TOWARDS AN EVERLASTING ARCHITECTURE

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ABSTRACT

The following paper examines the approach of very long-lasting architecture to utilise the initial embodied carbon for as long as possible. Since the largest proportion of embodied carbon is in the load-bearing structure, it is investigated which of the three materials concrete, brick masonry and timber can be used to erect a load-bearing structure that can last for centuries or millenia. After defining the objectives, three historical case studies are analysed regarding their durability. A contemporary case study is used for technical comparisons. In addition, the thesis regarding the sustainability of durable structures is tested by attempting to calculate the GWP of the Pantheon. By comparing the case studies, concrete and especially modern variants of opus caementicium could be identified as suitable building materials due to its self-healing ability and remarkable durability.

KEYWORDS: *Embodied Carbon, Durability, Service Life, Structural Materials, Ancient Architecture*

I. INTRODUCTION

1.1. Operational Carbon and embodied Carbon

The construction industry plays a significant role in causing the climate crisis, accounting for 39% of global carbon emissions per sector (Fig. 1). Of this, the so-called operational carbon (OC) is the larger part with 28%. The OC is emitted during the service life of buildings through use (e.g. heating, electricity, etc.). With 11%, embodied carbon (EC) is a smaller but no less important share. It describes the carbon footprint of the building materials used. (UNEP & IEA, 2017)

There are numerous tools to reduce energy consumption during the use of buildings and operational carbon. Both passive and active measures can help to save and even gain energy, so that it is possible to build houses that are 100% self-sufficient. This paper therefore focuses on the other side: embodied carbon and possibilities to reduce it. The researchers Victoria and Perera (2018) differentiate between two categories of EC. 'Initial embodied carbon' which is emitted during the 'cradle to end of construction' phase (raw material extraction, manufacturing, transport, construction) and 'recurring embodied carbon' which is emitted during the use phase due to maintenance, repair and replacement.

1.2. Potential embodied Carbon reduction Methods

A look at the material pyramid (Fig. 2) shows the potential of using materials with a low or even negative global warming potential (GWP) made from renewable resources such as wood. An obvious option to save EC would therefore be to reduce the use of materials with a large GWP and instead use these sustainable alternatives. However, around 12 billion tons of concrete are produced every year (Hossain et al., 2022). Cement, one of its main components alone is said to be responsible for 8% of global carbon emissions (BZE, 2017). This would mean that the use of concrete is responsible for more than two thirds of all embodied carbon. According to Jeremy Gregory (2021) from MIT, its "durability, affordability, and availability make it essential to countless construction projects". That explains its intensive usage. After water concrete is the second most used material worldwide.

Since the use of concrete and other materials with a very large GWP is widespread, the second option to reduce EC would be to increase the lifespan of the building elements made from these. In this way, the invested initial embodied carbon would become more and more sustainable in relation to the growing service life of the entire building. Mooiman and Van Nunen (2012) investigated the relation of the lifespan of buildings to their environmental impact. They refer to a study of the Delft University of Technology which shows that most of the studied buildings were demolished between an age of 75 and 125 years. To show the development of the environmental performance over time, they did a case study of a typical Dutch single-family house. The calculated graph (Fig. 3) shows that building elements that were never repaired or replaced had a 40% lower environmental impact after 125 years than after 75 years. Mooiman & Van Nunen (2012) state, that "if a material lasts ten times longer than other materials, the environmental impacts of such material in principle counts, only for one tenth". That underlines the chances of very durable buildings in terms a good environmental performance.

The approach of a very durable architecture, which is based less on the use of materials with a low GWP than on the relation of embodied carbon to lifespan, will be explored further in the following paper. The focus lies on significantly extending the conventional service life. To identify the building elements with the largest embodied carbon share and therefore the best potential to lower the GWP by extending the lifespan, the composition of EC was investigated regarding its distribution to the building components. Three consecutive studies were consulted (see Appendix). Figure 4 to 6 show that the load-bearing structure of buildings is the largest carrier of embodied carbon with an average share of over 50%. The services also play a major role due to recurring embodied carbon from maintenance.

