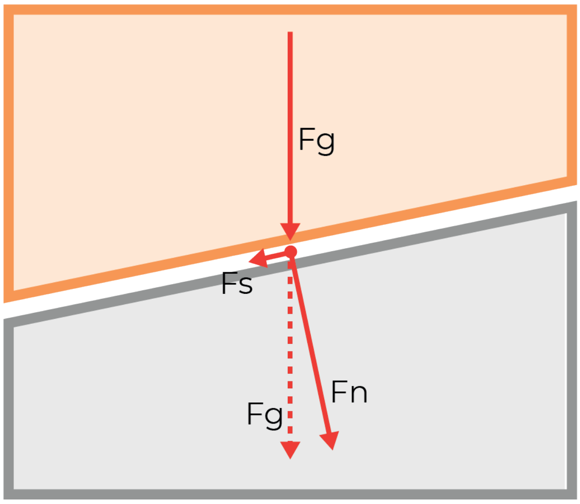


Figure 102: Static scheme of the forces in these connections

Shaping the Teeth

The proposed interlocking teeth can be made from two materials. The first option is to shape the glass element in such a way that it will interlock with the carvings made in the marble. The other option is that the teeth are made from titanium. In this case, the marble will still be carved, but now, channels are made in the cast glass elements in which the titanium blocks will fit. Both options are shown in a diagram below. For each option, two alternatives are made. One with straight sides and one with inclined sides.

All four alternatives have been tested in a Finite Element Analysis. In the software program DIANA, a fictionary load case of 20 Tons was attached on the orange geometries to see which stresses would develop in the glass. Since the load case is fictional, the numbers itself do not give any valuable information. This test is only done to see the difference in maximum stress between the four alternatives. In every test, the only parameter is the shape of the geometry, so every difference in stress is directly caused by that variable.

The FEA result of the best performing alternative has been shown on the left. This is the alternative with a titanium joint, with straight edges. With this 20 Tons load case the maximum tensile stress would be 30.38 Mpa. This proved to be much lower than the other three alternatives.

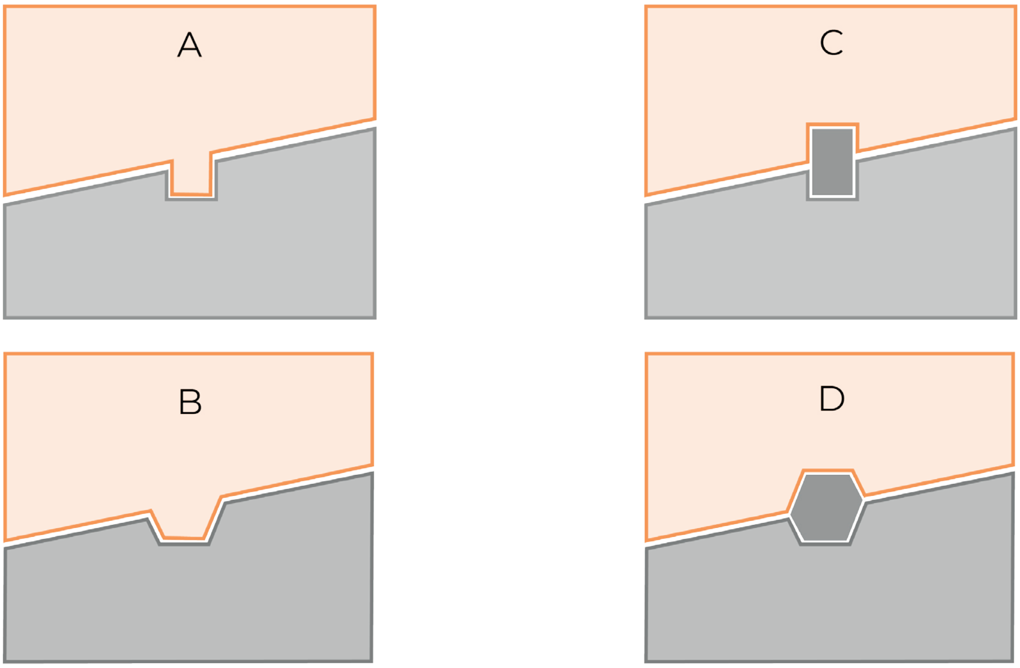


Figure 105: Simplistic overview of the alternatives

In options A, B and D the tensile stress is respectively 186, 240, 666% higher than in case C. This difference can only be caused by the changes in geometry, so from this can be concluded that option B, a titanium joint, with straight edges is the best material and shape to make this connection. All FEA results can be found in Appendix D. The different between A and C can be declared to the amount of glass the reaction forces can be spread over. In a small body, the force is distributed over a much smaller area, causing higher stress. The higher result for both inclined geometries (B and D) is likely because this inclined edge now also takes up a part of the vertical force. Since this force is much higher than the lateral force, the combined reaction forces in that support will increase enormously. This created an equal opposite force in the glass, which resulted in a significant increase in stress. So the best option is alternative C: A titanium insert, with straight sides. The edges of these joints will, however, be chamfered to prevent the annealing of sharp angles in the glass elements. Between the titanium on one side and glass and marble on the other, a thin layer of mortar will be applied to protect the glass and marble from contact damage with the hard titanium joint.

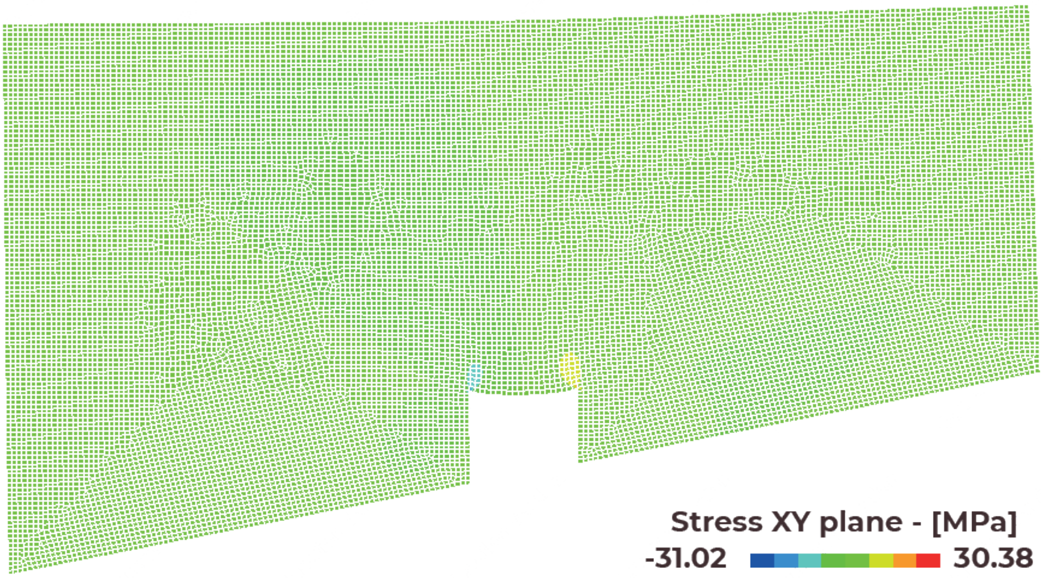


Figure 104: FEA result of the best perfoming alternative: C. The other results are shown in Appendix D

Mortars

To join the glass and marble element together, a mortar layer will be applied between the surfaces. There are a lot of different types of mortar in the world, but only a couple are allowed to be used for this application. Mortars that come in contact with the authentic Pentelic marble in the Parthenon, must be based on the same physiochemical and mechanical properties as the original materials. Moreover, the mechanical strength of the mortar cannot be higher than the strength of the marble. In case of failure, it will be the mortar that fails and not the authentic marble. Yet, the mortar must be strong enough to assure satisfactory joining and durability and flexural enough to deal with minor deformations. Based on these requirements, the desired mechanical properties of mortar for the Parthenon can be described as follows: **Compressive strength, 6 – 10 MPa; Flexural strength: >1.2 MPa; Modulus of Elasticity: <12,000 MPa**, (Aggelakopoulou, 2013)

Figure 106: Marble to marble connection filled up with mortar, source: (Barou, n.d.)

In 2013 several tests have been done to find mortars that could be used in the restoration of the Acropolis. These experiments were done with two different types of mortar: filling and sealing. The base for these mortars was either quartz sand or calcareous sand, both with grain sizes varying between 0-1 and 0-4 mm. During testing, some of the mortars were proven to be too strong or too weak, but three types showed the physicomechanical properties that are required for this application. The first one is a mixture of hydraulic lime and calcareous sand in a ratio 1:3. The second mortar has the same ratio, but this time quartz sand is used. The third option is a mixture of 75% calcareous sand, 20% Lime hydrate powder and 5% metakaolin.

These mortars are specifically designed to be compatible with Pentelic marble, but with this application, the compatibility with glass is also important. Glass is a very durable material but prone to strong acids and alkalis. No acidic materials are used in these three mortars, but calcareous sand and especially the hydraulic lime could contain alkalis. In two of the three mortars, hydraulic lime is used which often contains calcium hydroxide (Ca(OH)2). When this material comes in contact with water, the hydroxides will cause an alkali reaction with the glass, thereby dissolving its molecular structure. So if hydraulic lime is used in these mortars, only non-alkaline calcium bonds are permitted like calcium carbonate (CaCO3) or calcium silicate (Ca2SiO4), (LaFarge, 2010).

The third mortar contains only calcium oxide (CaO) and metakaolin (Al¬2O3 and 2SiO2). These molecules do not cause alkaline reactions and are thereby better to be used in combination with glass. Moreover, the metakaolin mortar is slightly stronger than the ones with hydraulic lime, regarding all this, the metakaolin mortar is preferred in this application and will thereby be used as mortar between the glass and marble elements like is shown in Figure 106.

6.7 Interlayers

Besides the connection with the mortar, there are three other types of connections, two with glass to glass contact and one with glass to marble. All three of those connections are based on a dry assembly since it matches the traditional methods and makes the connection reversible.

All the connections will involve glass to glass or glass to marble contact. As explained in Chapter 3, glass is very prone to surface contact since it could lead to small flaws and defects, risking total failure of the element. Moreover, if forces are transferred from glass to glass, it is important to do this as evenly as possible and prevent peak stresses during the load transfer. Given these problems, an interlayer is required to make the connection between the glass and marble or between two pieces of glass. Given the different types of connections, different types of interlayers are required.

Types of Dry Interlayers

There are several types of materials that could be used as interlayer in a dry cast glass connection. From all the six families of engineering materials, polymers, elastomers and metals are the most common ones to be used as interlayer between cast glass elements, (Dimas, 2020). Other families like ceramics, including other glasses, are not suitable to use. To protect a glass from surface damages it is not desired to do that with a material with similar but some polymers, elastomers, metals or hybrids between these materials have the properties that are required in an interlayer.

In Dimas (2020) several materials out of the above-mentioned families are given. These materials are based on existing interlayers, other applications with glass, or previous experiments with these materials. Also, some hybrid options are proposed, but these are still in the research phase and not widely applicable. The selected materials are shown in the image below including the family they belong to. These materials are mentioned by Dimas (2020) and show the potential to be used as dry interlayers in different applications. Polymers like PU and PVC have been tested on strength and creep by Oikonomopoulou (2019) and Aurik (2017) and some variants did show promising results. In Akerboom (2016) Vivak was chosen as an interlayer in a cast glass column. These sheets are made from PETG, which is slightly stiffer than PU and PVC. From the elastomer family, neoprene and silicon are widely applied materials for interlayers between the glass and other building materials like window frames and metal joints. Another type of elastomer is Teflon, known for its non-sticking properties. This could cause problems since the friction coefficient could be too low. However, since it is very durable and resistant against corrosion, it is still a commonly used material in combination with glass, (Dimas, 2020).

From the metal family, Dimas (2020) selected copper, lead and aluminium as possible options. This was based on glass compression test by Akerboom (2016) and Daryadel et al. (2016). Finally, some hybrid solutions show potential to be used as interlayer. However, these hybrid compositions are still mostly under development and experimental. This makes it

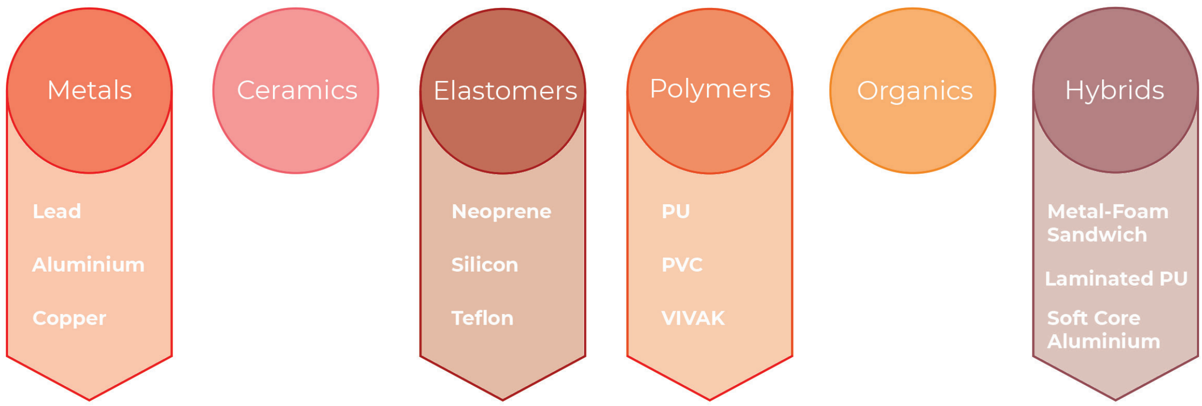


Figure 107: Overview of potential interlayer materials, based on Dimas (2020)

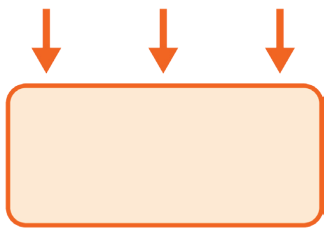
for now not possible to use for this project, given the restriction to use untested materials and solutions in conservation projects.

Dry Connection

There are three different types of dry connections in the design, although two of them are very much alike. There is a vertical connection, where to drums meet, and a horizontal connection between two glass pieces within a drum. During normal conditions, both connections have different load cases. In the vertical connection, there will only be compression force, while the horizontal joint will not be load bearing at all. Here the main purpose of an interlayer is only to prevent glass to glass contact. These and all the other required material properties for the interlayer are discussed below.

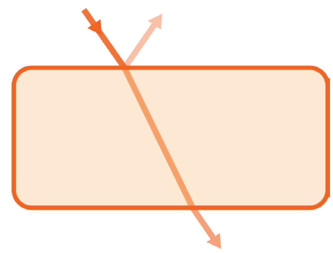
Transparency

The transparency of the interlayer is very important for the aesthetical appearance of the glass. The glass itself will be translucent so if an opaque interlayer is used, it will still be visible. However, thanks to this translucent glass that is chosen, the interlayer does not have to be fully transparent. The required transparency for the interlayer will be determined by the transparency of the glass blocks.



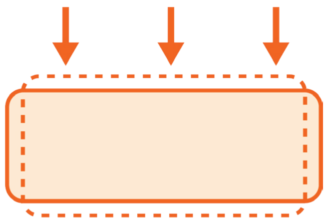
Shear Resistance

Eventual lateral loads could lead to shear stresses in the interlayer. The amount of shear force that will occur depends for instance on the magnitude of an earthquake or kind of impact damage. The interlayer should have some shear resistance, but since it is only important in rare cases like earthquakes, it is not a hard design criterion.



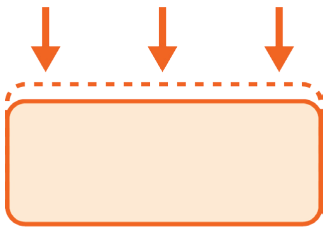
Compressive Strength

The main load case the interlayer is exposed to includes only compression forces. Due to the large mass of the structure, these forces can become very high. For comparison, the compressive strength that is given for Pentelic Marble is 76,2 Mpa, (Skoulikidis, Vassiliou, Tsakona, & Kritikou, 1993). If this value is lower, the interlayer might not be strong enough.



Creep Resistance

Creep is the permanent deformation of a material due to a continuous load and is a very common phenomenon in building materials. The amount of deformation caused by creep varies for each material and is often dependent on the temperature of the material. Some materials, like most metals, barely creep at room temperature while others like concrete and some polymers creep at almost every temperature. The creep factor of the interlayer should be as low as possible. This is an important property in the assessment of the materials

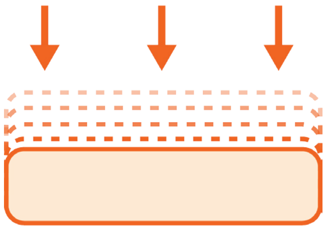


Friction Coefficient

Friction can be explained as the resistance that occurs when two materials are sliding past each other. The friction coefficient gives the relation between the force of friction and the force pushing the two objects together. A higher coefficient means more friction between materials which leads to more tensile forces in the surface area of the objects.

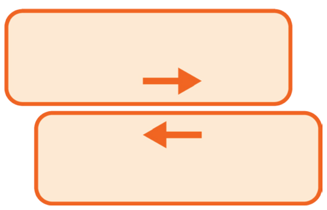
Poisson Ratio

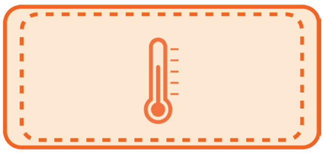
The Poisson ratio is the relation between the axial strain and the corresponding transverse strain of material. Since the axial compression load on the interlayer can be quite large, due to the high mass a high Poisson ratio could lead to a large expansion in the transverse direction. This could lead to stress in the interlayer if it cannot expand or in the glass connected to it due to friction. So ideally the Poisson ratio should be as low as possible. If it is higher, there should be room for expansion and a relatively low friction coefficient.



Youngs Modulus

The higher the Young's Modulus of a material, the less deformation occurs at a certain load, which is often favourable for materials. However, too high elasticity could be problematic in this project. If the Young's Modulus of the interlayer is higher than that of glass, the interlayer cannot adjust to the profile of the glass. Instead, the glass will deform, since it bends easier, towards the shape of the interlayer. This is also why for instance metals like copper and aluminium are possible options for an interlayer and stainless steel is not. The Young's Modulus of stainless steel is too high to be used as an intermediate layer between glass elements.



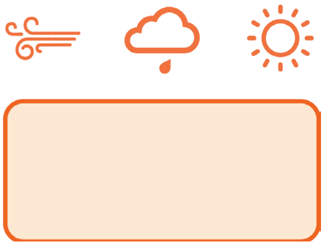


Durability

The final criterium that should be taken into account is the durability against water and UV-light. If the interlayer erodes or decays under these circumstances it could lead to damages to both marble and glass.

Thermal Expansion

Thermal expansion leads to strain, strain leads to stress and stress, which could lead to fractures in the glass. Like many other design decisions, thermal expansion is an important assessment criterium. However, in this case, it is not the most important one. The relation between thermal expansion of the interlayer and the amount resulting in stress in the glass depends heavily on the friction coefficient of the glass.



Thickness

The thickness of an interlayer can have a big influence on its mechanical behaviour. A thicker layer results in higher bending stiffness and a more homogeneous load transfer but is also more visible. The minimum and maximum thickness of an interlayer are often defined by the manufacturing process.

	POLYMERS			ELASTOMERS			METALS		
	PU	PVC	VIVAK	NEOPRENE	SILICONE	TEFLON	COPPER	ALUMINUM	LEAD
TRANSPARENCY	Transparent / Translucent	Transparent / Translucent	Transparent / Translucent	White Opaque	Translucent	Translucent	Reflective / Red brown	Reflective / Silver	Opaque / Ash-gray
COMPRESSIVE STRENGTH [MPa]	48 - 61	37 - 44	225 - 248	14 - 29	8.4 - 13.8	11 - 12	28 - 1250	24 - 764	4 - 75
SHEAR RESISTANCE	0.83 - 10	0.75 - 1.1	5.3 - 5.5	0.05 - 7	0.3 - 20	0.14 - 0.19	25 - 58	23 - 35	4 - 8
POISSON RATIO	0.47 - 0.49	0.395-0.405	0.333 - 0.347	0.48 - 0.495	0.47 - 0.49	0.44 - 0.46	0.27 - 0.35	0.32 - 0.37	0.435 - 0.445
CREEP RESISTANCE	MAYBE	NO	MAYBE	MAYBE	NO	MAYBE	YES	YES	YES
YOUNG'S MODULUS [GPa]	2.5 - 30	2.2 - 3.1	14.1 - 14.8	1.65 - 2.1	5 - 50	0.4 - 0.55	68 - 158	63 - 92	13 - 17
THERMAL EXPANSION [Strain/°C]	1.6 - 1.65 E-4	65 - 81 E-5	2.87 - 2.93 E-5	2.02 - 2.45 E-4	2.5 - 3 E-4	1.2 - 1.7 E-4	1.45 - 2.27 E-5	2 - 2.5 E-5	1.8 - 3 E-5
DURABILITY	Excelent	Excelent	Fair (UV)	Poor (UV)	Good (UV)	Good (UV)	Fair (Corrosion)	Fair (Corrosion)	Fair (Corrosion)

Figure 108: Structural en mechanical propeties of the different interlayers, based on Dimas (2020), source: Granta Design Limited (2015)

Interlayer in Connection 1

The second required interlayer will be the one between the glass pieces in a drum. Instead of the first case, this interlayer will not be loaded in normal conditions, so creep resistance is not a limiting factor. For this application, Vivak will be the chosen interlayer. It is one of the most transparent options, so it will be barely visible for the observer. An advantage of Vivak is that it can be easily shaped, but it is still a hard material. Since the glass pieces will have to be shifted into each other. They will slide alongside the surface of the interlayer. If this interlayer deforms easily, it will possibly slide down. With Vivak this risk is minimised as much as possible, without compensating for transparency.