1.3. Research Question

This paper serves as a basis for the author's parallel design. The fundamental idea is to design a highly durable structure which could be used for centuries or millennia to use its large share of initial EC as long as possible. The inspiration for this was the Pantheon, as well as the desire to develop an alternative to buildings built with low-GWP materials such as wood. To create a durable and therefore more sustainable load-bearing structure, it is essential to analyse which building materials are suitable for maximum durability. The goal of this research is to identify this material and to test the author's hypothesis on the example of the Pantheon. Since the active services are responsible for the second largest share of the carbon footprint, the examined materials are also analysed for their suitability for passive measures. The research question and the sub questions are as follows:

Which material is best suited to create a durable and therefore sustainable structure for the design?

> *Which material is the best for integrating passive measures to minimise active services and the embodied carbon associated with them?*
>
> *How does the Pantheon perform in terms of embodied carbon footprint at the present time in comparison to a contemporary case study?*

II. METHOD

2.1. Definition of Requirements for the load-bearing Structure

The basic methodology of the research is the comparison of the different structural materials concrete, brick masonry and wood. For this purpose, a catalogue of requirements adapted to the construction task is developed. It is partly based on the 'physical' and 'environmental or sustainable' 'Types of Obsolescence' established by Grover and Grover in 2015 (Table 4). In the following the single reasons for obsolescence and other requirements are translated to a goal/discipline for the structure.

2.1.1. Physical Requirements

→ Goal/discipline 1.1, Durability: The structure very durable and needs minimal maintenance.

→ Goal/discipline 1.2, Repair options: It is easily possible to repair the structure in case of damage.

2.1.2. Environmental Requirements

→ Goal/discipline 2.1, Environmental impact: The GWP of the structural material is considered and put into perspective with the possible lifespan.

→ Goal/discipline 2.2, Passive measures: Possibilities for passive measures for instance thermal mass and transmittance of the material are considered.

2.2. Case Studies

Since the aim is to identify and develop a highly durable structure, a look into the past is made to investigate three particularly old and therefore durable buildings made of the three different materials. They are investigated regarding their age and damages/repairs over their life span on the structure. In addition a contemporary case study is investigated to compare technical properties. All the results are compared in a matrix and discussed in terms of their suitability for the project. In addition, the Pantheon is examined as an inspiration for the project with regard to the hypothesis that it was able to achieve good environmental performance over its long service life.

III. RESULTS

3.1. Historical Case Studies

In order to compare the possible service life of buildings with the respective structural material, the selected case studies ages serve as an example. Care is taken to ensure that the buildings are still as intact as possible. The projects are among the oldest of their kind within their construction materials. Although they should provide an orientation but are not to be understood as an absolute number. Since the age of buildings is constantly enlarged by maintenance and repair, the age of the case studies alone does not tell about the materials durability alone. Therefore, the case studies history in terms of damages and reparations is examined. The criteria for selecting these case studies were as follows: Age (as old as possible), Condition (good condition and at best still in use, Dimensions (similar building dimension, no comparison of a shed with a cathedral), Information available (accessibility to information about the building).

3.1.1. Case study 1 - Pantheon - Concrete

The first historical case study considered is one of the most iconic buildings in history, the Pantheon in Rome (Fig. 7-14). Completed around 126-128 AD, it is one of the best-preserved buildings from ancient Rome. The architects and the exact construction period are unknown. In the year 609 AD its function as a pagan temple changed and it became a Christian church. It is chosen as a case study for this paper since the structure which is made of Roman concrete has remained until. (MacDonald, 1976)

The Pantheon consists of two parts. The main part is the almost windowless rotunda, which is closed off by dome. The second part is the portico which marks the entrance of the building. The following examination purely focusses on the structure of the rotunda and the dome. The Pantheons structure is mainly made of opus caementicium, also known as cast masonry or Roman concrete and has been standing for around 1900 years. Opus caementicium would be the equivalent of today's cement. It was mixed with volcanic ash (pozzolana) and other aggregates such as brick fragments and thus formed concrete (Kyropoulou et al., 2022). The buildings constructed with it are remarkably durable. There are Roman marine structures "which have remained practically intact for 2000 years" (Palomo et al., 2019). Figure 11 shows the various aggregates used in the concrete. The builders use concrete mixtures that become lighter from the bottom to the top in order to create the greatest possible strength at the bottom and the lowest possible load at the top (Lancaster, 2005, p. 62). The ring forming the foundation cracked during construction, so a second larger ring was poured around the first one to provide stability. This was successful as the Pantheon still stands on it today. The load-bearing concrete of the rotunda walls is sandwiched by horizontal and vertical brick layers which can be seen looking at the outer surface of the rotunda wall (Fig. 12). This configuration is called ‘opus latericium’ (ArcheoRoma, n.d.). Inside many niches drastically reduce the weight as the wall does not have the full thickness of 6.2 metres everywhere (Dewidar et al., 2016). The condition of the brick skin (Fig. 13) around the concrete clearly shows the age of the Pantheon. Not only are large sections broken out of the wall and the cornices of the outer wall, but many bricks also show clear signs of wear from the weather. It looks as if many parts of the wall have been patched up over time with various stones and bricks.

Almost two millennia ago, the Romans managed to build “the largest dome made of unreinforced concrete in the world” (Masi et al., 2018). However, the dome has some cracks, which can be seen in Figure 14. In an article of these cracks with a computational simulation in 2018 it is stated that “the meridional cracks may have been produced in the early stage of the dome’s life by the action of concrete shrinkage and gravity" (Masi et al., 2018). The authors therefore come to a similar result as Alberto Terenzio in 1934, who states that the cracks most probably occurred shortly after the Pantheon was built, as they were repaired with bricks that have the same markings as other bricks initially used in the building (Terenzio, 1934). Since the cracks are proven to be nearly as old as the entire building, they apparently did not have a negative effect of the Pantheons durability.

In his book "The Pantheon Design, Meaning, and Progeny", William MacDonald (1976) describes the changes that the Pantheon has undergone over the centuries. He states that "the building was altered by cutting passages trough one of the great piersby the south apse, in ignorance of its structural function". Despite that, no changes in the structure if the rotunda were done, while other building components as the roof tiles were replaced multiple times. That means that the structure is almost completely existent as it was built in the 2nd century. This might be due to the already mentioned incredible durability of opus cementicium. An article from 2019 examines the future viability of opus caementicium. According to the authors, it has a significantly longer service life than the nowadays usual Portland cement. This is due to the cementitious matrix that develops over time (Palomo et al., 2019). This matrix is created by a process called post-pozzolanic reaction. Small lime clasts trapped in the concrete react with water as soon as it enters the concrete. To put it simply, these clasts are too large to react completely with the water when the concrete hardens initially. They only chemically react on so-called hydration rim at the outer edges. In the event of a crack in the concrete, moisture can enter through the crack, the lime clast reacts and, in the best case, closes the crack as it can now release its remaining chemical potential and creates a new matrix (Fig. 15). Ideally, the concrete always cracks where these lime clasts are trapped. The whole process enables a self-healing effect in the event of damage. Because of this property, Roman concrete has recently been the subject of increased research. The first companies such as DMAT are already offering a modern successor to opus caementicium since the material is very promising. (Maragh et al., 2023) Steel reinforcement, which was not used in ancient Rome, also plays a role, as it can corrode and weaken the concrete. The absence of reinforcement therefore benefitted Roman buildings in terms of durability. (Palomo et al., 2019)

To summarise, it can be concluded that the Pantheon's load-bearing structure is in very good condition for its age. Apart from the cracks in the dome and the partially weathered bricks, there is no recognisable damage. The assumption that the cracks most likely occurred shortly after construction and would therefore also have survived for almost 2000 years underlines the resistance and durability of the Pantheon. Furthermore, after 2000 years, research has finally begun to investigate Roman concrete in depth and has shown what potential its self-healing properties could have for durable building materials. The fact that the material can react to cracks on its own is a great opportunity for the design project.

3.1.2. Case study 2 - Aula Palatina - Masonry

The second case study is also of Roman origin. It is the Basilica Aula Palatina (Fig. 16-27), also known as the Basilica of Constantine. It was built between 300 and 312 AD in Trier, which was then part of the Roman Empire. In the Middle Ages, it served as the seat of the Bishop of Trier. Afterwards it was used as barracks until it finally took on its current function as a Protestant church in 1856 (Evangelische Kirchengemeinde Trier, 2021). Although it has been restored several times, it is still one of the oldest masonry buildings currently in use and was therefore selected for this study. Richard Krautheimer states in an article from 1967 that "no Constantinian basilica is better preserved than the one at Trier".