Interlayer in Connection 2 and 3

The table above shows the assessment of the interlayers proposed by Dimas on the different criteria. As mentioned before, the structural and mechanical properties are the most important criteria for an interlayer in this design. According to conservation guidelines, a material has to be proven to be strong and stable enough before it can be used in a restoration project like this. Based on this, the creep resistance seems to be the decision-making criterion. Most interlayers are stronger than Pentelic marble itself, but besides the metals, none of them has been proven to be creep resistant. Since the interlayer between the drums is continuously loaded, creep will occur if a material is not resistant to it. So that leaves only the metals for valid options and from these, an aluminium alloy is the most suitable one. It is strong and stiff enough and is the least visible from the three. Moreover, it has a high shear resistance and low poison ratio and the durability is sufficient. The type of aluminium will be a zinc alloy (AL 7055) since this type has the best stiffness to strength ratio. It has a silver appearance, but with the translucent glass, it will not be very noticeable.

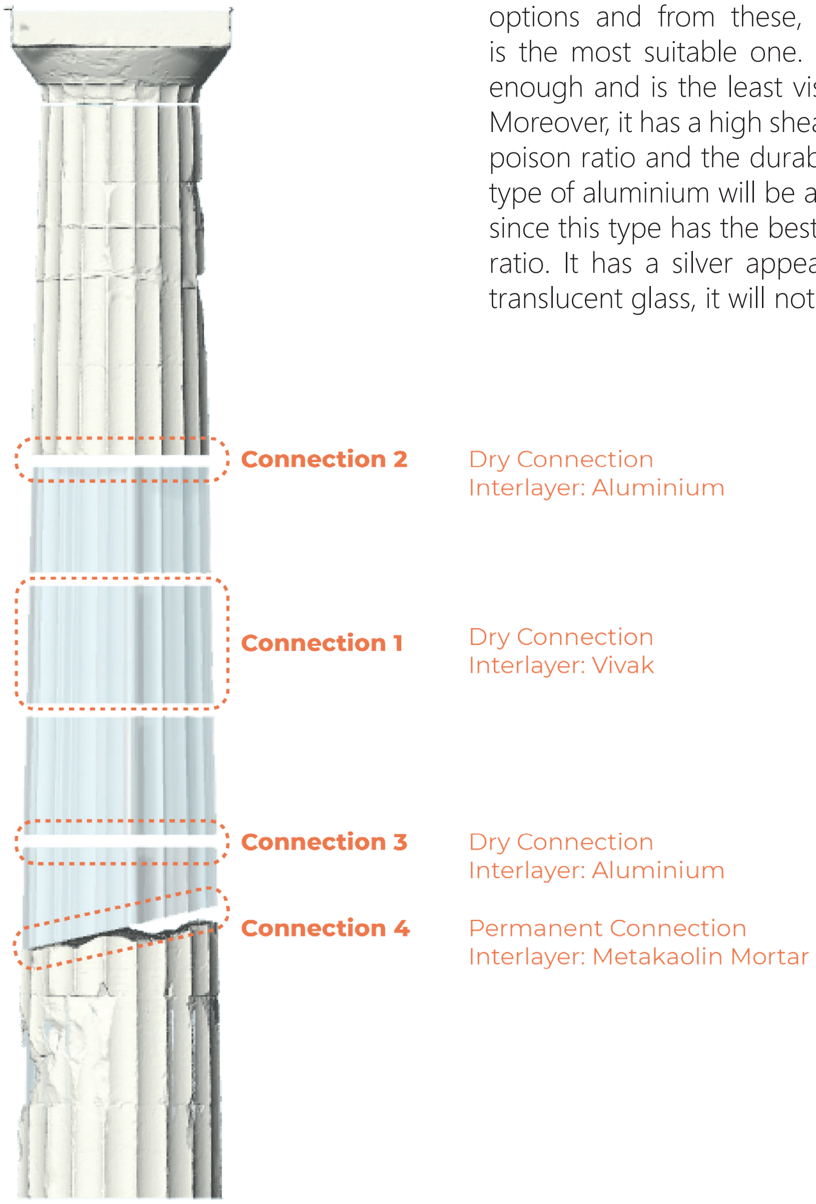


Figure 109: Overview of the different connection types and used interlayers

5.8 Reducing the Annealing Time

The final step of the design phase is to optimise the geometry. Right now, the glass geometry is split into drums which are all fragmented into five glass pieces with a marble core, Figure 110. These fragments are easier to produce and make the structure safer and more stable. However, with these sizes, a single pie piece still weights about 1.5 Tons. This is producible, but it will be very time consuming to anneal given the high mass and pointy shapes of the flutes. It is thereby desired to further reduce the mass of the cast glass elements. This would reduce the total production time and costs of the design.

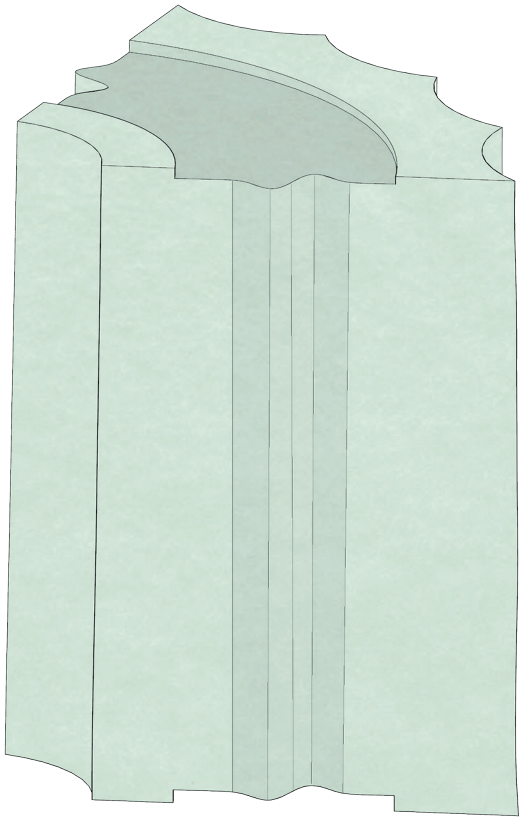


Figure 110: Final geometry of a glass pie piece

Three options are proposed which could reduce the annealing time of the fragments, shown in the table below. The first option would be to split the drums up in ten fragments, instead of five. This would reduce the mass of each piece by half. The pieces can then be annealed simultaneously. This larger number of fragments is however compromised by the transparency, there are more connecting surfaces and despite that the glass is translucent, they will still be visible. It will also require more connections, which will make the structure less stable and the required tolerances could become problematic too.

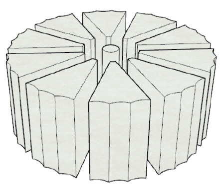
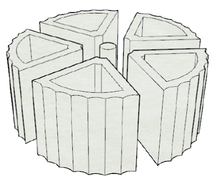
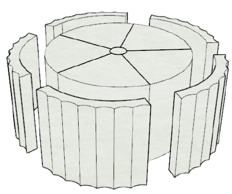
	Concept	Evaluation
Smaller Pieces		⊕ Effectiveness ⊖ Compatibility ⊖ Tolerances ⊖⊕ Stability
Hollow Elements		⊕ Effectiveness ⊕ Compatibility ⊕ Tolerances ⊖⊕ Stability
Seperatable Skin		⊖⊕ Effectiveness ⊖ Compatibility ⊖⊕ Tolerances ⊕ Stability

Figure 111: Overview of the different options to reduce the annealing time of the glass pieces

Similar problems would occur in the third option, in which the flutes of the drum are split from the core. With a separable skin, the sharp and pointy edges of the flutes can be annealed in a different mould. This skin would be much lighter and thereby easier to anneal, while the core would be heavy but without sharp edges. This would, however, complicates the design a lot, requiring different connections and assembly methods. Simultaneously the effectiveness of this design on the annealing time might not be so large since the total mass of the glass remains roughly the same.

The second option, the size and shape of the glass pieces will not change, but they will be made hollow. This is possible with a 3D printed sand mould as long as the sand can be removed from the cavity via a hole in the glass. Making the pieces hollow does not change anything on the design of the connections so the compatibility remains the same. The load is admittedly distributed over a smaller surface area but this is structurally similar as in the connection between two drums and not different from the original connection between the marble drums, where contact only was made at the periphery.

This connection is shown in the image on the right. Despite the monolithic character of the drum, the load transfer is concentrated the small area near the periphery. Given that glass has higher compression strength than Pentelic marble, 300 MPa compared to 77.8 MPa, it should be possible to spread the load over a similar area as shown on the right, instead of over the whole section. This allows for optimisation of the mass by making hollow elements instead of monolithic ones.

The load is already concentrated around the edges as it enters the glass drum. Instead of spreading the load over the whole section area, like is the case in monolithic marble drums, it can also be kept at the edges. This allows for making the pieces hollow, as long as the section thickness is big enough to support the load and allow for proper annealing. These structural principles are shown below, with monolithic pieces on the left, and hollow ones on the right.

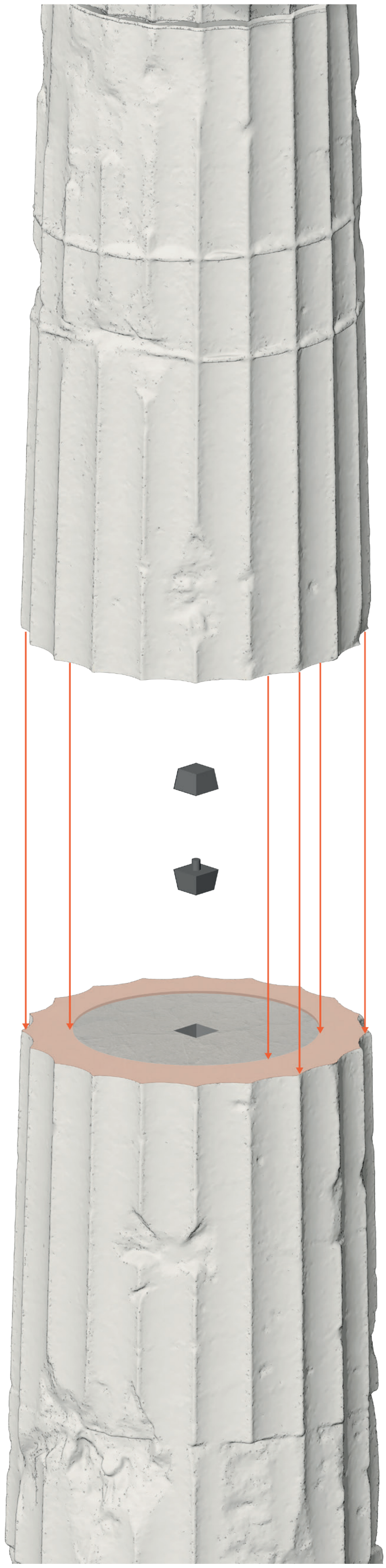


Figure 112: Structural principle of the original connection between two marble drums where all load is transferred at the periphery

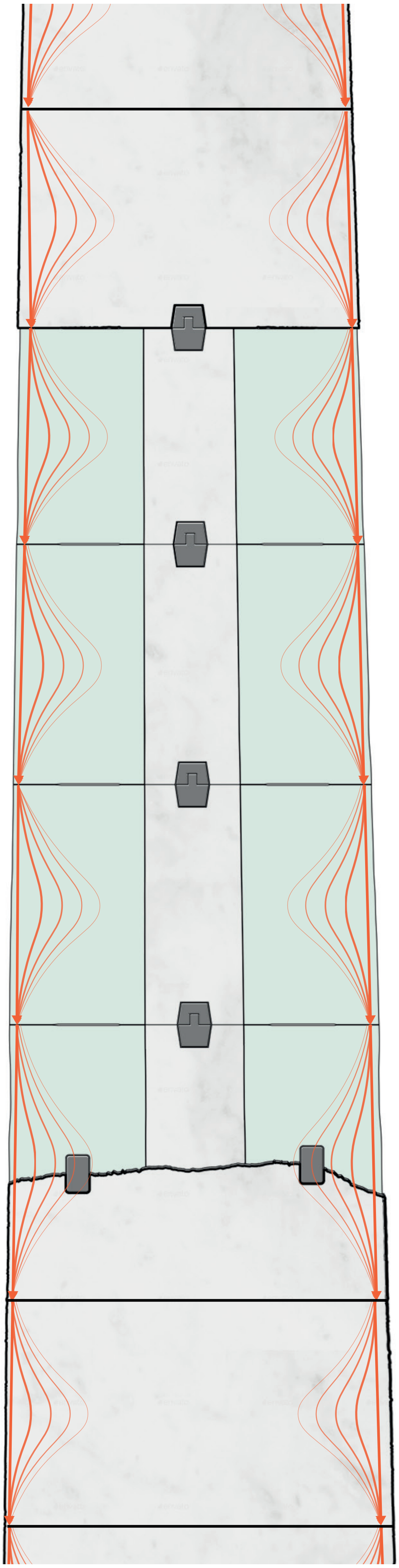


Figure 113: Structural principle when using only solid, monolithic pieces

What stands out is that the amount of stress in both cases is equal at the connecting point between the drums. From there, in monolithic elements, the load will spread over a larger section area before it clusters again at the bottom side of the drum. In a hollow piece, the force goes directly downwards after entering the glass, given the smaller section thickness. The stress is thereby more constant over the whole length of the glass drum. The smaller section surface does, however, result in higher local stress but this does not exceed the level in the connections between the drums.

In case of a fractured drum, where a glass piece is joint to an original marble drum, the glass will be hollow as well. As shown on the next page, the main difference between the alternatives is that with the hollow glass two different structural principles are combined in one drum, while with the monolithic pieces, there is only one. This does, however, not have any effect on the structural performance of the hybrid drum. To assure proper annealing of the piece, the section thickness of the connecting surface and around the titanium joint remains constant.

The pieces will not be tubular, as the top and bottom surface will be closed. This provides more stability to the elements than a tubular shape. However, to produce such a hollow shape, a small hole is required to remove the mould material from the cavity. This hole will be placed in the centre of the bottom surface where it will be minimally visible. By using high water pressure, the sand can be removed from the cavity via this hole, which has a radius of five centimeters. The glass around this hole will not be loaded since all load transfer occurs at the periphery of the drums. So making this hole will not result in any structural compromises for the design.

So it can be assumed that for compression strength a hollow glass element is sufficient, however, in this case, the effect of buckling should be taken into account. The section should be thick enough to prevent the glass from bucking. The buckling distance is however very small so no big problems are expected here, although the structure does become a little more unstable due to this buckling phenomena. This is however neglectable regarding the height of the drum and a thickness of 100 mm.

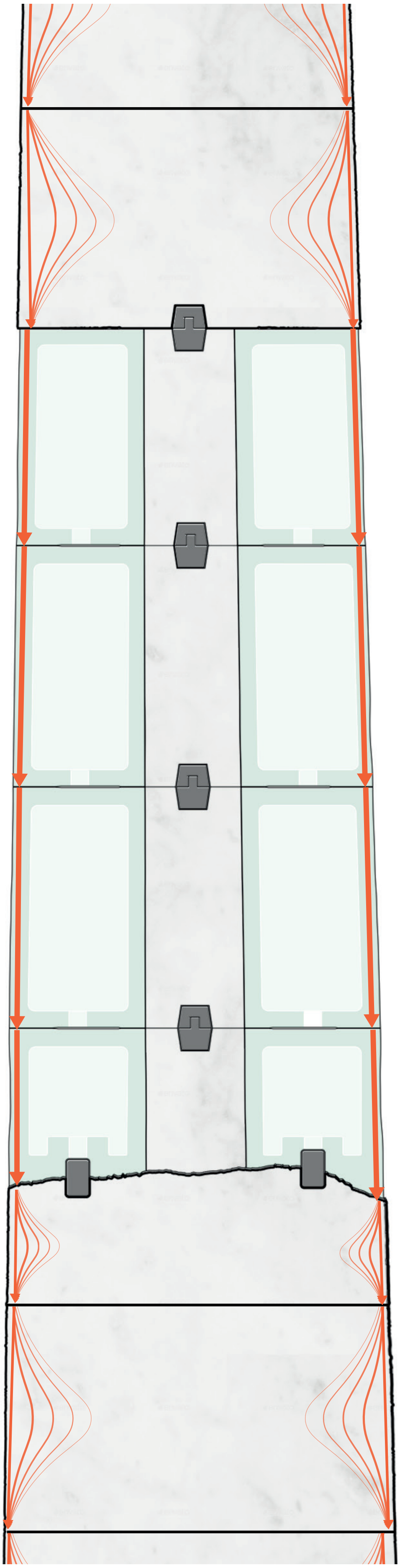


Figure 114: Structural principle when using only hollow, monolithic pieces

With this hollow pieces, the total mass of each piece will be reduced by half to about 750 kilos. This would significantly reduce annealing time. Moreover, the section thickness is now more constant as well. This means that the cooling rate is similar for all areas of the piece, speeding up the total process even more. These advantages are without compensating for compatibility with the other parts of the design like stability and connections. Another advantage is that these hollow pieces require only half the amount of glass than the other options or the initial design. This reduces the material use and thereby environmental impact.

Figure 115: Eastern view of the Acropolis, source: (Earth Trekkers, 2020)

07.

FINAL DESIGN

7.1 Overall system

All the proposed design decisions do not address a single restoration project, but can be applied to every temple in the classical would, as long it is made from marble. Naturally, some design decisions would turn out to be different, since not every temple has the same mechanical system.

In this thesis, the Athenian Parthenon has been used as a case study, given the excellent documentation of the monument. So this chapter will show how the design proposal is applied to the Parthenon, but it could be any other project as well. It is not designed specifically for the Parthenon.

On the right, a damaged column of the western colonnade of the Parthenon is shown. It is the fourth column measured from the north and is heavily damaged. In this design case, several pieces of the original Pentelic marble are missing. Drum 1 and 2 are still intact, but the third drum is heavily damaged. Half of the drum is split in half and the top piece has never been recovered. Drums 4, 5 and 6 also have never been found and need to be completely remade. The top four drums are luckily found and still intact, just like the capital.

So in total 3,5 drums are missing from the original structure and will be reconstructed from glass according to the in Chapter 6 proposed design. This design will be shown below, starting with an elevation and cross-sections of the column. Further in this chapter, other design components like connection details and element sizes will be shown.

Figure 117 shows the front view of the western colonnade of the Parthenon, the middle column being reconstructed from glass elements. The translucent glass and rough surface make the appearance of the filament less intrusive, but it is still clearly distinguishable from the marble. This translucency also hides the marble core that is in the centre of the glass but this core is naturally still visible in the shade.