The basilica is remarkable for the fact that it has neither the classic columns in the interior nor the side aisles. As a result, there is also a band of windows in the lower wall area, making the interior appear very bright. (Kleiner, n.d.) Originally, the basilica was part of a palace complex, but this no longer exists. The largest part of the load-bearing structure, the walls, are made of brickwork. Their thickness varies between 2,7m and 3,4m and are therefore much thinner than those of the Pantheon (Trierer original, n.d.). This might be caused by the fact that they do not have to bear horizontal loads of a vault. According to Krautheimer (1967), the choice of material is mainly due to the location of Trier, as the romans used the local available materials. Concrete was only used for the foundation (Hahn, 2019). The wooden ceiling has been destroyed and replaced several times. In order to assess the condition of the load-bearing brick walls, it is necessary to take a look at the history of changes of the building.

The floor plan in Figure 18 shows the remains of the ancient palace complex around the building. At that time, the building was plastered, and the interior was heavily decorated (Fig. 19). The interior furnishings and panelling were looted during Germanic raids. With the decline of the Roman Empire, the Aula Palatina also fell into disrepair. For example, the wooden roof truss rotted so that only the walls remained. In the Middle Ages, the large window openings were closed, and the building was converted into a retreat (Hahn, 2019). The roofless space in the centre of the walls housed smaller buildings until the church took over the building in the year 1000 and turned it into a fortress (Fig. 20). Significant changes were made during the Renaissance. Around 1615, Archbishop Lothar von Metternich decided to replace the basilica witch a palace complex. The original plan was to demolish the entire basilica, but for cost reasons only the entire east and south walls were torn down, while the north and west walls served as the outer wall for the palace complex (Fig. 21). Figure 22 shows which walls were left standing at the time and therefore still consist of the original Roman masonry today. After the decline of the Trier Electorate around 1800, the palace was used as a military hospital and barracks. In 1846, the Prussian King Friedrich Wilhelm IV rebuilt the original Roman structure. The basilica was then given to the Protestant church. During the Second World War a bombing raid on Trier caused the building to burn out. Figure 23 and 24 show the extent of the destruction. However, it is striking that the brickwork was able to withstand the attack almost completely. The basilica was rebuilt in the post-war period and has served as a Protestant church ever since. (Triererer original, n.d.)

Regarding the durability of the structure, it can be said that the apse in the north and the west wall should be almost entirely from the Roman period. According to the Trier original, also a plastered area dating from this period remains. However, it is not known to what extent there were repairs to the masonry and mortar joints. Looking closely at the pictures after the destruction by the bombing raid, many small damages can be seen on the outer walls. A look from the inside at the west wall (Fig. 25) (the wall that dates back to Roman times) shows that it consists of a patchwork of different brick sizes and colors, and that some bricks and joints seem to be newer than others. It can also be seen that earlier openings were closed. In Figure 26 and 27 spots where repairs can be assumed are highlighted. The two historians Dr. Beth Harris and Dr. Steven Zucker emphasize in a video about the Aula Palatina that it is a "reconstruction of a reconstruction of a reconstruction" (Smarthistory, 2023).

In any case, it can be concluded that the Aula Palatina has had an impressive lifespan so far. Although at least half of the supporting structure (east wall and south wall) was only reconstructed around 1846, it is very durable overall. It is also important to emphasize that most of the destruction of the building was caused by humans. The building was looted in antiquity, half of it was demolished in the Renaissance and then it was bombed. If these things had not happened, it is very likely that much more of the original structure would still be preserved. On closer inspection, you can see from the masonry how many conversions and repairs have been carried out, but this is also a great advantage compared to concrete: masonry can of course be easily repaired by replacing individual bricks and mortar joints.

3.1.3. Horyuji Temple - Wood

The third selected case study is the Horyuji temple complex in Japan (Fig. 28-33). The first buildings were erected around 616 AD but burnt down only 20 years later during a military conflict. When talking about Horyuji Temple today, the western temple district is meant (Fig. 28) (Lan, 2010). This is part of an entire city quarter that today consists of around 45 buildings that are all part of the temple. Many of them are today listed as national treasures of Japan (Encyclopaedia Britannica, 1998). The western temple district, built around the year 670 AD, consists of a pagoda and main hall, which form the heart of the temple. They are surrounded by an ambulatory, which was extended around 990 AD so that it also incorporated the reading hall, which burnt down around 925 AD, into the inner courtyard (Lan, 2010). As the temple consists of so many buildings, this paper will focus primarily on the pagoda (Fig. 30). At the time the temple was built, the pagodas were used to store the temple shrines and considered the most important part of the temple. Erwin Lan (2010) emphasises in his thesis on the Horyuji temple that the "five-storey pagoda (...) is one of the oldest wooden buildings in the world". For this reason, the temple and especially the pagoda are chosen as case study for this paper.