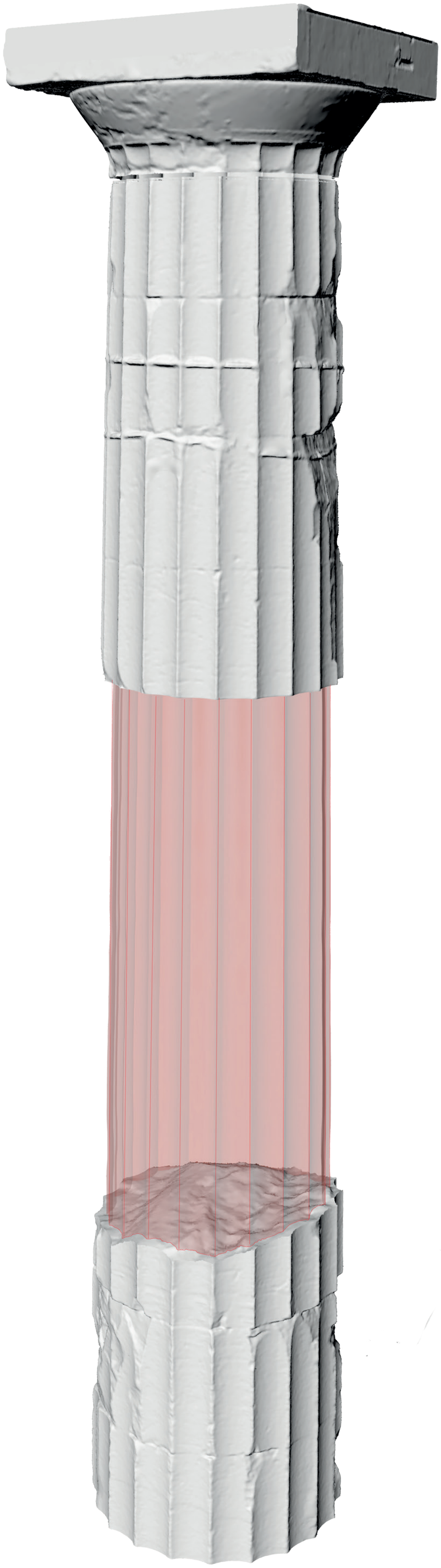


Figure 116: 3D of the missing geometry of the Column

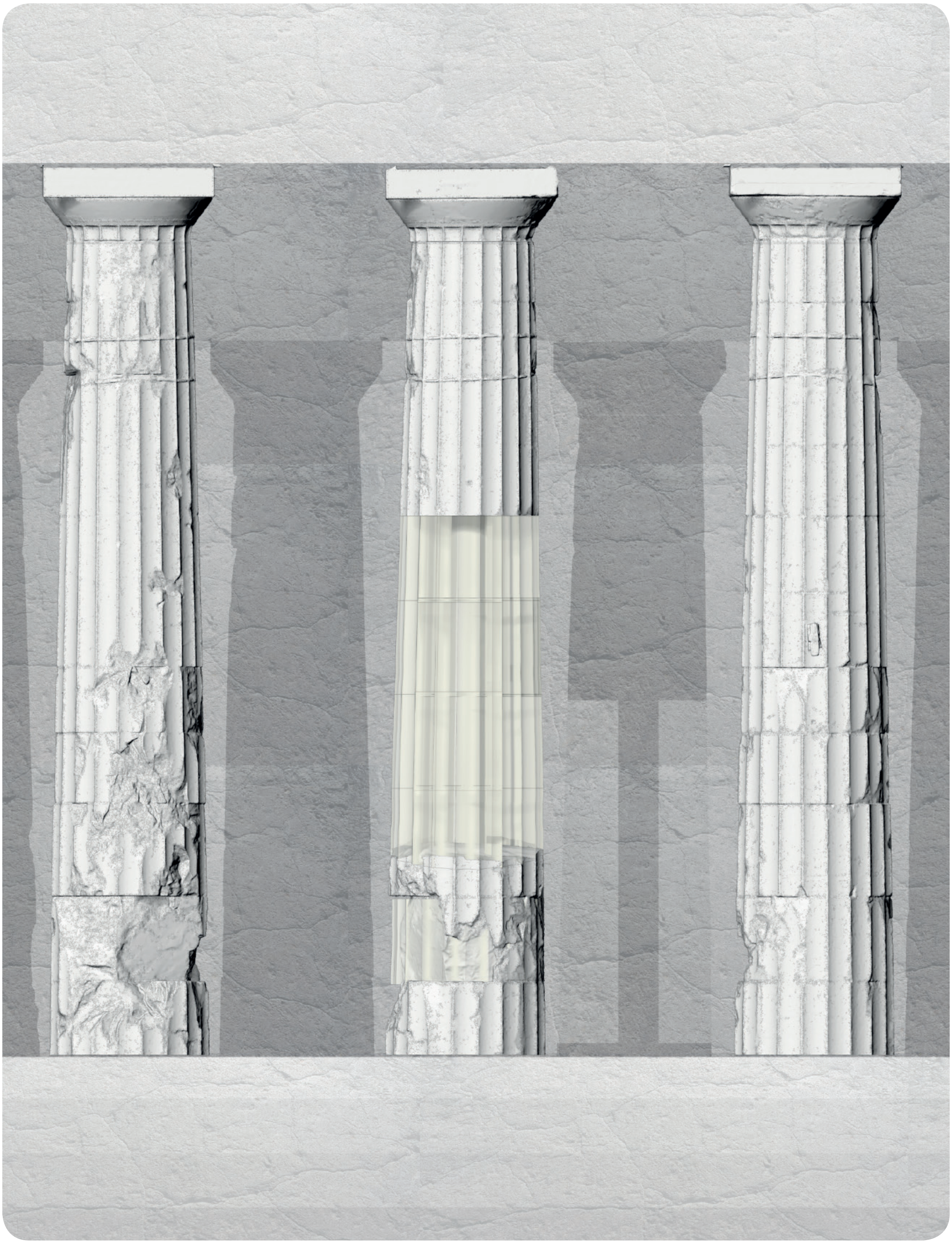


Figure 117: Front elevation of the western collonade of the Parthenon, including the glass reconstructed column.

In Figure 118, the corresponding cross-section is given. Here the marble core and other segmentations of the design are better visible. Also, the titanium empolions can be seen. These joints are completely invisible from the observers' point of view since they are embedded in that marble core. Around the core, the cast glass pieces are highlighted in blue, stacked on top of each other. the other components in the design are shown in exploded view in Figure 119.

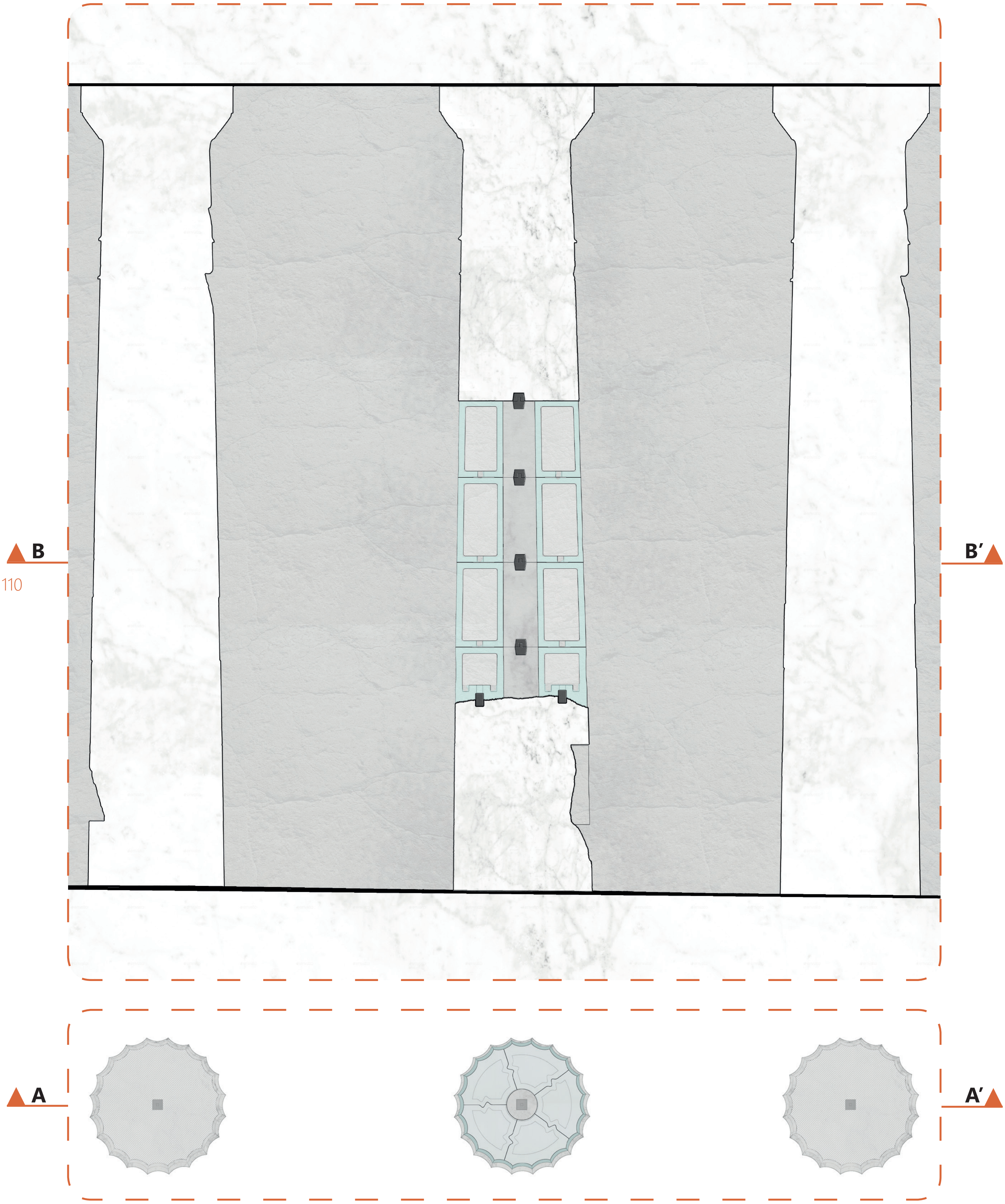


Figure 118: Vertical (A) and horizontal (B) cross-section of the new Parthenon western collonade.

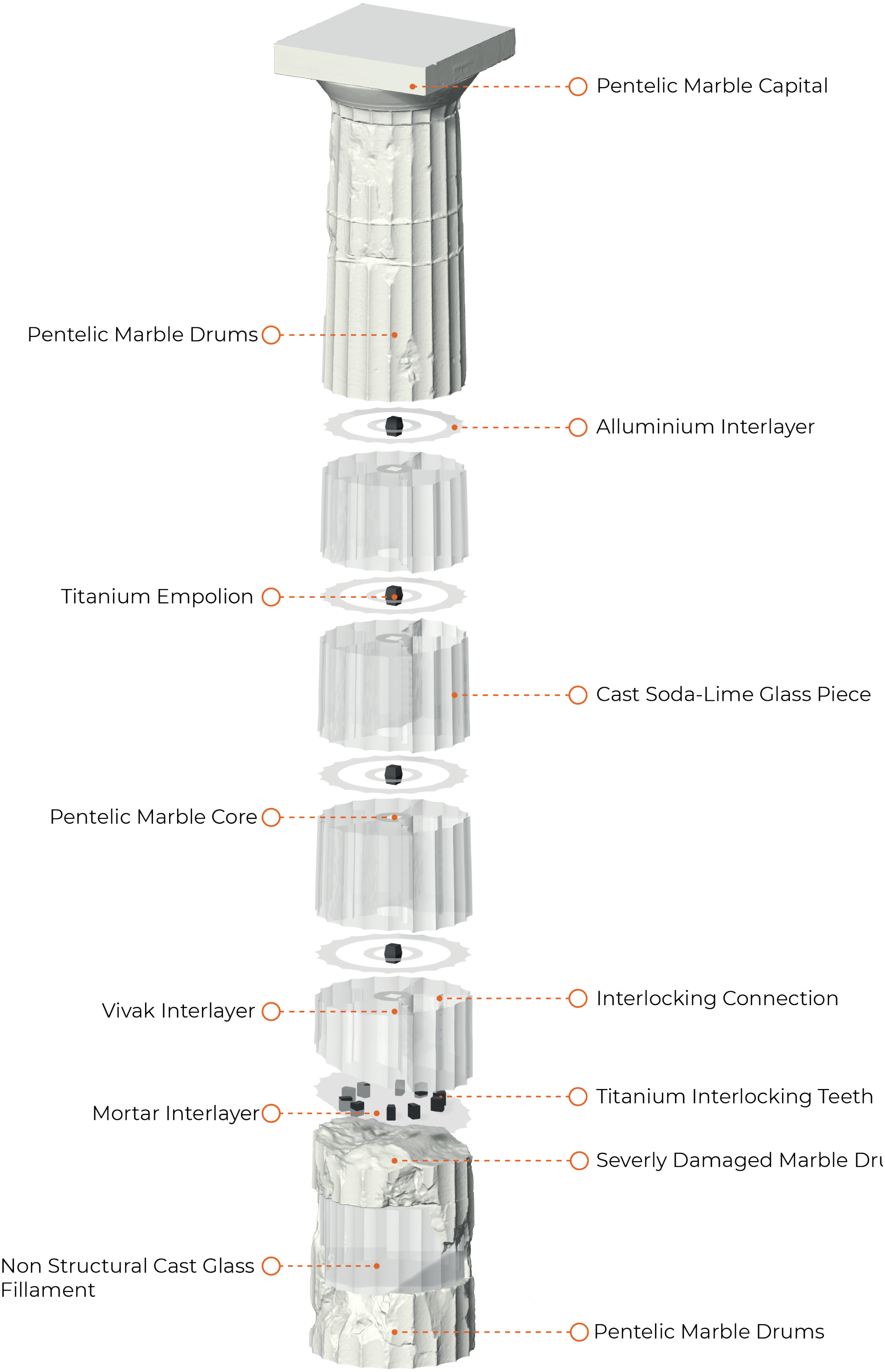


Figure 119: Exploded view of the with glass reconstructed column

7.2 Cast Glass unit

Figure 119 shows all the components that are used in the design of the glass reconstruction. The most representative and critical element, the cast glass element, is shown below in Figure 120. Each drum is constructed from five of these units, each having a mass around 750 kilos. This weight is reached by making the pieces hollow. To ensure good annealing and structural integrity, the thickness of the section is minimal 100 mm. A consequence of this hollow unit is the opening that is required to remove the moulding material. The diameter of this opening is 100 mm but it is placed in an unloaded surface, so it will have no structural consequences. In each drum, the positioning of the pieces is rotated by 36° compared to the drum below. With this rotation, each glass element is supported by two other pieces, each carrying 50% of its load, assuring that a piece will not drops if the one below fails. Other characteristics of the cast glass unit are shown in the image below.

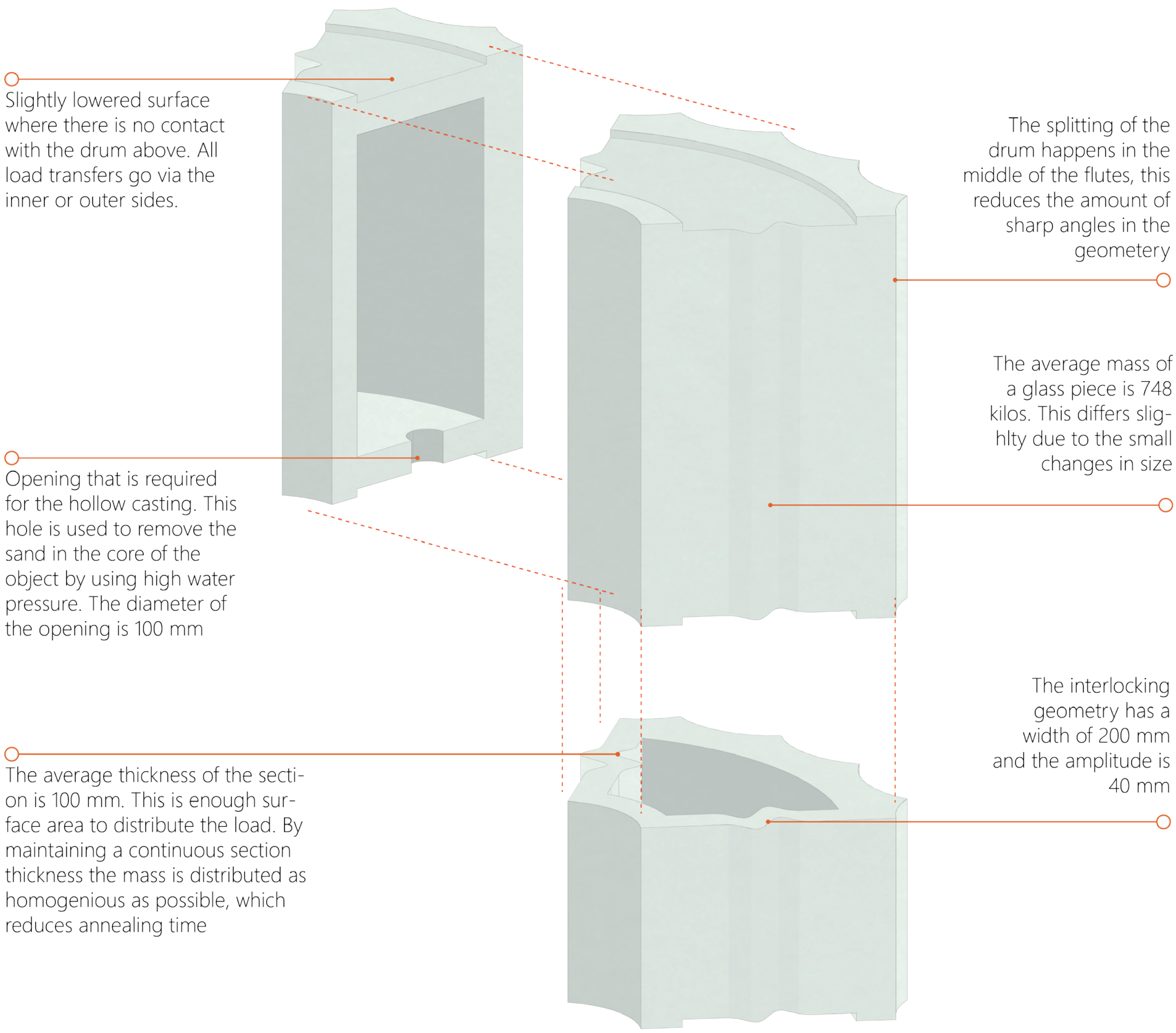


Figure 120: Characteristic cast glass unit in the reconstruction

7.3 Connections

Glass Drum Connection

As discussed in Chapter 6.6 there are four different connections in this design. In this paragraph, all of them will be shown in a 2D technical drawing including all the materials that are used in these connections. The first one is the connection between the five pieces in a drum, shown in Figure 122. On the left a small exploded view of the composed drum is shown, containing all the used elements and materials, which also can be seen in the exploded view on the right

This connection between the pie pieces is similar in each of the glass drums, including in the hybrid marble-glass drum one. Included in the section below is the horizontal section of the titanium empolion which forms the connection between two drums. This section is identical in all the connections between the drums.

Glass – Marble Drum Connection

The second type of connection is where the transition is made from a glass drum, back to an authentic marble drum, Figure 123 and 124. This connection is comparable with the one that has been designed during the construction of the Parthenon, 2500 years ago, and the one that is being applied in the current reconstruction works.

In the connection, a titanium empolion is embedded in the cores of both drums. This connection is then fixed with mortar. This mortar is only to keep the empolion in place during the assembly, it has no structural function and will crack during the slightest of lateral displacements but that is not a problem. The empolion helps during the assembly of the drums as the top one can be shifted over the bottom one. Before the drums are connected, an interlayer will be placed on the contact surface. This interlayer, made from an aluminium alloy with zinc, AL7055, will protect the glass and marble from contact damage.