The supporting structure (Fig. 31) of the pagoda consists of a central trunk in the middle, which is encircled by two ranges of smaller supports. These each support the next storey and move further and further up towards the centre so that the pagoda attains its shape. In the case of the Horyuji pagoda it was long assumed that the central vertical beam carried most of the load and was anchored to the ground (Fig. 32). However, it was discovered it had rotted at the bottom and was now hovering a few centimetres above the ground. Investigations revealed that the assumption was exactly the opposite of the facts. All other supports etc. also bear the weight of the centre pillar. While the columns spreading out downwards take on the vertical load transfer, the continuous centre pillar is essential for absorbing horizontal forces such as wind loads or earthquake shaking. (Lan, 2010)

In Japan, moisture, acidic soil and termites are a major threat to the traditional building material wood. The architect Akihiro Yamamoto wrote in 2020 that there would be a fundamental difference between historical European masonry architecture and wooden buildings in Japan, since it'd be clear from the very beginning that there is a certain risk of decay, whereas European buildings could last for centuries. That is why it would be completely normal to replace damaged wooden parts. (Yamamoto, 2021) It goes without saying that the wood must be protected from moisture. This is mainly achieved by the large roof overhangs and by lifting the supports off the ground. Fig. 33 shows how the columns of the arcade of Horyuji Temple rest on stones to remain dry.

Mark Cartwright (2017) writes in an article about the temple complex that it "benefitted from major restoration works in 1374 AD, 1603 AD, and in the mid-20th century". The UNESCO World Heritage Convention website describes how the authenticity of the building is ensured by only replacing damaged wooden parts when absolutely necessary. The high safety standards are also described. In addition to the technical fire protection provided by fire alarms, hydrants etc., there is also a private fire department that is shared with another temple complex. (UNESCO World Heritage Centre, n.d.)

It is difficult to say what condition the original load-bearing wooden parts are in, because it is not known exactly whether and to what extent they have been replaced. The central pillar of the pagoda, for example, is original, and the tree was evidently chopped down around 594 AD (Horyuji Temple, n.d.). Therefore, it is an extremely old component. However, in this case it is rotten at the bottom as described and is held up by the rest of the supporting structure. Looking at pictures of the wood used as in Figure 33, it clearly looks old, as it is worn in the lower area of the columns and the door. Presumably this is simply the result of the many hands that have touched the wood over the centuries. The author's personal assumption is that most of the load-bearing components are the original ones.

It can be concluded that in addition to the brilliant construction method and the very durable wood used for the structure, the temple was able to become so old thanks to the constant maintenance by the users. This is also necessary, as wood is naturally much more vulnerable to damage from fire or water than concrete or masonry. However, of these three materials, it is probably also the easiest to repair or replace, as it is designed from the beginning in such a way that this is possible as Yamamoto explained.

3.2. Contemporary Case Study

In order to compare the three materials on a more technical level, the case study "Building Simply – research houses in Bad Aibling" (Fig. 34) is discussed in this chapter. The architecture professor Florian Nagler from the Technical University of Munich has built three almost identical houses right next to each other. However, one is made of cavity bricks, the second of solid timber and the third of lightweight concrete. None of the three houses has additional insulation so that the thickness of the components also differs depending on the materials U-value. (BDA Hamburg, n.d.) The case study was selected because it allows an extremely good comparison of the construction materials due to the same floor plans, openings, dimensions, etc. and everything was monitored in detail. The different values for GWP, thermal mass and U-value are compared below.

In a life cycle assessment (LCA), the three houses were compared in terms of their GWP per m² of floor space. Figure 35 shows that the lightweight concrete building has the highest GWP with a value of 4.00 $kgCO_2eq/m^2$. The masonry building follows closely behind with a value of 3.93 $kgCO_2eq/m^2$ and the solid timber building performs best with a value of 3.13 $kgCO_2eq/m^2$. It is important to note that all building components and not just the supporting structure are taken into account here. However, Figure 36 shows that only the external walls are responsible for the difference in values, which is not surprising as the rest of the houses is almost identical. (Jarmer et a., 2021) In terms of thermal mass, the concrete house comes out on top with 5600 Wh/K per room. In second place is the masonry house with 4400 Wh/K per room and in last place is the solid timber building with 3300 Wh/K per room (Franke et al., 2023). The values are not that far apart, which is due to the fact that all three buildings have reinforced concrete floor slabs, which was also essential for the solid timber house to increase its thermal mass. There are differences in the U-value of the single-skin exterior walls. At 0,22 W/m²K, the timber wall has the lowest heat transfer coefficient despite the fact that it has lowest component thickness. The second best performer is the masonry wall with 0,25 W/m²K, followed by the concrete wall with a significantly worse u-value of 0,35 W/m²K. (BDA Hamburg, n.d.)