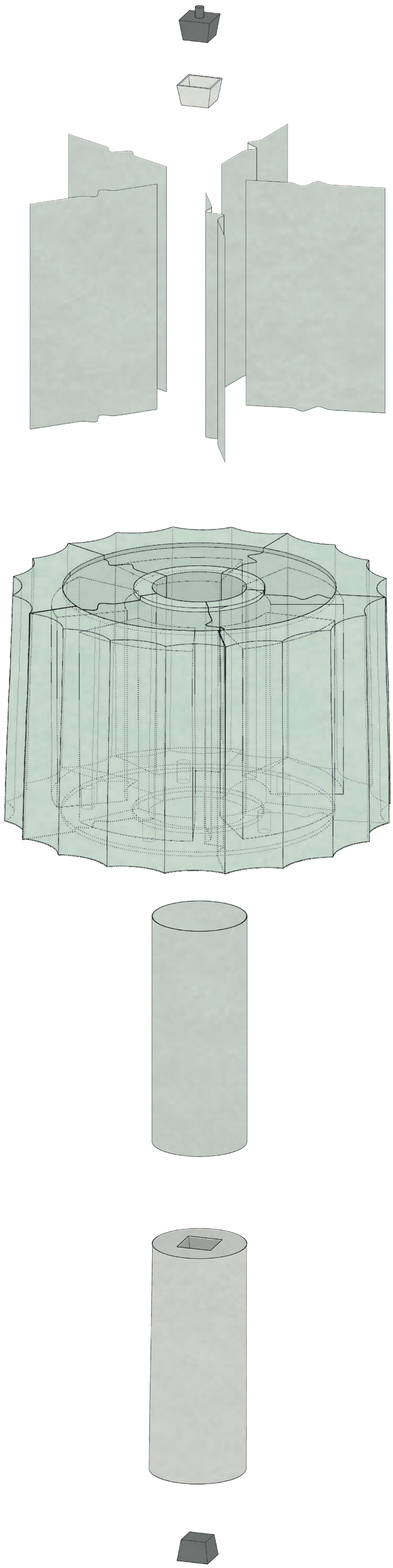


Figure 121: Exploded view of a single glass drum

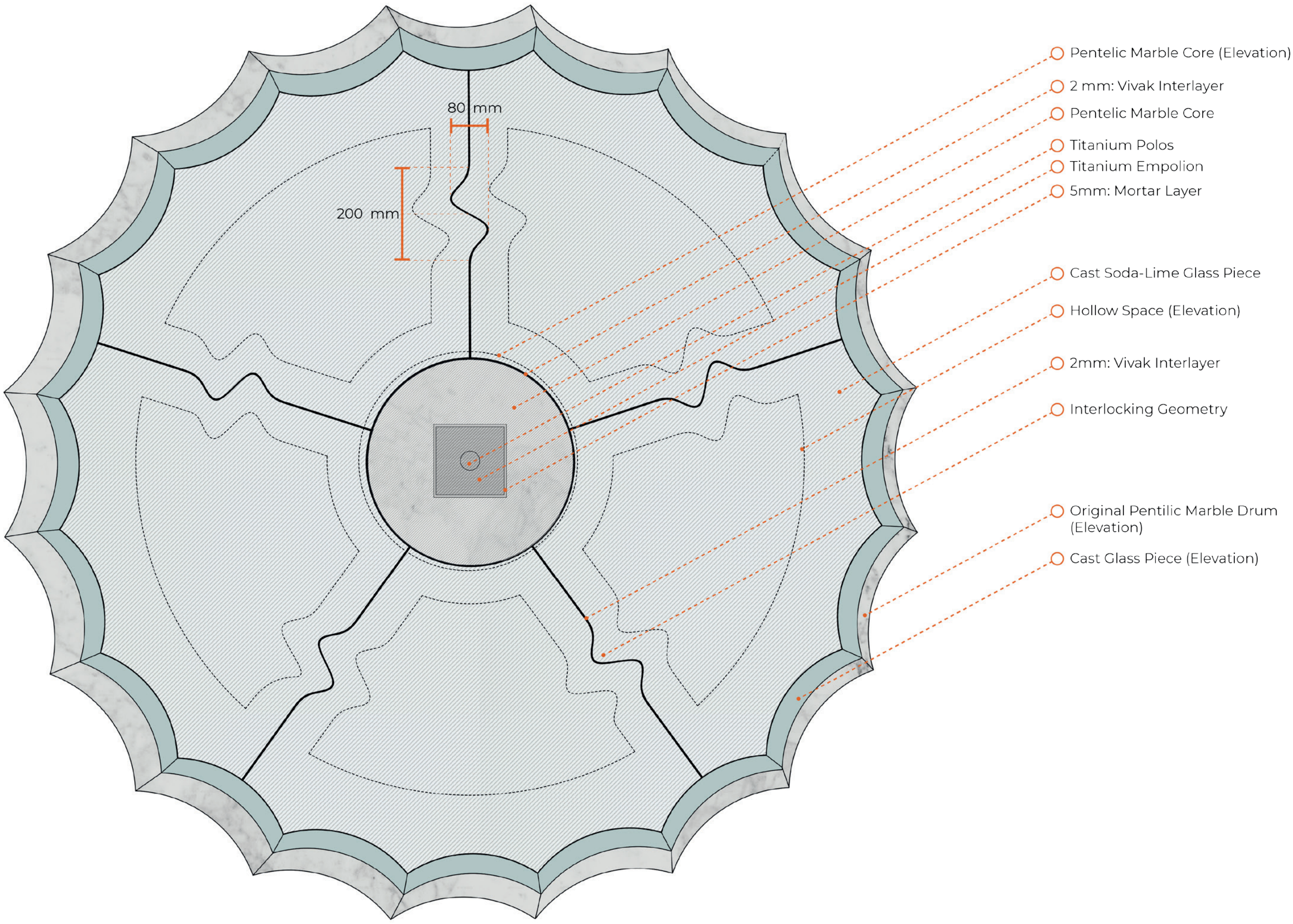


Figure 122: Horizontal section of connection 1. Scale 1:10

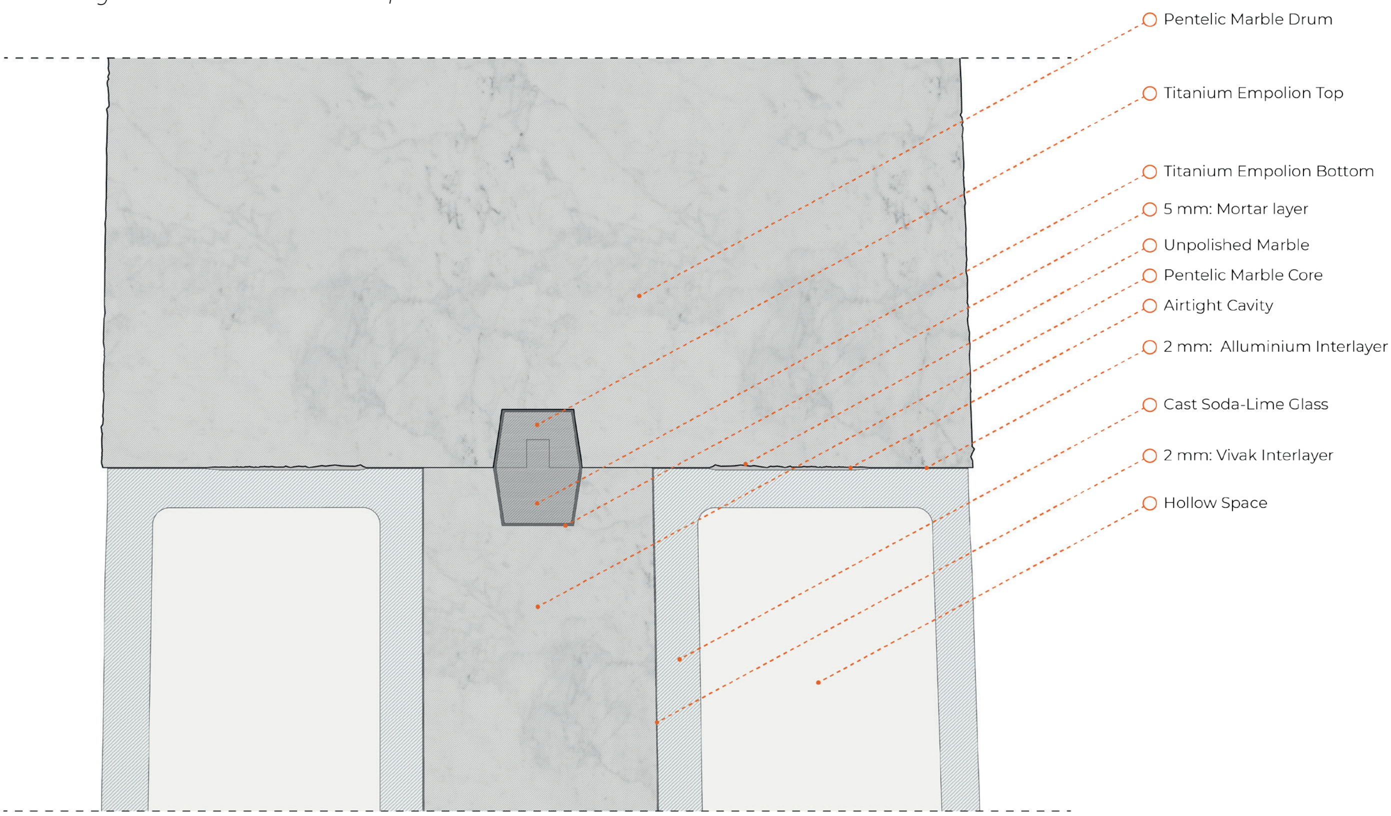


Figure 123: Vertical cross-section of the connection between a marble and glass drum. Scale 1:10

Connecting two glass drums

The connection between two glass drums is practically the same as between a marble and glass drum., Figure 125 and 126 The same materials are used; a titanium empolion, fixed with a thin layer of mortar into a carved embedding in the marble. Also, the same interlayer has been used to protect the glass objects.

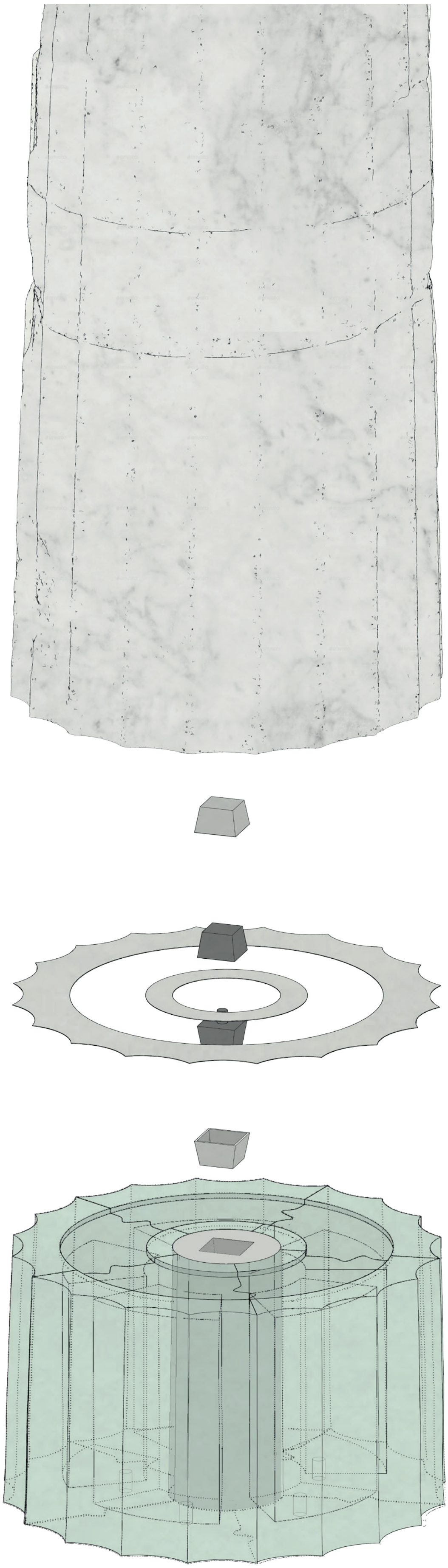


Figure 124: Exploded view of the connection between a marble and glass drum

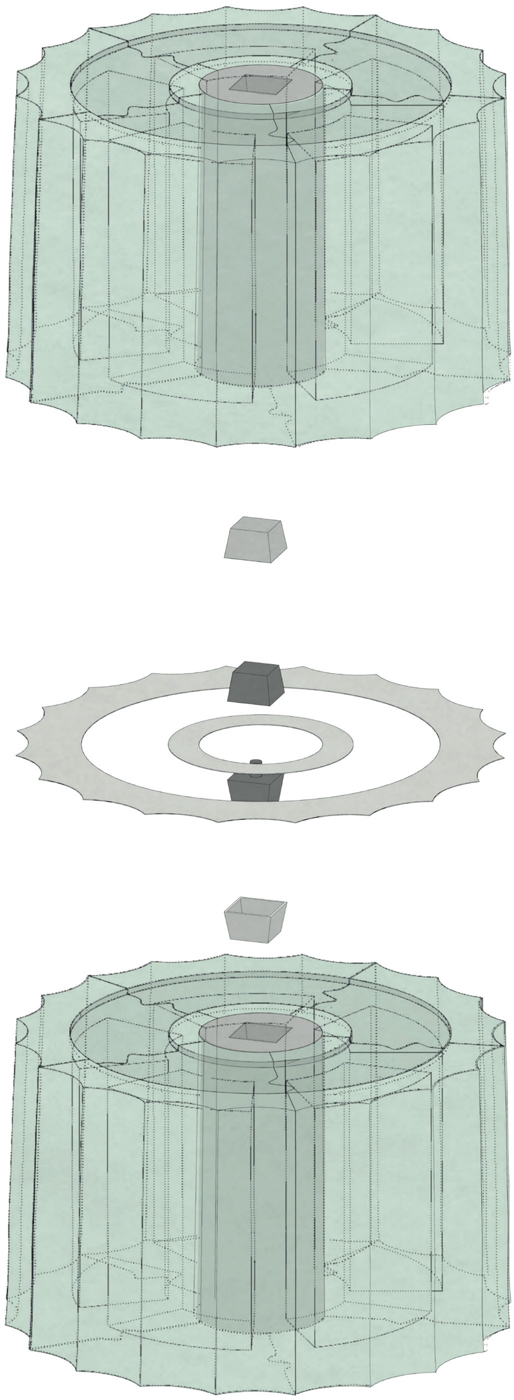


Figure 125: Exploded view of the connection between two glass drums

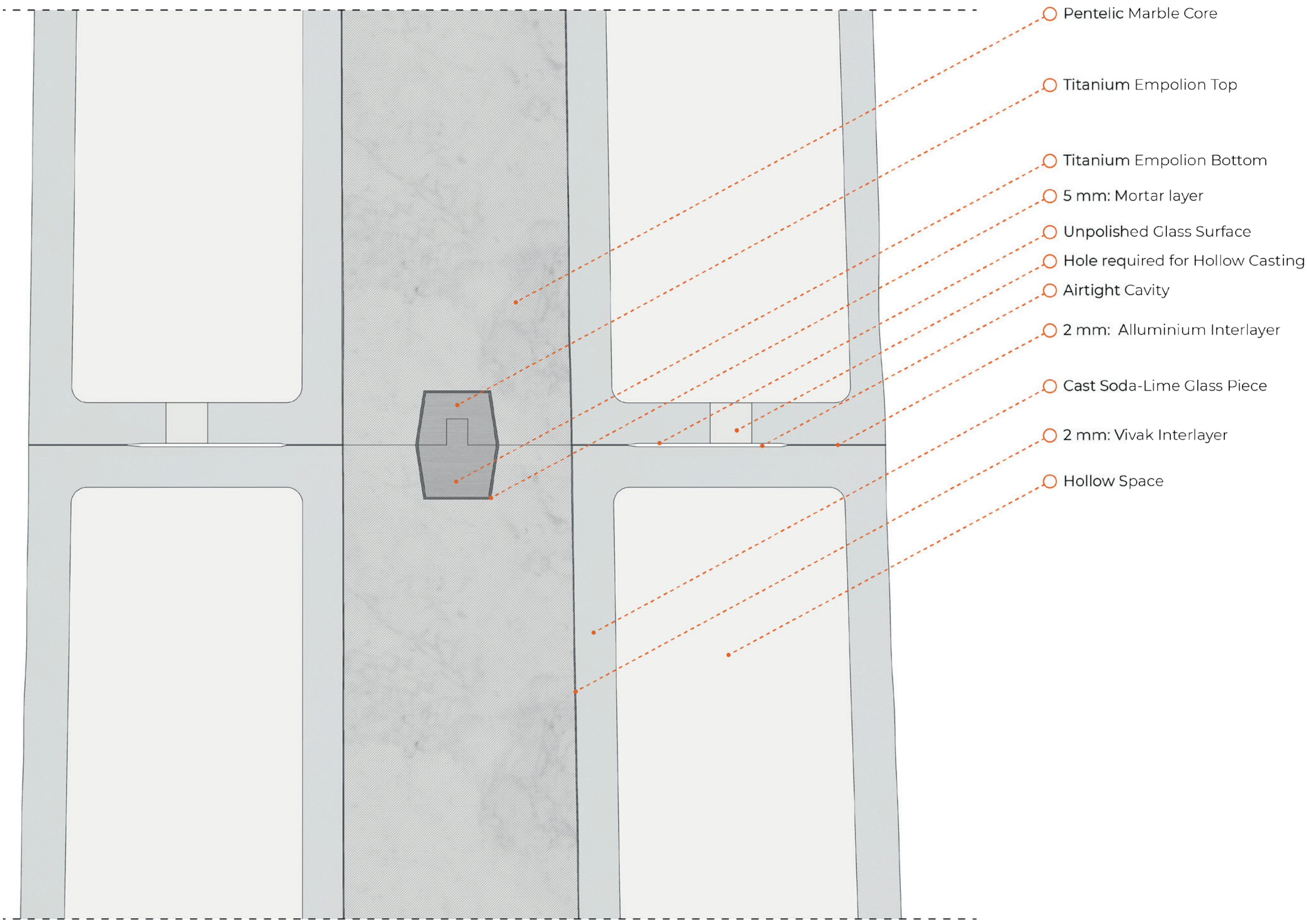


Figure 126: Vertical cross-section of the connection between two glass drums. Scale 1:10

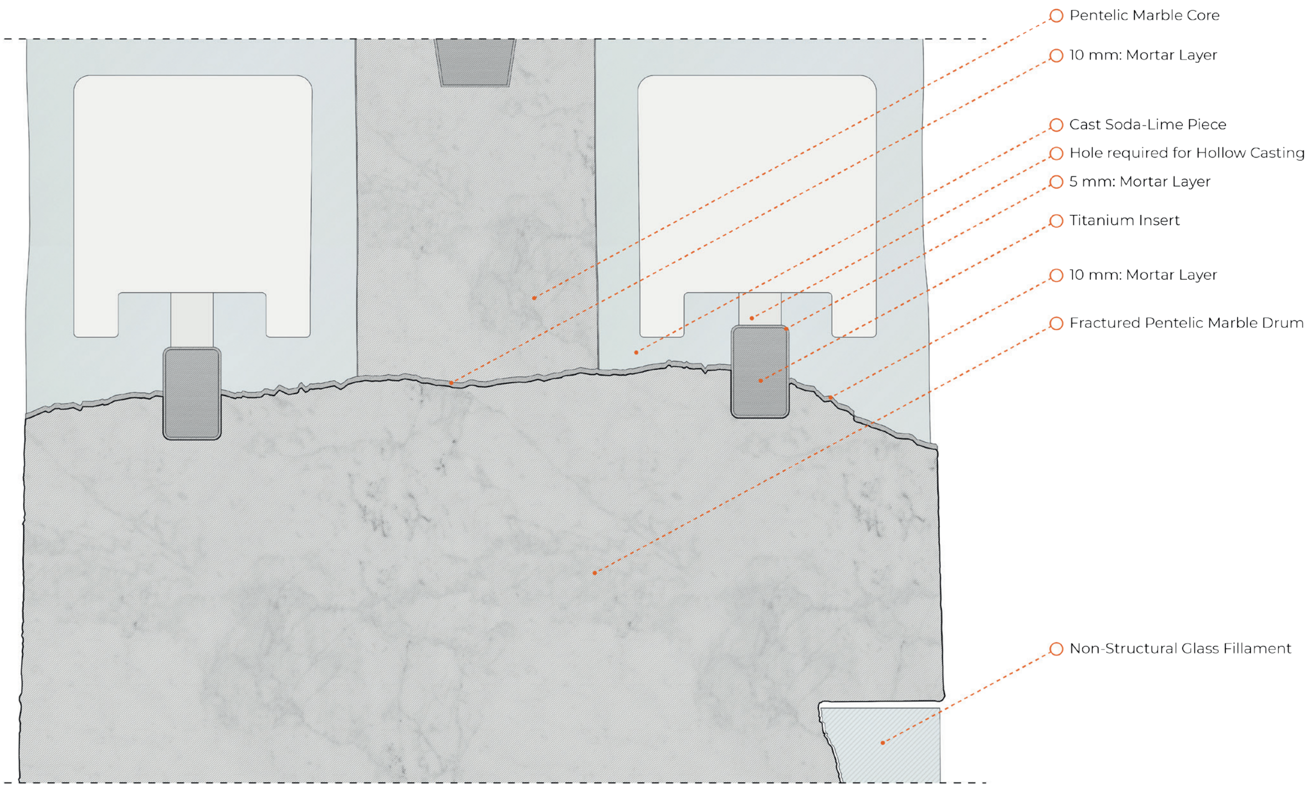


Figure 127: Vertical cross-section of the connection of the hybrid marble - glass drum

Fixing the glass to a fractured marble drum.

The fourth and final connection is between the broken surface of a marble drum and a fitting cast glass counterpart. This is a different type of connection than the other three since this one will permanently join the pieces together.

The binding material will be a mortar layer with a thickness of 10 mm. This mortar is strong enough to carry the vertical loads of the column. The shear force, caused by the inclined surface will be taken up by ten titanium inserts, two per piece of glass. These joints are embedded in the marble surface and the glass. This requires small carvings being made in the marble, while the embeddings in the glass are shaped in the casting process.

Around the titanium joint, a thin layer of mortar protects the marble and glass from contact damage with the hard metal.

Just like the all glass pieces, the ones in this connection are hollow. However, since not every piece has the same size, the dimensions of the cavity can differ for each piece. Important in determing these dimensions is the section thickness of the glass. This thickness should be minimal 100 mm and be as constant as possible to allow for a faster en better annealing process.