It can be concluded that concrete and masonry differ only slightly in terms of GWP, while timber construction performs better. On the other hand, concrete construction excels in terms of thermal mass, followed by masonry and timber construction. Regarding the U-value timber is ahead, followed by brick masonry while concrete performs clearly the worst.

3.3. Environmental Performance of the Pantheons Structure

As a final step, a small "experiment" is carried out in this paper. Since the Pantheon, as already mentioned, serves the author as inspiration for the entire project and since concretes that are based on the Roman opus caementicium are increasingly becoming important due to their self-healing ability, the following attempts to determine what environmental performance the Pantheons structure of the Rotunda had or would have had over its lifetime, if carbon would have been monitored in the antiquity already. The production of opus caementicium at that time differed significantly from today's industrial production of concretes. Nevertheless, GWP values of today's concretes are assumed in this experiment. The Pantheon has the different aggregate mixtures shown in Figure 37. Based on the different mixtures, Masi et al. (2018) estimated the densities of the layers (Table 2). They vary between 2000 kg/m³ (foundations) and 1350 kg/m³ (upper dome). Thus, all concrete mixtures would fall into the category of lightweight concretes today. A 3D-model of the Rotunda was created to determine the different volumes of the individual concrete layers (Fig. 37). Subsequently, contemporary lightweight concretes that correspond to the densities of the different layers were identified using a table on solid building materials that shows both the mass and the GWP (Table 1.1) (IBO, n.d.). By multiplying the respective density with the respective volume of the concrete layer, the total weights per concrete mixture were determined. These were then multiplied by the GWP/mass of the material to obtain the total GWP of the different layers. The entire calculation can be seen in Table 2. Overall, the structure of the Pantheon would have a GWP of nearly 10 million kg or 10 thousand tons of CO_2eq assuming the used values.

As expected, the calculations conclude that the Pantheon would have an enormous embodied carbon footprint. To put this in relation to a contemporary building, an LCA made by Asif et al. (2007) of a regular contemporary residential building was compared with the Pantheon. Only the mass of the concrete structure and the dimensions of the building were used and the same calculations were carried out as with the Pantheon (Table 3). A service life of 75 years was assumed. To make the environmental performance comparable, the total GWP per year of service life [kg CO_2eq/year], per surface area [kg CO_2eq/m²] and per interior volume [kg CO_2eq/m³] were calculated for both buildings. As can be seen, the Pantheon performs worse in all disciplines. This is not surprising, as it is much larger and has a dome, which requires much more mass in the supporting structure than interior walls that support the ceilings as in the case study. As the Pantheon does not have several storeys but a storey height more than ten times as high as the reference project, the GWP/interior volume is more meaningful. If one calculates the environmental performance per volume and service life, the Pantheon is ahead.

Of course, all these calculations are rather hypothetical, as many assumptions were made and the Pantheon could probably be built much more efficiently today, etc. Nevertheless, the comparison shows well that even buildings that have an enormous embodied carbon footprint can negate this over a long lifetime. The author's thesis has therefore been confirmed by this experiment.