Figure 128: Exploded view of the connection between the broken marble and fitting glass element

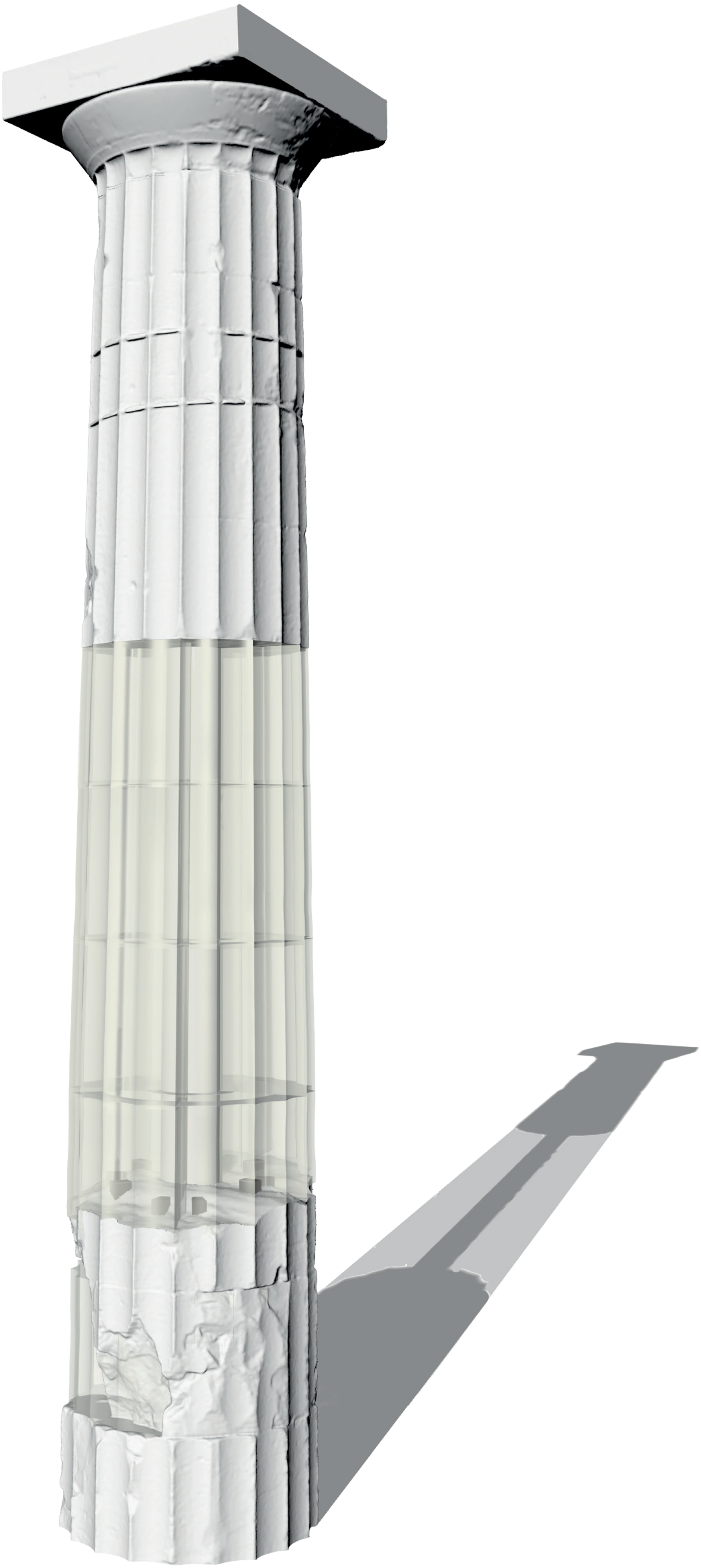


Figure 129: Final design of the reconstructed column

Figure 129 shows the final concept of the cast glass restoration. In this case, the glass is still slightly translucent, so the connections, interlayers and marble core are very well visible in the column. The same grade of transparency is applied to the impression in Figure 130. Although the titanium connections are visible, through the glass, the observing angle still makes them almost impossible to see from ground level. Only standing directly next to the column, the titanium joints can be seen. However, the interlayers between the drums and the marble core are visible from the ground level, assuming that the glass is translucent. However, the neutral colours of these elements will minimise the visual impact as much as possible. With the translucency, it is possible to look through the glass and see the current and original state of the Parthenon simultaneously.

However, it is also possible to make the glass look more opaque, as is shown in the impression in Figure 131. In this impression, the corner column has been restored with opaque glass instead of Pentelic marble. With its opaque characteristics and surface texture, it is barely distinguishable from the Pentelic marble which is used in the other columns in the impression. The advantage of this opaque glass is that it hides all connections and interlayers from the observers' view. It looks just like a piece of marble, but now artificially produced. With this artificial marble, the authentic appearance of the Parthenon can be approached very closely.

The only difference between the two options is the appearance. Structurally and mechanically the translucent and opaque glass are identical. It is up to the architect in charge of the restoration which alternative is the most suitable for that specific restoration case. The advantage of the opaque glass is that it matches with the original appearance of the Parthenon, while the translucent glass allows seeing both the current and original state of the monument.

Figure 130: Impression of how a with cast glass restorated column, third from the left. The glass is translucent so it is possible to see the marble core within the glass and the interlayers between the drums, edited from: (British Museum, 2012)

Figure 131: Impression of a with cast glass restorated column, at the corner of the temple (front). In this case, the glass is made opaque with a rough surface, making it hard to distinguish from real Pentelic Marble, edited from: (Earth Trekkers, 2020)

Figure 132: Bird eye view of the Parthenon during the reconstruction works. The surroundings of the temple are scattered with ancient pieces of Pentelic marble, source: (British Museum, 2012)

08.

FROM DESIGN TO ASSEMBLY

PHASE 1: DESIGN

1.1: Case study Research – location – materials – history

Do extensive research to fully understand the restoration project. Evaluate its cultural and historic value. Understand what caused the damage you try to repair. Is it caused by the climatic environment, by earthquakes or other natural phenomena? Look into the materials that are used in the original design and how they have to withstand the passage of time. Based on these materials, it is possible to choose the fitting materials that can be used for the restoration. But how do these new materials withstand the local climate?

1.2: Case study Research – structural behaviour – stability

The next step is to investigate the current conditions of .the monument. Determine how the used materials have aged over time and if they are still reusable after the restoration. Look into the structural behaviour of the superstructure and determine which role the damages element plays in this. Where does the stability come from and how is it connected to the rest of the monument

1.3: Determine the intervention you want to do

Determine the type of damage you want to repair with glass. Is it only a cladding element or has it a structural purpose as well. What is the size of the missing element and to which pieces is it connected?

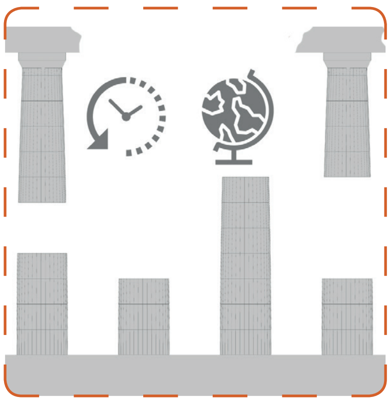
1.4: Surface scan

To make the glass fit exactly on the original tissue the connecting surface needs to be accurately modelled. This will be done by 3D scanning, using the principle of triangulation. This is an active, close-range scanner, which has an accuracy of up to 0.1 mm.

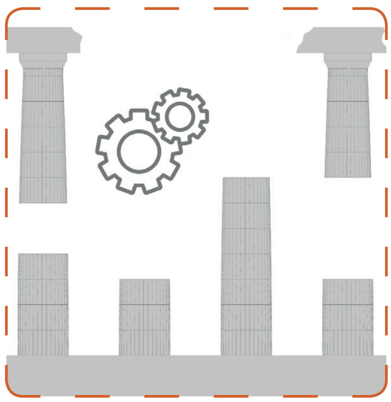
1.5: Determine original shape

With the scan of the surface, the missing element can be modelled in 3D. To do that, the exact shape of the missing geometry needs to be found. However, if the element is missing, the exact shape of the replacing one cannot be found with 3D scanning. If there are original drawings or other documents that contain the exact dimension of the geometry, those could be used, if not, it can be done by estimations based on other columns of the monument.

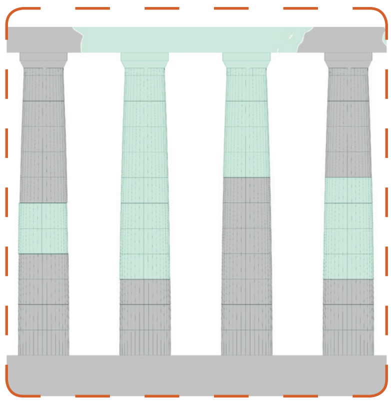
1. CASE STUDY RESEARCH
Location and History



2. CASE STUDY RESEARCH
Structure and mechanical behaviour



3. DETERMINE INTERVENTION



4. SURFACE SCAN

1.6: Fragmentation of missing element

Once the final geometry is set it likely has to be fragmented in several pieces due to its size. If this is the case, the fragmentation will be based on the characteristics of the original column. Dimensions like drum height and the width and number of the flutes will determine how the glass element will be split up.

1.7: Connections

Once the glass is split in fragments for annealing they need to be connected again. These connections are not standardised. They also have to be based on the structural and mechanical principles of the original column. A hard criterion is that the connection needs to be reversible, so interlocking elements and mechanical joints are preferred here.

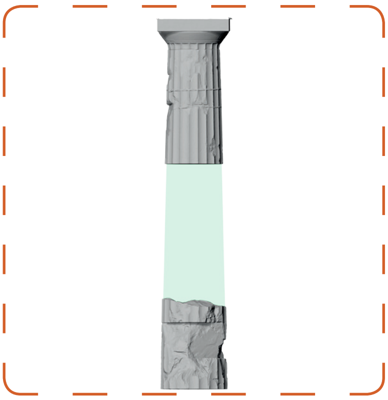
1.8: Materials

When the connections are designed the correct materials can be chosen. This choice is completely dependant to the materials that are used in the original structure, with the thermal expansion coefficient being the leading criterion. The thermal expansion of the Pentelic marble that was used in the Parthenon leads to choosing soda-lime glass, with titanium joints. However, in a temple with a different type of marble, the thermal expansion coefficient will be different as well. This could result in using borosilicate glass and stainless steel joints if those match the thermal expansion of that specific type of marble

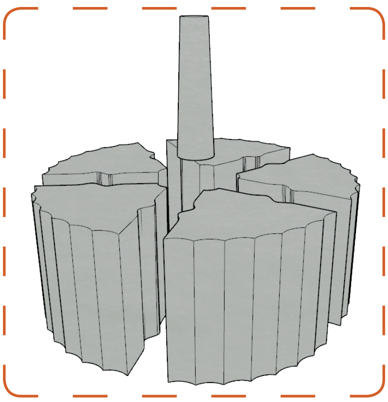
1.9: Cad Model

If the design is completed, it can be transferred in a digital CAD model. This model will be the base for the manufacturing of the glass and joints and is the final step in the design phase.

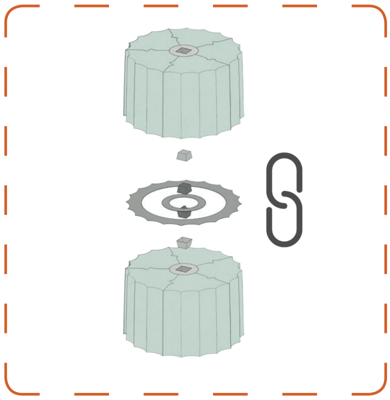
5. DETERMINE ORIGINAL SHAPE



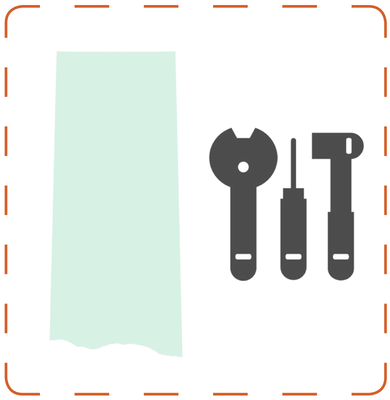
6. FRAGMENT MISSING ELEMENT



7. DESIGN THE CONNECTIONS



8. CHOOSE THE MATERIALS



9. MAKE CAD MODEL

PHASE 2: PRODUCTION

2.1: 3D print Sand mould

The counter shape of the glass elements will be retrieved from the CAD model. This shape will be used to make the 3D printed sand moulds. Every fragment will require its mould, given the shape of the column.

2.2: Cast pie shapes

Pre-heat the mould to the right temperature and cast the glass. The pre-heating of the mould is essential to ensure proper annealing of the glass. This temperature depends on the type of glass and used mould. The working temperature of soda-lime glass lies around 1000°C.

2.3: Annealing

Start the annealing process by rapidly cooling down the glass from its working temperature to a few degrees above its annealing temperature, which lies around 600°C. After maintaining this temperature adequately, the glass is cooled further, but with a much slower rate. During this entire process, the glass remains in the mould.

2.4: 3D print sand mould broken surface

Simultaneously, the sand mould of the broken piece of marble is made with 3D printing. This printing is based on the 3D scan of the broken surface will be done with ceramics. This is stronger than 3D printed sand, and thereby applicable for pressing into the softened glass.

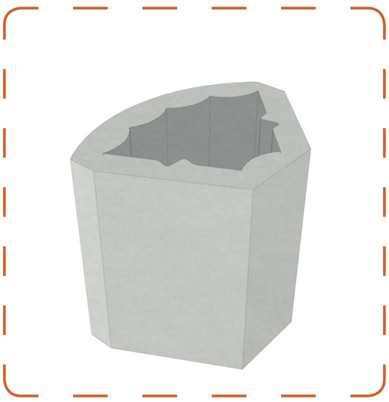
2.5: Reheat pie pieces

When the glass is annealed, it will be removed from the sand mould. After that, it will be reheated again until the softening temperature of the glass. At this point, the glass is viscous enough to imprint it, but still solid enough to retain its shape under its own weight.

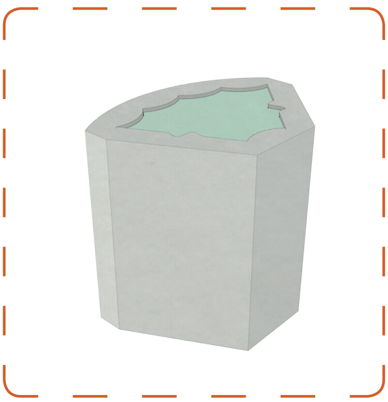
2.6: Imprint with a press mould

When the glass has reached its softening temperature, the 3D printed copy of the broken marble is pressed into the softened glass. When the right shape is reached, the mould is

1. 3D PRINT THE SAND MOULD

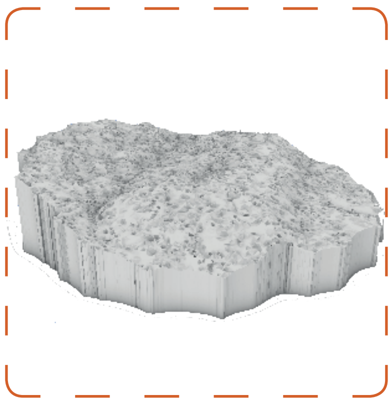


2. CAST THE PIE SHAPES



3. LET THE PIECES ANNEAL IN THE SAND MOULD

4. 3D PRINT BROKEN SURFACE



removed leaving the imprint of the fractured marble behind in the glass

2.7: Annealing

The imprinted pieces are annealed again. For the pieces that do not connect to a broken marble drum, these steps (2.4 until 2.7) can be skipped.

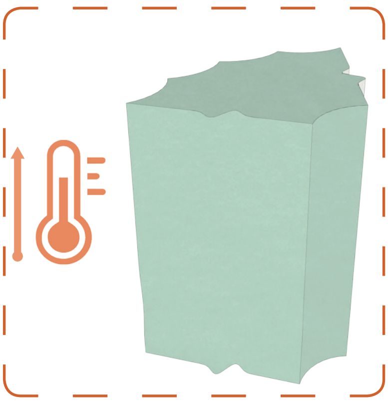
2.8: Post-treatment

Once the glass has cooled down till room temperature, the post-treatment can begin. The glass surfaces that make contact need to be polished to smoothen the contact area or if wanted, the surface needs to be polished to make it smooth and glossy

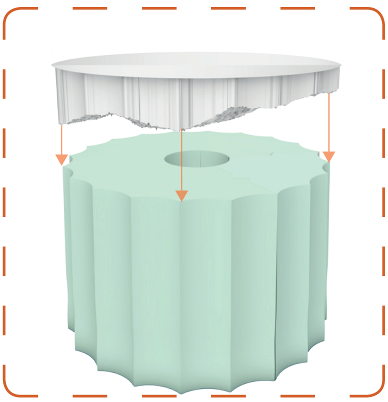
2.9: Assemble drums in factory

If all pieces are finished in their processing phase, they are assembled to form the drum in the factory. After that, they are ready to be transported to the restoration site, where they can be positioned in the temple's columns.

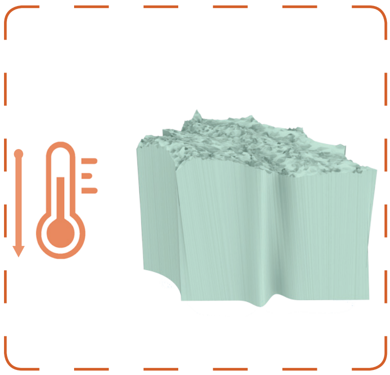
5. REHEAT PIE PIECES



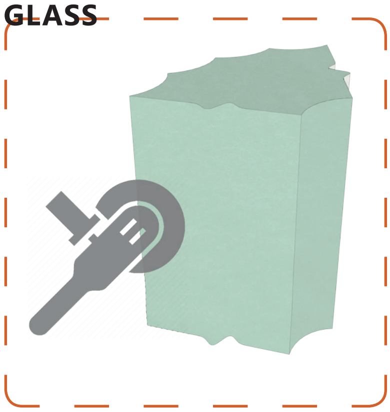
6. IMPRINT WITH A PRESS MOULD



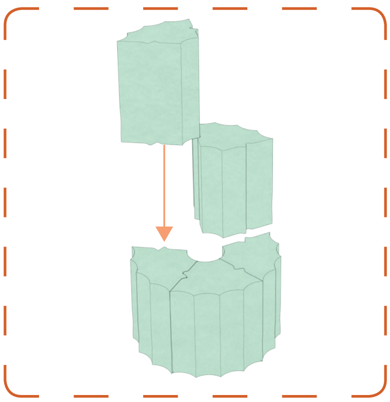
7. ANNEAL THE IMPRINTED PIECES AGAIN



8. POST TREATMENT OF THE GLASS



9. ASSEMBLE THE DRUMS



PHASE 3: ASSEMBLY

The glass drums arrive at the restoration site, fully assembled. No glass treating work has to be done at the construction site, which is both safer for the construction workers and the glass itself. The reconstruction process of a column with glass elements is similar to the original one and is explained below

3.1: Collect all pieces of a column

Before the reconstruction of a column can begin, all pieces need to be found and be in good shape. In the 19th and 20th century, Nicolas Balanos lead the restoration project of the Acropolis and the Parthenon. During his reconstruction, he put marble pieces on the wrong places in the temple, causing even more damage to the structure. Since every piece of the Parthenon has a unique shape, it is essential to trace it back to its original position.

3.2: Insert and join the metal connections into the marble drum

In case only a part of a drum can be used in the reconstruction, it will receive a glass counterpart, which completes the shape of the original drum. To do this, the marble will be carved out slightly, to make a place for the titanium joints. These joints are vital for the structural performance of the hybrid drum. To protect the marble from the hard metal, a layer of mortar will split the two materials.

3.3: Apply mortar to the surface of the fractured drum

Once the joints fit in, a layer of mortar will be put on the surface that will connect with the glass. This mortar protects the glass and marble from contact damage and allows for a smoother and more equal load transfer between the two parts. This mortar is specifically composed to be used in combination with Pentelic marble and soda-lime glass. It does not chemically attack the vulnerable marble and no alkali reaction occur, which can damage the glass. If a future case study contains a different type of marble, a different mortar is likely required. One which is specifically designed for that type of marble.

3.4: Bring the assembled glass drum in the right position

Shortly after the mortar is applied, the glass drum is joined to the marble surface. The building equipment will keep it into place till the mortar has dried out enough to support the glass. Once the joining is finished the hybrid drum will approach the structural behaviour of a solid monolithic one

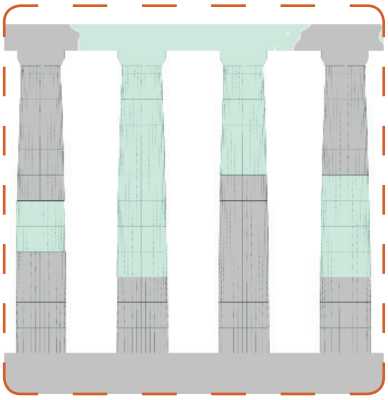
3.5: Position the hybrid drum on the one below

The assembly of the hybrid drum will happen on-site, but not yet in the right position in the temple. After the glass is properly joined to the marble, the complete drum is lifted and placed in its original position in the temple. To assure a proper alignment the titanium empolions are used. The bottom half will be placed in the centre of the lower drum, the top half in the upper. When the upper drum is lifted, the two halves of the empolion are precisely aligned before the drum is lowered to its final position.

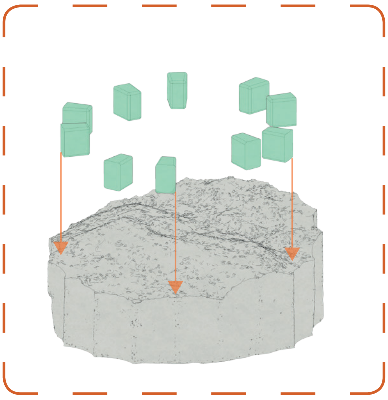
3.6: Repeat till column is finished

This process will be repeated until the capitol completes the column. Each time before a glass drum is placed, the interlayer and titanium empolion will have to be applied first. Marble drums are still places without an interlayer, but including the empolion. Once the column is finished the superstructure can be placed on top of it, starting with the frieze.