IV. CONCLUSION

To finally compare the three building materials, the case studies were entered into a matrix (Table 1, see next page). All three historical case studies are remarkably old and their structures are very durable. However, there are some differences. The Pantheon is the oldest building at almost 1900 years old. It is closely followed by the Aula Palatina, which is just over 1700 years old, and finally the Horyuji Temple, which is 1350 years old. At this point it is important to mention that all three buildings were able to become so old primarily due to their aesthetics and relevance, as they were worth preserving. The supporting structure of the Pantheon has experienced cracks in the concrete both during the construction process (foundation) and shortly after completion (dome). Those in the foundation were repaired by a second concrete ring and the cracks in the dome do not appear to have had a negative impact on the stability of the dome as they appear to have been there for so long. All in all, it can be concluded that the Pantheon's structure is in very good condition. With the Aula Palatina, it is not quite so easy to make this statement, as only half of the supporting structure still consists of the original Roman walls. However, the many changes and damage to the supporting structure over the centuries were mainly caused by human intervention, so it could be stated that significantly more of the original walls would still be standing if these had not taken place. The walls are definitely very resistant as they even survived a bombing raid. Despite this, or probably because of it, you can see many spots today where they have been patched up because changes in the size of the stones or mortar joints can be seen. The pagoda of Horyuji Temple is also surprisingly well preserved. The only known damage is the rotten central trunk. However, some of the buildings around the pagoda have burned down in fires. This shows the well-known vulnerability of wood to fire and moisture. In general, however, it is much more common in Japanese culture to accept the decay of individual wooden parts from the outset and to replace them. This of course makes it difficult to estimate how much of the original wood structure is still original. It is known that the temple has been significantly renovated three times in the last millennium. In addition, fire protection and authentic maintenance also play a major role today. I suspect that a large part of the wood is still original, but replacement certainly plays a greater role in timber construction than in the other two materials. Since the personal design task is to develop a load-bearing structure that is as durable as possible, the case studies suggest that concrete or masonry would be more suitable as they do not need to be protected as actively as wood. Above all, the self-healing properties of the ancient opus caementicium could benefit the design. Even the construction method without reinforcement could be inspired by the Romans in order to avoid corrosion at all costs.

The contemporary case study “Building Simply” offered very good insights as the houses were built specifically for comparison. In terms of GWP, concrete construction performs the worst and timber construction the best. There is only a small difference of less than 2% between concrete and masonry, so it is virtually non-existent. As expected, the thermal mass of concrete is the best, even though it is a lightweight concrete. In terms of U-value, wood is ahead. The thermal mass of the concrete would benefit the design project as a passive measure. The higher GWP is secondary due to the intended long service life. This was also shown in the last part of the paper with the environmental performance analysis of the Pantheon. Based on the previous analysis, it can be concluded that concrete would be best suited for the design project in terms of both durability and passive measures. A crucial point is the possibility of self-healing concretes to reduce the necessary maintenance to a minimum.

It must be emphasised that the calculation about the GWP of the Pantheon is hypothetical and intends to give a feeling for the subject matter. In general, the analysis of building materials in this paper is based more on the study and interpretation of historical case studies than on the comparison of technical material properties. This is also where the limits of the methods used lie, as there is certainly greater scope for individual interpretation than with a pure comparison of technical facts or tests. The research focuses primarily on the durability and history of the individual case studies, so the extent to which the results of this paper can be applied to other design tasks must be evaluated. A very interesting and relevant topic for design would be the applicability and durability of the new building materials based on opus caementicium. Further research could follow in this direction. In terms of existing research dealing with durability, I primarily found investigations of these concrete materials. However, the work was more on the scientific side, so that, for example, the chemical processes were described. There are also many analyses Roman long-lived architecture that establish a connection to opus caementicium.

	Concrete	**Masonry**	**Wood**
Historical Case Studies	**Pantheon**	**Aula Palatina**	**Horyuji Temple**
Age [years]	- built 128 AD - 1896 years old	- built 312 AD - 1712 years old	- built 670 - 1354 years old
History (changes, destruction, repair, replacement on structure)	- crack in foundation (during construction) - damages and replacements in brick envelope of opus latericium - cracks in dome (probably soon after construction, so almost as old as the building itself) - small manmade passage trough load-bearing wall - potentially self-healing because of the lime clasts in the cementitious matrix	- destroyed by Germanics but structure remained - conversion into fortress - demolition of east and south wall in Renaissance - bomb attack in WWII but the structure survived with smaller damages - repairs over the centuries resolve in patchwork as some bricks and mortar joint have definitely been replaced	- complex partly burned down multiple times (vulnarability against fire) -> high fire protection standards - central trunk of pagoda is rotten (vulnarability against moisture) - the replacement of damaged wooden parts is completely natural and planned from the initial stage -> replacement more often but also very easily doable - major restoration works in 1374 AD, 1603 AD, and in the mid-20th century
Condition of Structure	- despite the cracks the structure is in very good condition	- todays structure is in good condition but only due to constant repair - although most damages were manmade so probably the structure would not have needed the repairs - „reconstruction of a reconstruction of a reconstruction“ - 2 of the 4 walls remain the roman original as well as some plaster	- the structure of the pagoda is despite the rotten central trunk in good condition although it is hard to say to which extent the wood has been replaced in the past - assumption that most of the wood is original
Contemporaly Case Study	**Building simply concrete house**	**Building simply masonry house**	**Building simply solid timber house**
GWP/surface area [kg CO^2eq/m^2]	4,00	3,93	3,13
Thermal Mass [Wh/K per room]	5600	4400	3300
U-Value [W/m^{2}K]	0,35	0,25	0,22