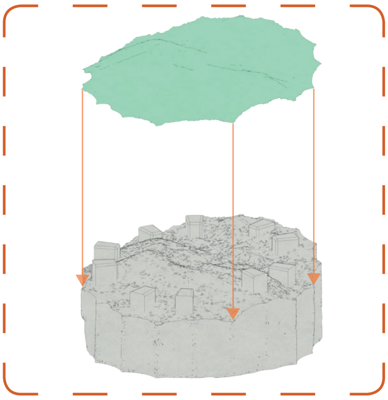
1. COLLECT ALL COLUMN PIECES



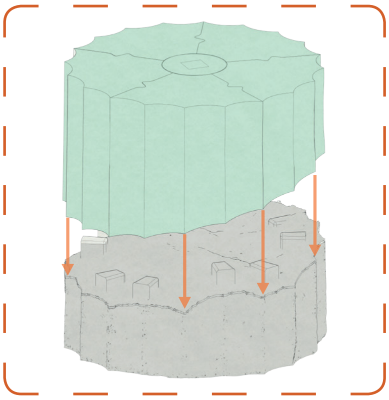
2. INSERT METAL CONNECTIONS IN MARBLE DRUM



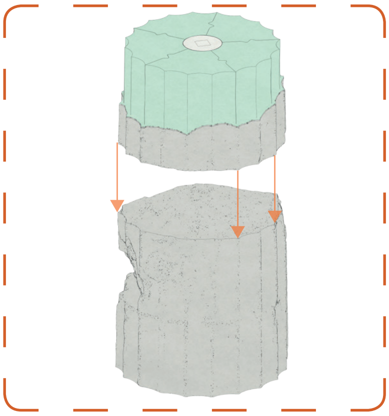
3. APPLY MORTAR TO THE SURFACE OF THE FRACTURED DRUM



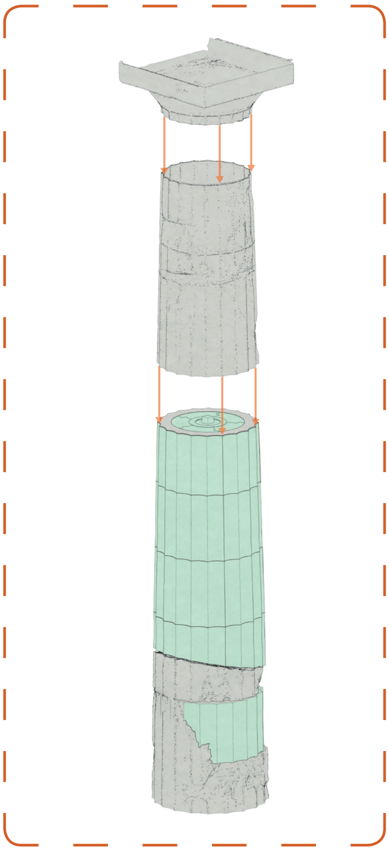
4. BRING ASSEMBLED GLASS DRUM IN POSITION



5. POSITION THE HYBRID DRUM ON TOP OF THE ONE BELOW



6. REPEAT TILL COLUMN IS FINISHED



PHASE 4: TEMPORARY REPAIRING

Although it is extremely unlikely, the cast glas pieces may severe some damage during their lifetime. As mentioned several times in this thesis, Greece is a very seismic active country where earthquakes occur on a daily base. Most of these earthquakes are not strong enough to cause damage to structures like the Parthenon. However, earthquakes with a higher magnitude may occur in the future. Besides earthquakes, extreme weather conditions could also cause damage to the temple, although this is much more unlikely than a high magnitude earthquake. However, a severe hail thunderstorm with strong winds could theoretically cause damage to the glass.

If this happens, the broken glass element should be replaced as soon as possible. The column is still stable if one of the five glass pieces in a drum is broken, but for structural and aesthetical reasons it is better to replace it. To do that, the column has to be completely deconstructed, a process which can take years but is inevitable. In the meantime, a temporary proposal is given below:

4.1: Evaluate the damage

Once a glass component has severed damage, it is important to know the cause of it. Is it due to external factors like weather or seismic activity or is there an internal cause which could potentially harm other elements in the structure as well?

4.2: Remove the damaged piece from the column

The first step in the process is to remove the damaged piece. Since only dry connections are used in the design, it can be easily detached from the other parts in the column. So all other materials, including the interlayers can be reused. If necessary, the damaged piece has to be broken into small pieces since it cannot be taken out as a whole.

4.3: Cast a temporary replacing part

Since the interlocking geometry is specifically designed to prevent the pieces to move in horizontal directions it is not possible to place a new piece into position from the side. Thus it is required to split the geometry up in three pieces which will be joined permanently with an adhesive.

4.4: Bring the two side pieces in their interlocking position

First, the two pieces on the sides will be placed. These pieces have the same interlocking geometry as the original design and will be placed against the sides. Just like the original connection, no adhesive is used as the connection remains dry. The Vivak interlayer still separates the pieces and prevents contact damage.

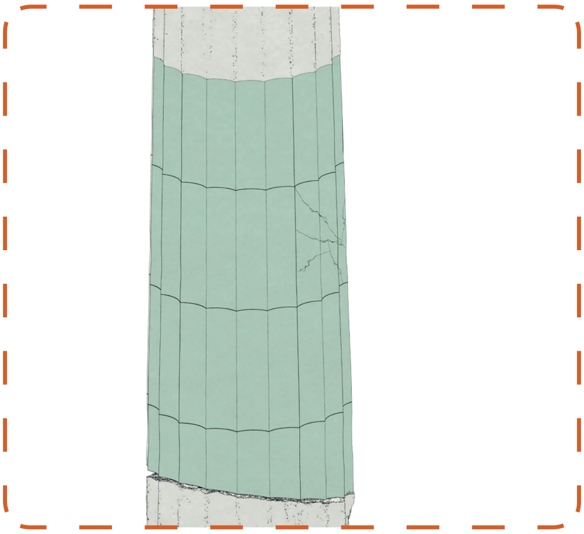
4.5: Join the third piece to the other two with an adhesive

Once the first two pieces are placed, the third one will act as a keystone and they will be permanently joined with an adhesive. This will interlock the replacing part again and will prevent it from falling out. Around the joint surface, there will not be any load, so the replacing part will not reduce the structural performance of the design.

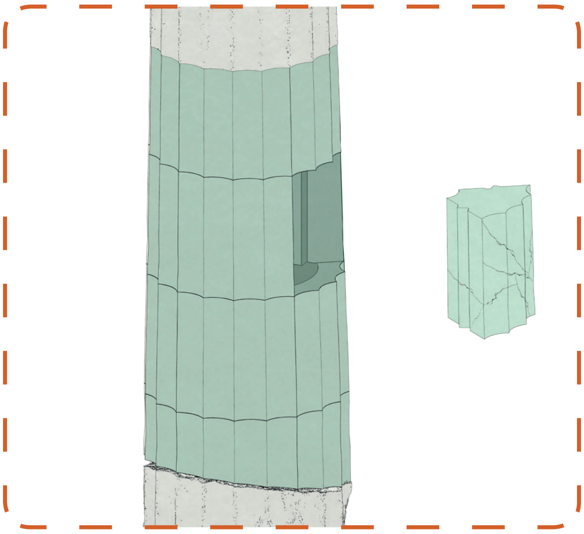
4.6: With the adhesive, the pieces can be used as a temporary solution

Once the pieces are joint, they meet the structural and safety standards as set in the design proposal. However, this solution will compromise for aesthetic quality and is thereby not seen as permanent. It is designed to bridge the gap until a permanent replacement can be made. This permanent solution is however much more complicated and will thereby be much more time-consuming. This proposal is given in Phase 5, on the next page.

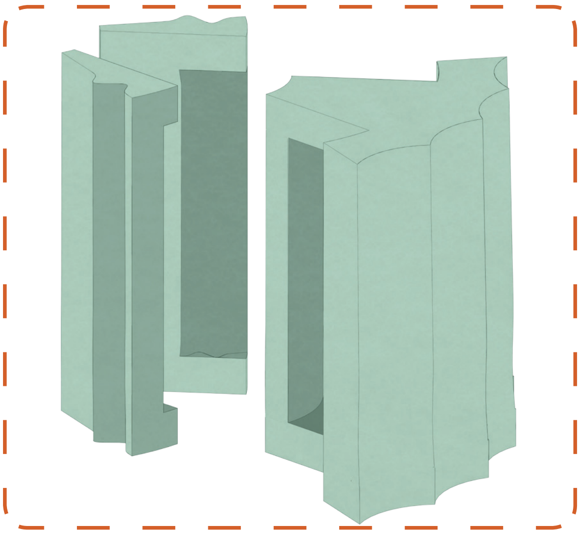
1. ONE OF THE GLASS PIECES HAS SEVERED DAMAGE, CRACKS APPEAR



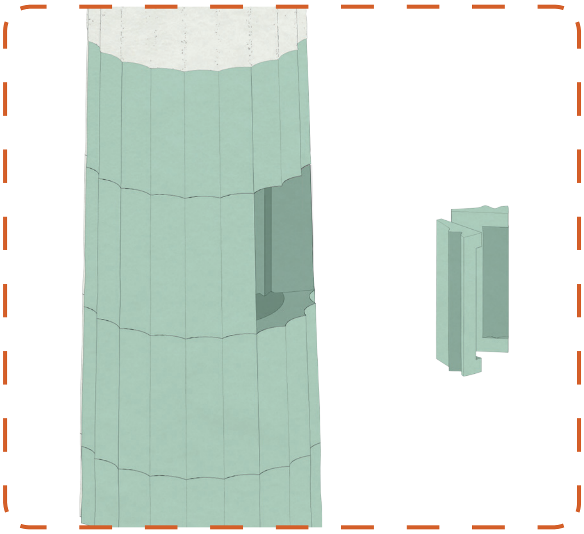
2. CAREFULLY REMOVE THE DAMAGED PIECE OF GLASS



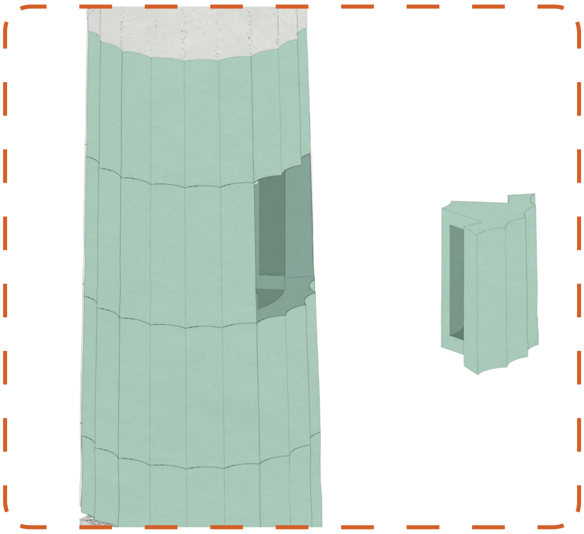
3. CAST A NEW, TEMPORARY, REPLACING PART



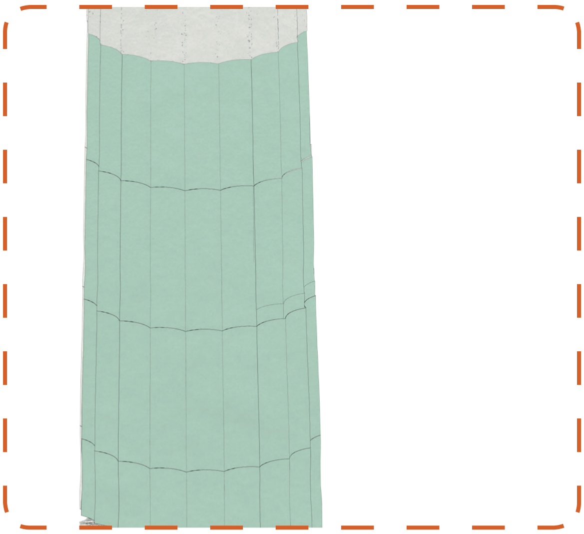
4. BRING THE FIRST TWO PIECES IN THEIR INTERLOCKING POSITION



5. PERMANENTLY JOIN THE THIRD PIECE TO THE OTHER TWO WITH AN ADHESIVE



6. WITH THE ADHESIVE, THE PIECES CAN BE USED AS TEMPORARY SOLUTION



PHASE 5: PERMANENT REPAIRING

The solution, provided in the fourth phase will only be a temporary one. Eventually, if a glass element is damaged or broken, it has to be replaced permanently with a monolithic piece of glass, similar to the original design. However, to put such a new element into place, the entire column has to be deconstructed and rebuilt again since the monolithic piece can only be placed from the top. This requires a deconstruction of this specific section of the temple. This includes the column itself but also the overlaying superstructure. This deconstruction will require long preparation and the process itself will have to be executed very carefully, making it a time-consuming effort. However, as mentioned in the previous phase, the chances of an element getting damages are very limited so it is unlikely that this permanent repairing phase is necessary. However, if needed, the following steps should be followed, in the rare case that it is necessary:

5.1: Remove the superstructure: roof, architrave, frieze

Before the individual drums of a column can be reached, all the load on top of it will have to be removed. This includes the roof of the temple, as well as the frieze, cornice and architrave. These elements will be replaced again once the damaged glass element is replaced and the underlying column is rebuilt.

5.2: Remove the drums one by one

Once the architrave is removed. The elements of the column can be removed, working from top to bottom. The geometry of the interlocking mechanism in the glass drums, allow it only to be accessed from the top. So to place a new glass element in the column, all the overlaying drums, both glass and marble, will have to be removed from the column.

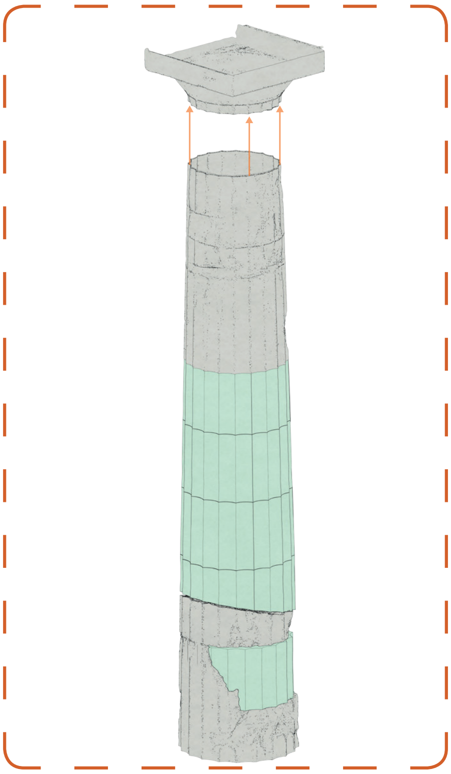
5.3: Disassemble the glass pieces off-site

To protect the other glass parts, surrounding the damaged one, the glass drum will be transported to the factory after it is removed from the column. There, it will be disassembled in a more controlled environment. Since all the connections are dry, the glass can be remolten and reused. The glass pieces that are still intact and undamaged, will be reused in a new drum, which is completed with a new piece that replaces the damaged one. After the reassembly of the drum, it will be transported back towards the construction site, where it will retain its original position.

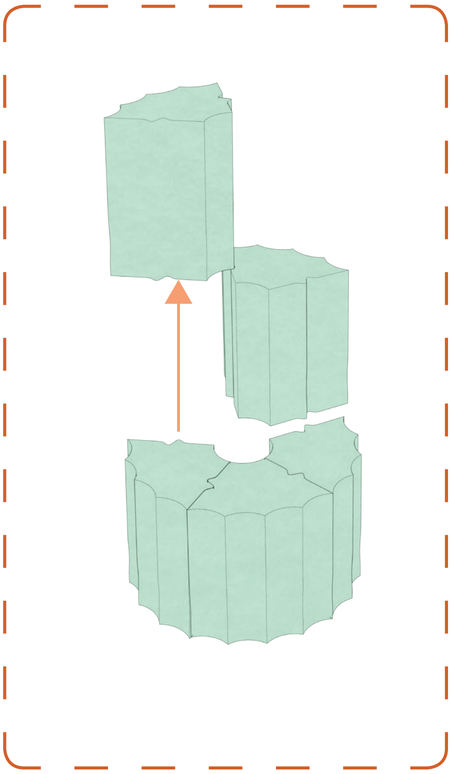
5.4: Carefully remove the mortar between the glass and marble pieces

In case teh damage glass belongs to a hybrid glass-marble drum, the repairing process is more difficult. The hybrid glass-marble drum has to be deconstructed carefully by removing the mortar layer between the materials. This is a delicate process that is very time consuming, but by slowly carving off the mortar the glass element can be eventually removed from the mortar. Thereafter, the process is similar as in step 5.3. The glass section of the drum will be reconstructed with a new piece, before it is reattached to the original marble piece.

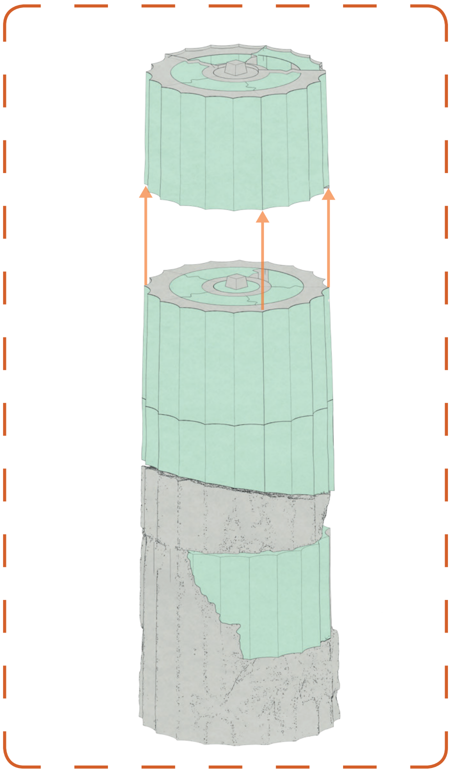
1. REMOVE THE OVERLAYING SUPERSTRUCTURE



3. DISASSEMBLE THE GLASS DRUMS OFF-SITE



2. REMOVE THE DRUMS ONE BY ONE



4. REMOVE THE MORTAR LAYER OF THE BROKEN MARBLE DRUM

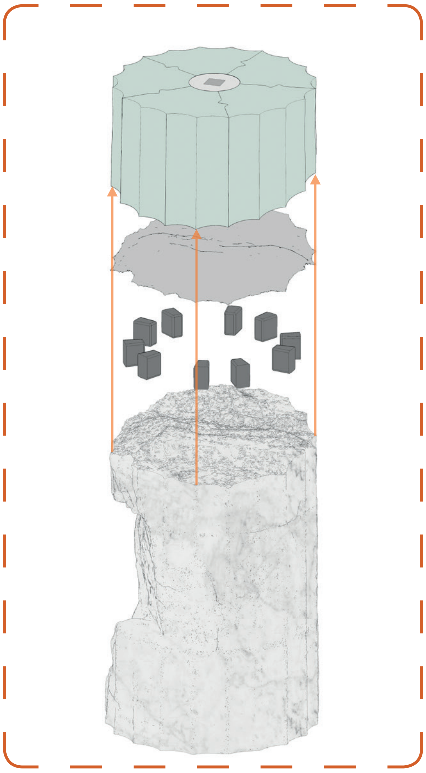


Figure 133 & 134: Impression of the two cast glass alternatives: translucent (top) or opaque (bottom), edited from: (British Museum, 2012) and (Earth Trekkers, 2020)

09.

CONCLUSIONS

9.1 Conclusion and Discussion

The research presented in this thesis shows how large monolithic cast glass elements can be used as an alternative to conventional materials for the restoration of the structural stability and integrity of historic marble monuments. Based on the involved working fields covered in this thesis, the main research question was stated as follows:

"To which extent can monolithic cast glass components of a substantial mass be used to reconstruct structural elements in marble monuments, while simultaneously complying to the international conservation guidelines?"

According to the international guidelines, two of the most important criteria in conservation are preserving the authenticity of the monument and minimising the visual impact of the intervention. Nowadays, most conservation projects are trying to match these criteria by using mostly traditional techniques and materials. However, these processes can be very expensive and time-consuming due to scarce or the lack of materials or in inadequate and time-consuming techniques. This allows for using new materials and techniques, like cast glass, to conserve and preserve these monuments. With its sufficient structural and mechanical properties, shaping possibilities and transparent appearance, cast glass could be a promising alternative to the currently used conventional conservation materials and processes.

With its transparency, using glass could lead to a minimal visual intrusion of the intervention, or, if desired, it could be coloured and texturised to match the appearance of the original material. Moreover, by casting, it is possible to shape the glass in almost any imaginable form. Combining this with the 3D scanning of damaged surfaces, perfectly fitting elements could be made to replace the missing pieces of the structure much easier than is done now. It would be much faster and cheaper than the existing techniques, given that the marble is still carved by hand and the scarceness of marble blocks with sufficient dimensions. Cast glass restoration could resolve these problems, but just like all conservation projects, there is not a single design solution that could be applied to every monument.

Besides preserving authenticity and minimising visual impact, reversibility is the third hard criterion for conservation and is mainly applicable for the connections. To reach reversibility, dry connections are used as much as possible. These type of connections are mechanically and visually the least intrusive towards the monument and will join the glass pieces that are used in the interventions. For both safety and production, splitting the glass geometry in fragments is essential. It creates a safe back-up since the load is spread over multiple pieces and the smaller pieces allow for a faster and thereby cheaper annealing process. By using interlocking elements of glass or titanium, the connections can be made strong enough but could yet be reversed according to the guidelines. Only if there are no other options available, permanent connections are allowed, like two pieces requiring structural coherence which cannot be reached by dry interlocking connections.

In this thesis, the Parthenon was used as case-study and the original design of the monument was from great value for the design of the connections. To assure the stability of the structure, the inserted pieces and corresponding connections must approach the mechanical behaviour of the original monument. The connections between glass and marble are based on the specific behaviour and composition of the Parthenon. Choosing a different case-study would thus have led to different connections, depending on that case study's own specific mechanical behaviour.

Just like the connections, the used materials are also based on the ones originally used in the monument. This led, in this case, to the choice of soda-lime glass and titanium connection elements. **These materials have compatible thermal expansion coefficients with the Pentelic marble used in the Parthenon, which is an important criterion in choosing the materials for the restoration.** If other monuments are made from a different type of marble, with a lower thermal expansion coefficient, borosilicate glass and stainless steel could, for instance, be chosen.

To shape the glass will be cast into 3D printed sand moulds. In most monuments, there is no repetition of elements, so using reusable steel or graphite moulds would be extremely expensive. 3D printed sand moulds have a very high accuracy, can be made very quickly and are cost-effective since the sand can be reused multiple times in new moulds. Moreover, the casting process in sand moulds does not differ from casting with other disposable moulds, although post-processing is required if a smooth and glossy surface is desired.

The answer to the main research question of this thesis can be split into two parts, based on the sub-questions. ***At first, is it allowed to use cast glass for restoration projects? And second; can cast glass be used for restoration projects, like the Parthenon?***

The answer to the first question is rather simple: Yes, it is allowed to use glass for this application. Within the international guidelines new materials can be used, if the common ones prove to be insufficient or inadequate. However, about whether the current restoration techniques of marble monuments like the Parthenon are insufficient or not can be debated. **The current restoration process is extremely time-consuming, and expensive since is still largely done according to traditional, manual, methods.** Based on that, it could be stated that a new material like glass could be a good alternative. Moreover, glass does obey to other important guidelines like minimising the visual impact, being reversible and preserving the authenticity of the monument. However, just like all restoration projects, discussion will occur whether the intervention would be appropriate or not. Some will say that it is way too intrusive and will reject the proposal for using glass as reconstruction material and some will appreciate the innovative design, reduced costs and restoration time. This discussion is, however, one of the ages and no matter what kind of new ideas will be proposed, there always will be people who will say that this intervention goes too far, or not far enough. Within this discussion, both opinions have good argumentation and support, so when designing such an intervention the most important value is to do it with respect towards the monument and its historic and cultural significance.

The second part of the research question, whether cast glass can be used to restore projects like the Parthenon, is more straightforward to answer. Technically speaking, cast glass could be used as a building material, as has been shown in several references. **However, the increased size of the elements makes this application more complicated as the cast glass used in the reference projects.** In the design for the Parthenon, the average weight of a single piece lies around 750 kilos. This requires a very delicate annealing process to prevent the glass from crystallisation, cracks or other defaults.

Several design decisions have been taken to allow for a faster annealing time, like chamfering corners, making the elements hollow and assuring a constant thickness over the section. Still, the annealing phase will require great delicacy and patience, but once the glass has been annealed properly it should theoretically be strong and stiff enough to be used as structural element in a monument like the Parthenon. However extensive testing is still required and recommended before it actually can be used in a monument of this importance. These experiments should include testing the compression strength and buckling behaviour of the glass under a constant vertical load. Also, the resistance of the glass and connections against large lateral loads like earthquakes should be tested in a simulation. The results of these test could have implications for the design of the glass element, especially regarding the thickness of the section and the width of the hollow core.

So based on the research done towards conservation guidelines and properties of glass, there is great potential in using large monolithic cast glass elements in restoration projects, instead of conventional materials. However, not every monument is suitable for cast glass restoration. Factors like historic and cultural value, the rarity of the monument, materialisation have a great influence in whether a monument should be restored and if so, with which techniques and materials. It remains thereby vital that every monument is extensively researched before is decided which type of restoration will be applied. In this thesis, the Parthenon was used as case-study, given the great accessibility of digital resources, but in practice, it would be hard to apply such an innovative approach on a monument which such value and representation, despite that it structurally possible. In future research it is thereby recommended to gather scientific evidence to support the principles of cast glass restoration. Glass still has the image of being a weak and fragile material and in combination with something vulnerable like a monument, people will even be more cautious. To convince the conservative world of conservation, it is vital to provide technical evidence that shows that glass is strong and save enough to be used in combination with vulnerable monuments.

9.2 Reflection

From the beginning of the design process, it was the goal to combine the inputs from the field of restoration, with those coming from glass technology and production. The extensive amount of information coming from the various conservation guidelines eventually set the base for what was allowed with glass. However, the freedom within these guidelines made it hard to evaluate different designs, since, in some way, they can all be considered appropriate. To reach this breakthrough in the design process, it was necessary to take a position in this discussion regarding the appropriateness of conservation based on personal values. With these values, which were shared with large majorities within the would of conservation, it was possible to critically evaluate design alternatives. However, in the future, it is important to find that position at the beginning of the process and not midway. It will help to make early design decisions and based on substantiated arguments.

Looking back at this design process, it stands out that most of the design decisions were made based on assumptions from literature studies and reference projects. During this thesis, it was not possible to make these decisions based on scientific testing or prototyping. In the future, it is strongly recommended to include these testing and prototyping moments in the design process. Besides the valuable input it gives to the decision process, it also makes the argumentation for a certain design choice much stronger since you have scientific evidence as support. Adding this scientific data about design alternatives to this thesis would have made it a stronger concept and design. However, the results do show potential that asks for further testing and thereby bringing the concept of cast glass restoration to the next level.

10.

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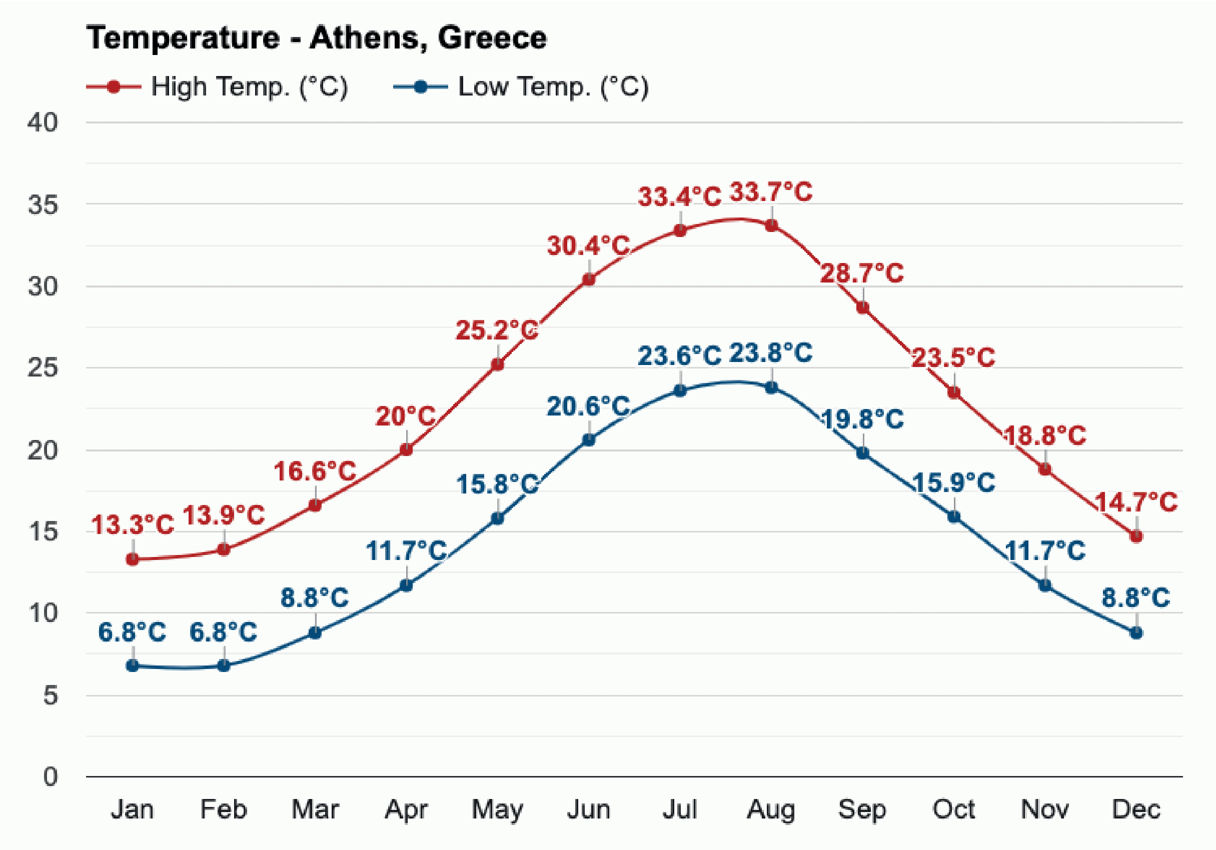
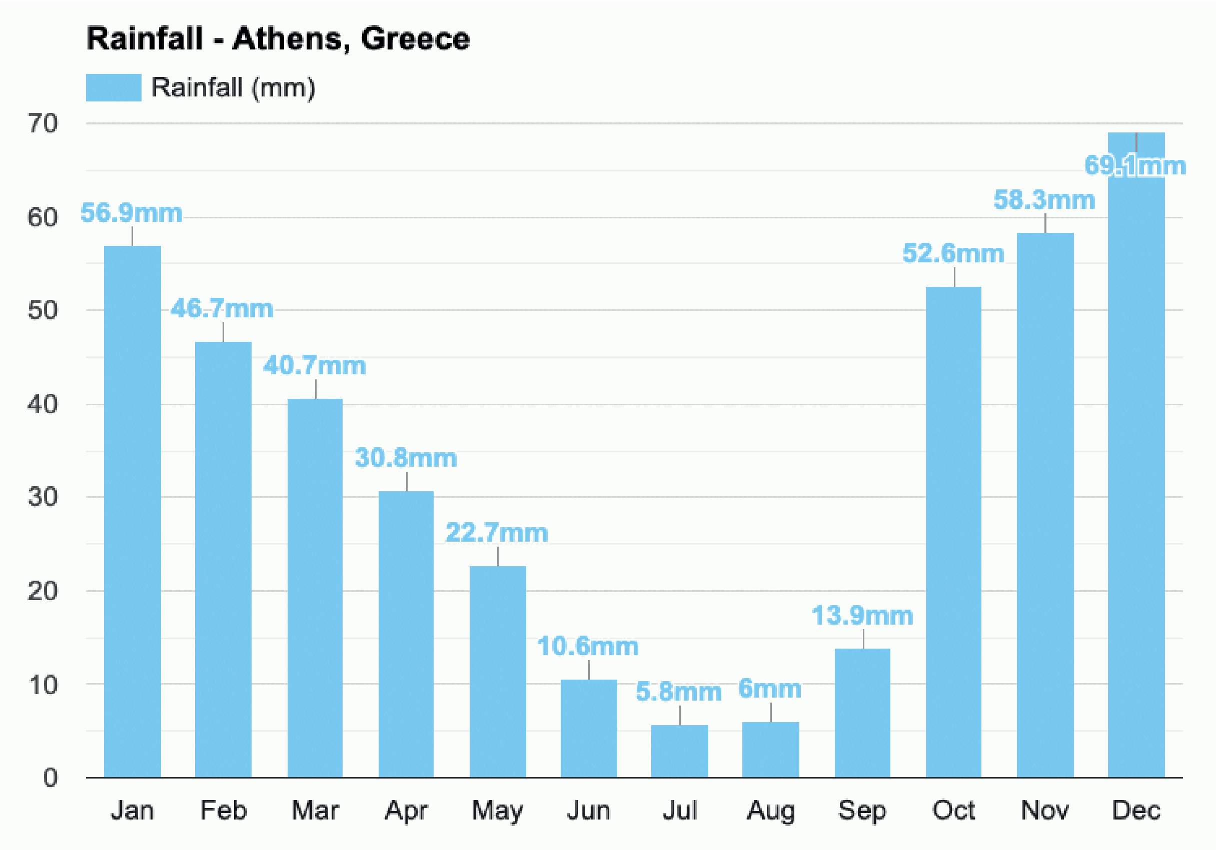
11.

APPENDIX

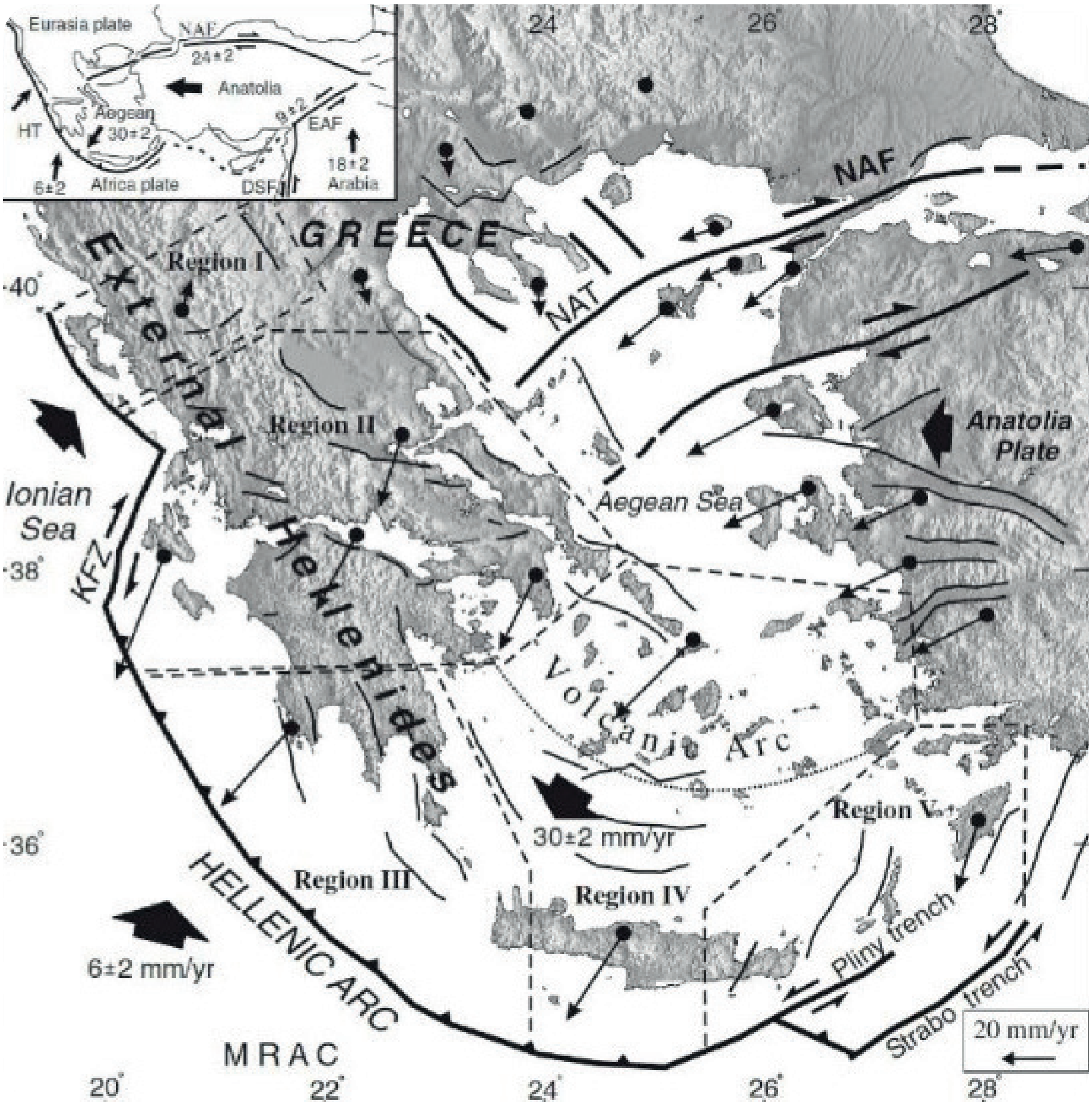
Appendix A: Climate in Athens





Average monthly temperature and precipitation in Athens, Greece, (Weather Atlas, 2020).

Appendix B: Geo-tectonic situation in Greece

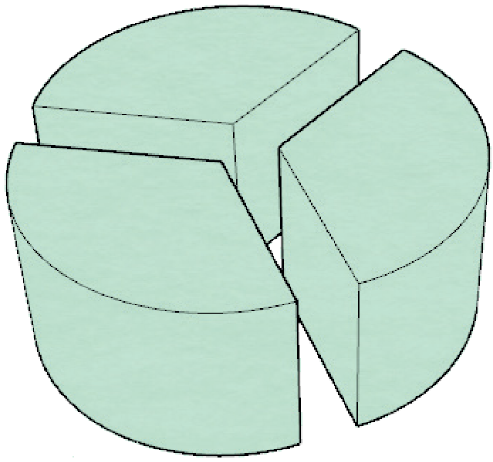


Greece lies within one of the most active seismic zones in the world, so tectonic and volcanic activity are a very common occurrence. This high seismic activity in the county is because three tectonic plates meet in this area. In the south, the African plate moves north, crashing into the Eurasian plate in an area that is called the Hellenic Arc. This fault starts in the Ionian Sea, off the coast of Epirus. From there it goes south, alongside the western Peloponnese, towards Crete and it ends near Rhodes, just outside of the Turkish coast. Alongside this fault lies an enormous subduction zone, where the African plate is pushed down by the Eurasian one. Simultaneously, in the north of Greece the Anatolian microplate, which is part of the larger Eurasian plate, rotates counter-clockwise, moving away from Arabia and into the African plate. This creates friction alongside the boundary with the Eurasian plate, called the Northern Anatolian Fault (NAF). This fault line starts in the Aegean sea, about 200 kilometres north of Athens and goes along the north coast of Turkey towards the east, (Patton, 2018).

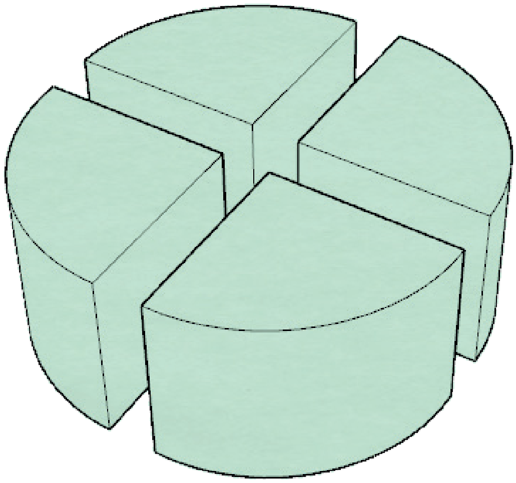
Appendix C: Design Alternatives

FRAGEMENTATION OF THE GLASS DRUMS

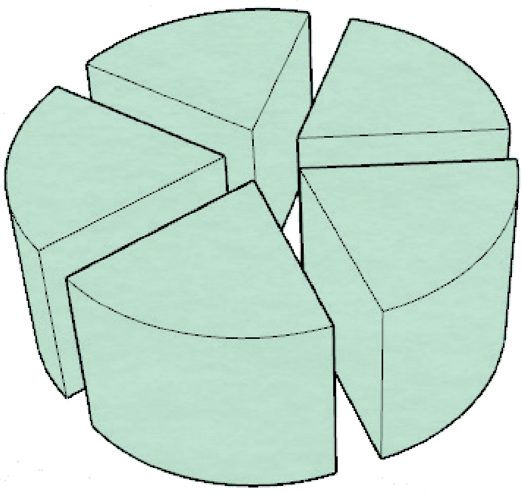
3 Pieces



4 Pieces

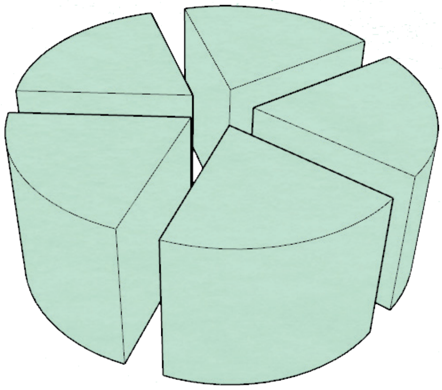


5 Pieces

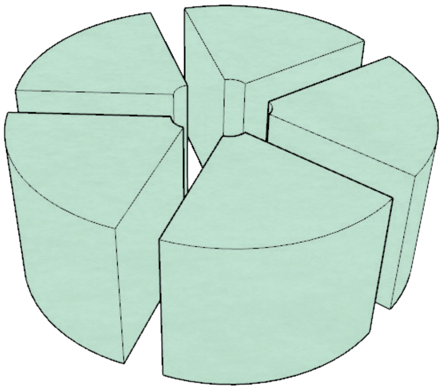


CORE SOLUTION

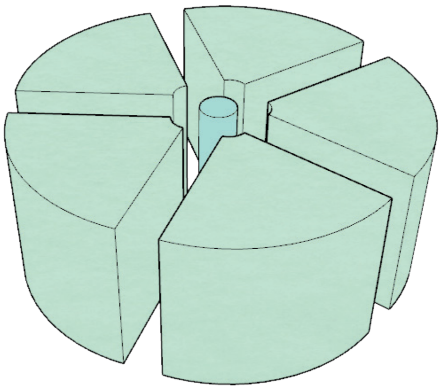
No Core



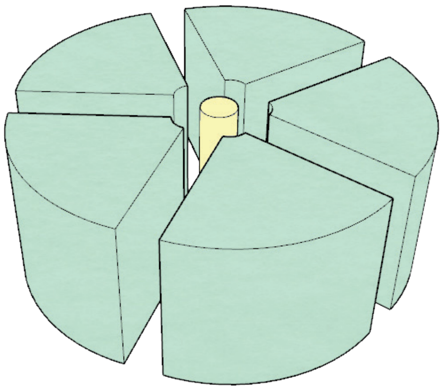
Hollow Core



Glass Core

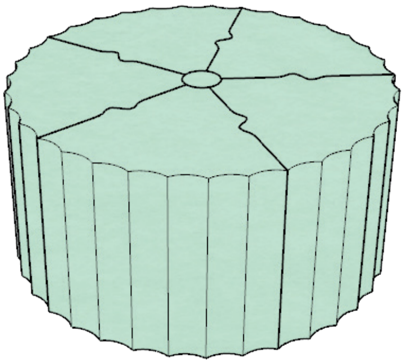


Marble Core

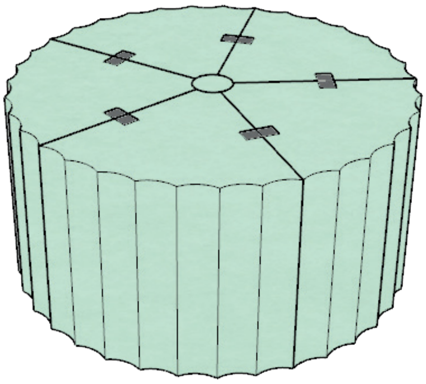


CONNECTION 1

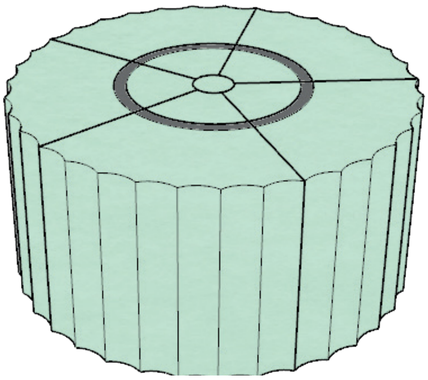
Interlocking Geometry



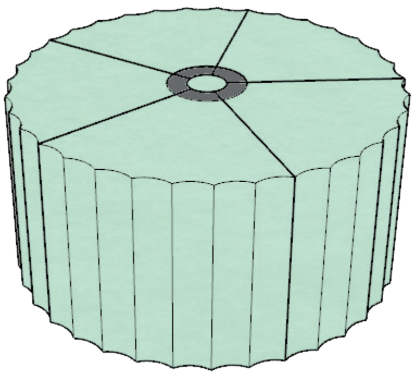
Embedded Titanium Joints



Titanium Compression Ring

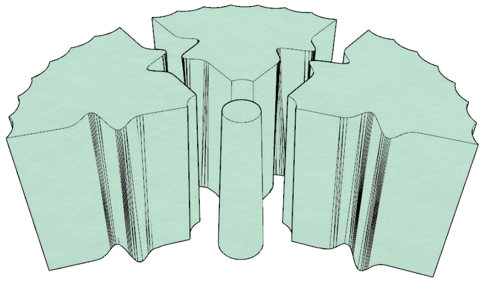


Titanium Knot

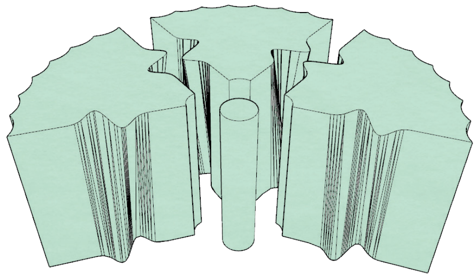


INTERLOCKING GEOMETRY

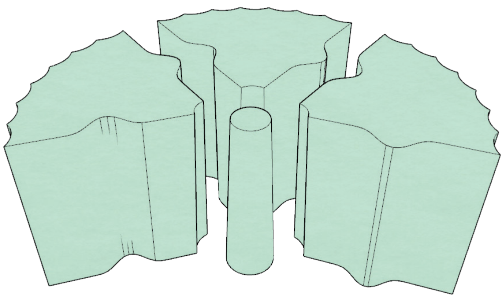
Full Sinusoid, Single Curved



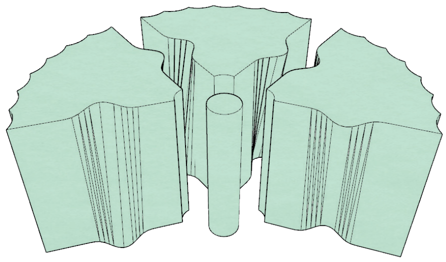
Full Sinusoid, Double Curved



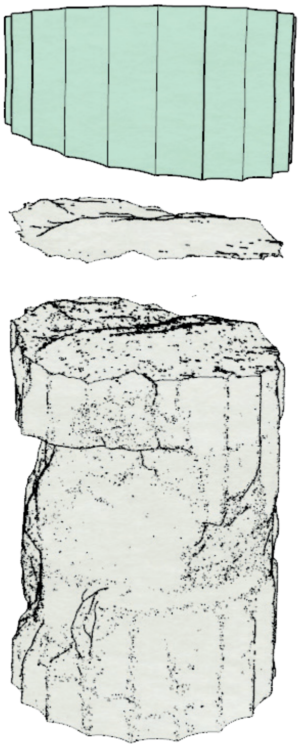
Half Sinusoid, Single Curved



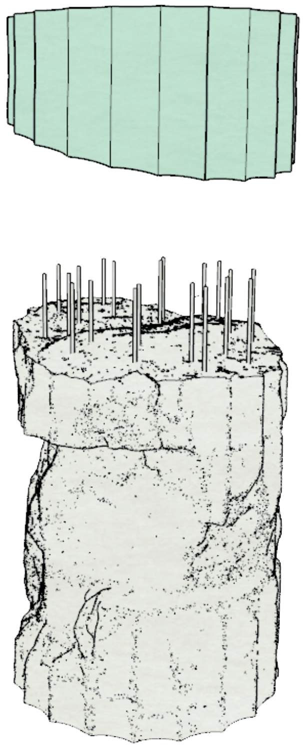
Half Sinusoid, Double Curved



CONNECTION 4

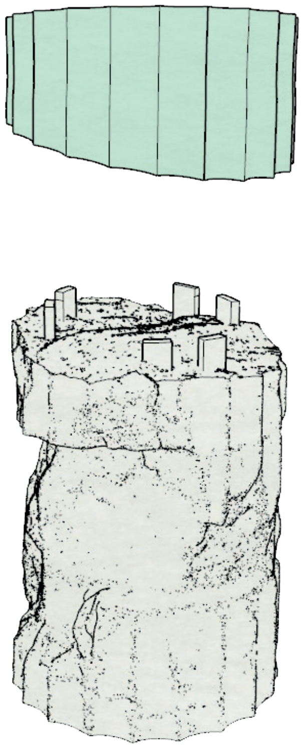


Mortar



Titanium Bars

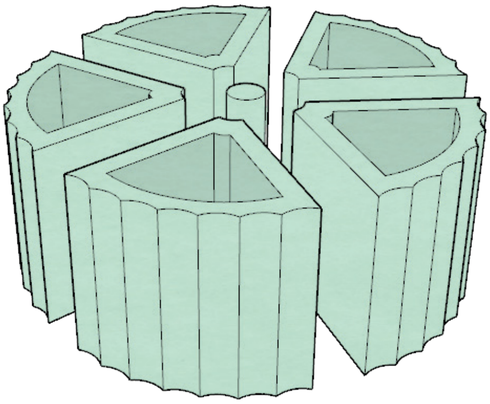
Interlocking Ring



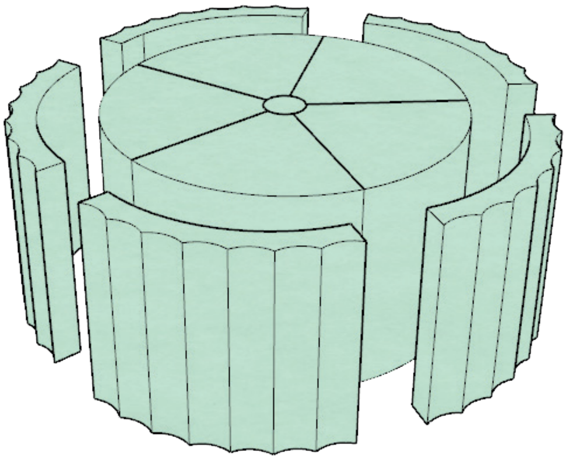
Interlocking Teeth

REDUCING THE ANNEALING TIME

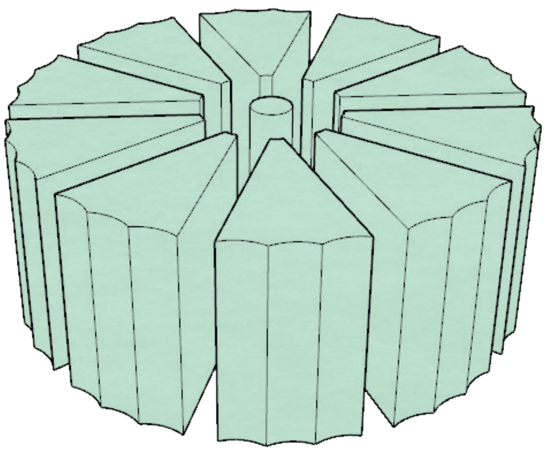
Hollow Pieces



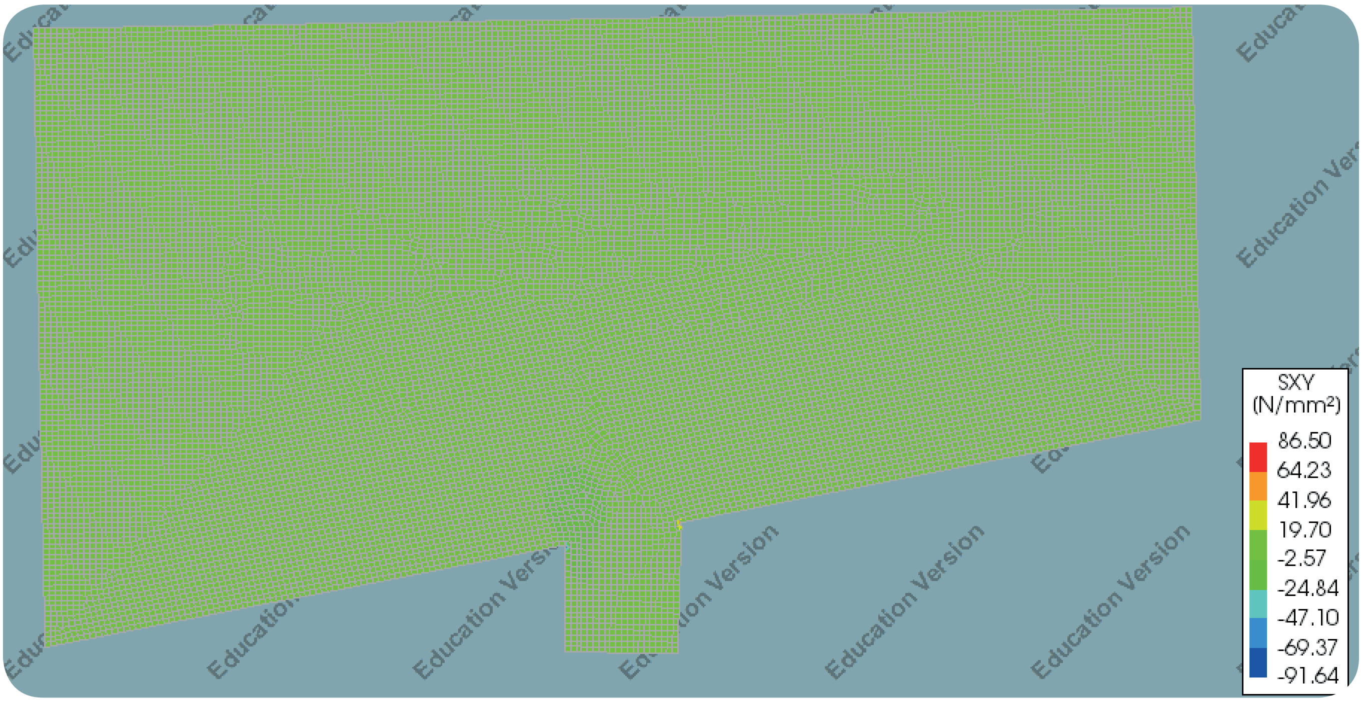
Seperatable Skin



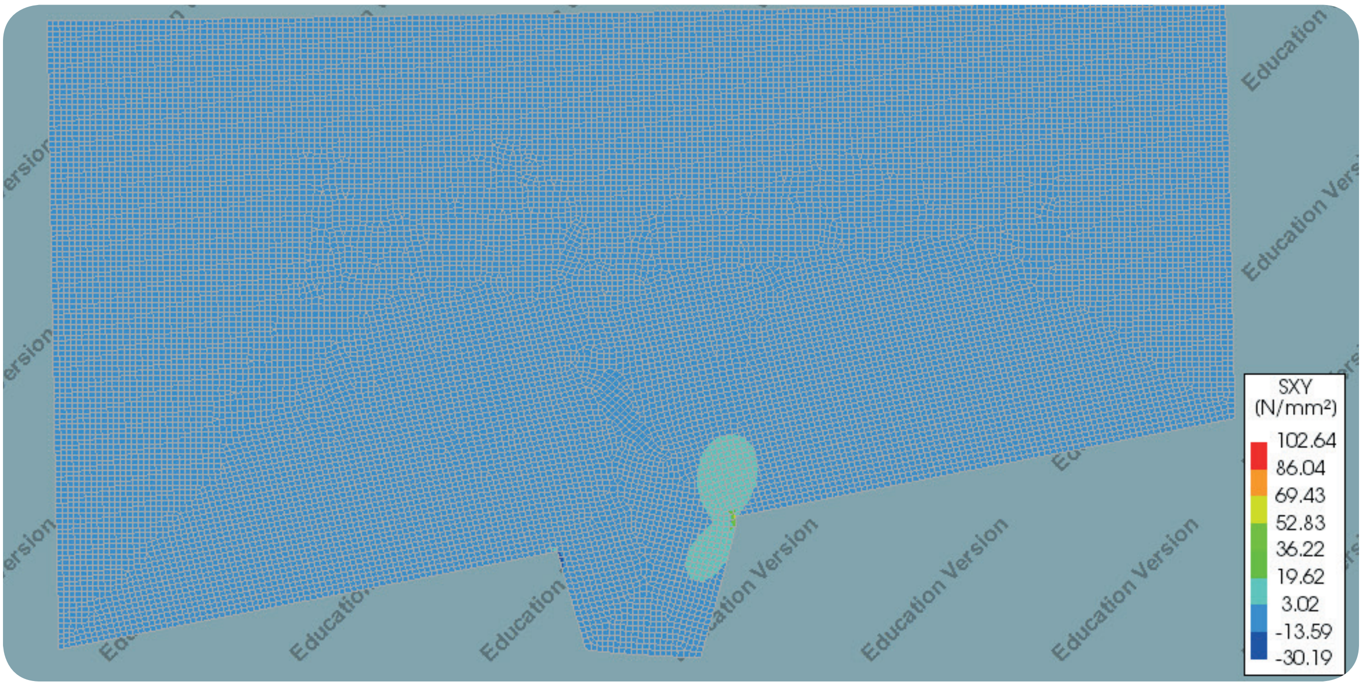
Reduce the Size



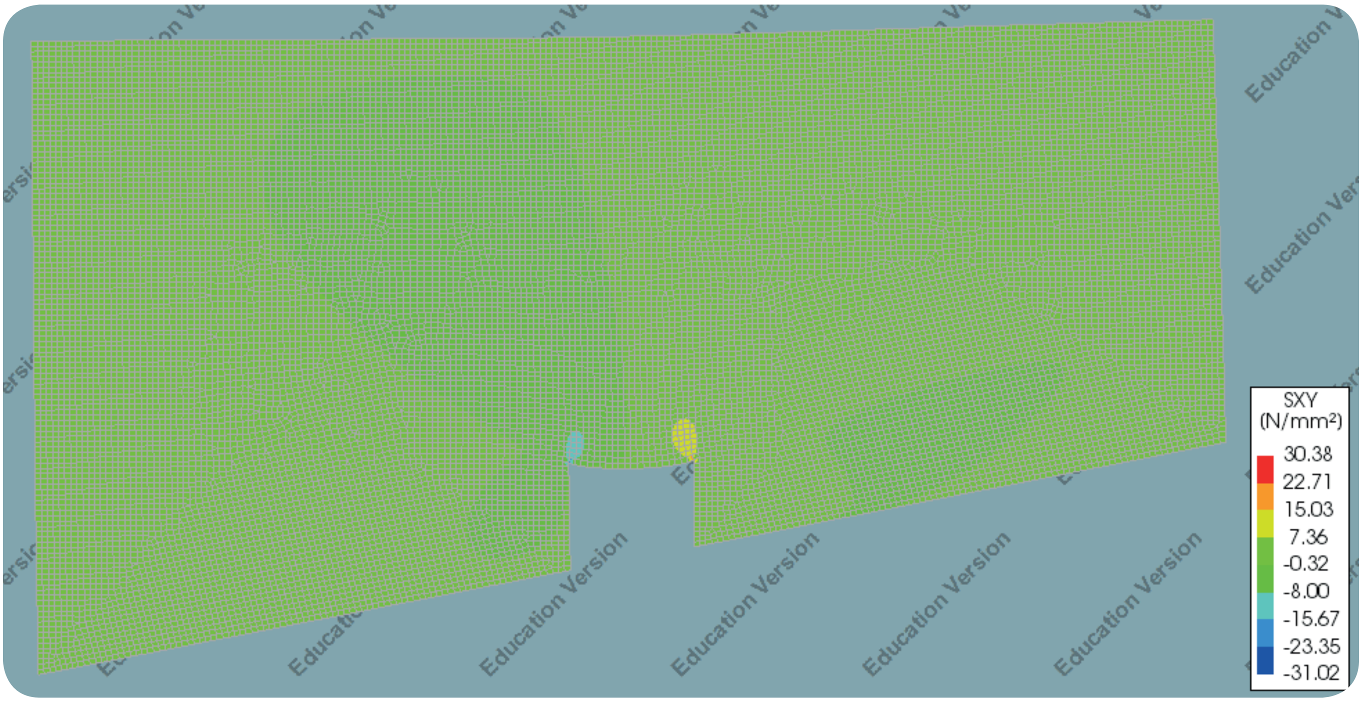
Appendix C: Finite Element Analysis Results



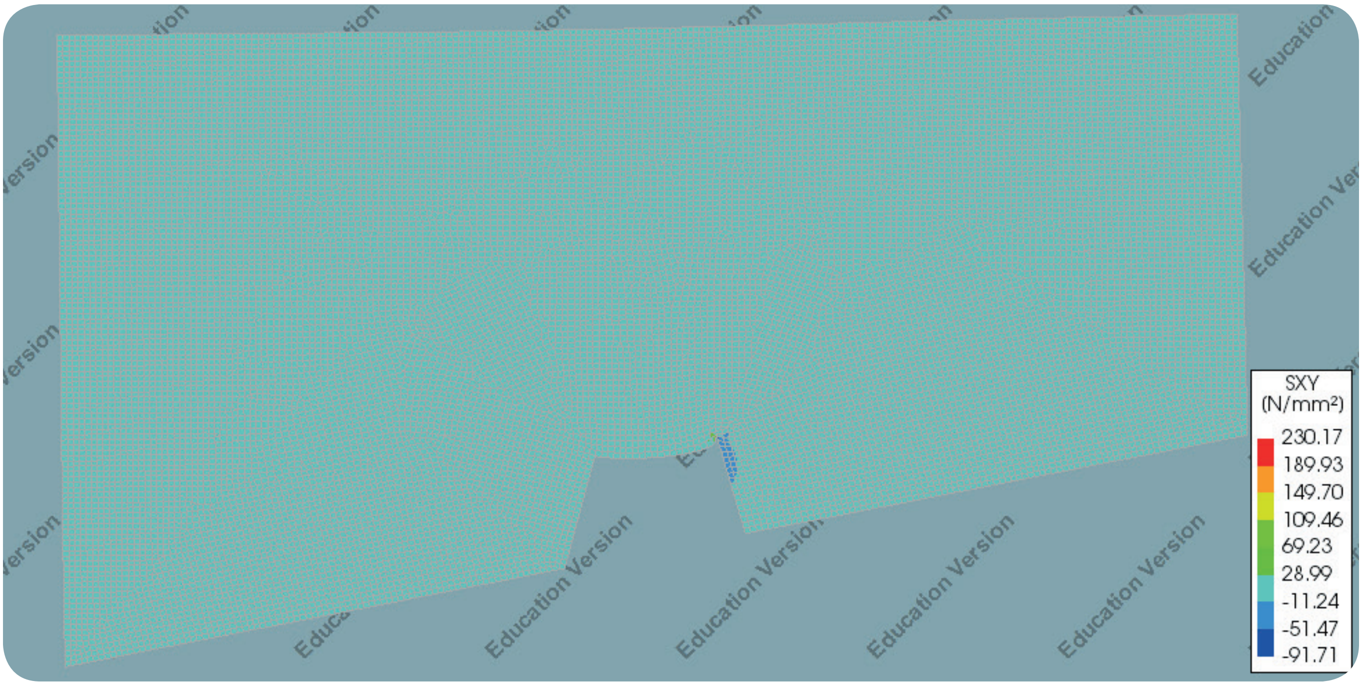
Result A: Glass with straight edges



Result B: Glass with inclined edges



Result C: Titanium with straight edges



Result D: Titanium with inclined edges