Table 1
Final Comparison

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VI. APPENDIX

6.1. Identification of building elements with the largest GWP

In 2018, a residential building complex in the UK was investigated regarding the embodied carbon distribution (Fig. 5) and compared to an earlier case study (Fig. 4). The authors used the division into frame, substructure, external walls, upper floors, finishes, roof and internal walls. These categories are based on the RICS definition of building components. (RICS, 2012) A brief definition is to be found in Table 5. It is important to mention that in Case Study 1 and 2 not 100% of all components could be considered because data was not available or could not be determined. Especially the building services (sanitary-, electrical-, ventilation-, disposal installations etc.) are excluded.

Case Study 1 from 2015 examined an office building. The three largest CO_2 emitters were the categories frame, substructure and upper floors. They accounted for 80% of the total embodied carbon. Case Study 2 of an apartment building looks slightly different. Here, the external walls are added as a carbon hotspot. Frame, substructure, external walls and upper floors contribute to 83% of the EC. (Fernando et al., 2018) The difference in the external walls in both studies can be explained by the fact that Case Study 1 has a curtain wall, while the external walls in Case Study 2 are load bearing. The authors M. Victoria and S. Perera conducted a third study in 2018, based on the initial one in 2015 (Fig. 6). For this, they analysed the EC in 41 office buildings. The number of different buildings makes the study much more representative for office buildings in general. In addition, more data was collected regarding the services. The result is astonishing: the CO_2 emitters from high too low are as follows: substructure, services, frame, upper floors, external walls, finishes, roof, 'rest' (External Windows and Doors, Stairs, Internal Doors, Fittings and Furnishings), internal walls. (Victoria & Perera, 2018)

This means that services play a much greater role than initially assumed. In the first study, the authors already pointed out the wide range of shares in the services category in various studies, ranging from 1-25%. This is mainly due to the fluctuating availability of data. (Victoria et al., 2015) In addition, the authors refer to another study that shows that the services category has an even larger carbon footprint when calculated based on the whole service time of a building. In the case of an office building in Canada, after a lifetime of 50 years, the recurring EC of the services due to maintenance etc. was almost as large as the initial EC. (Cole et al., 1996)

The studies show very well which component categories often have a high EC. Nevertheless, the distribution is of course different from case to case and varies greatly. It is striking that the categories that consist almost exclusively of the load-bearing structure (frame, substructure, upper floors) play a very large role with 49% (Fig. 6). External walls and roofs, which at least partially include structure, are responsible for another 15% EC. The largest part that does not contain any structure is, as mentioned, the services, which are also a large factor in the recurring EC. The biggest potential to save EC in either way lies in these categories.

Global CO² Emissions by Sector

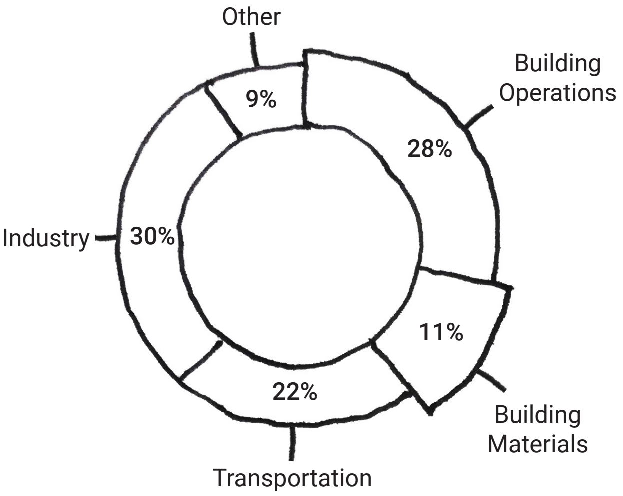


Fig. 1
Emmisions by Sector

Source: (UNEP+IEA, 2017)

Fig. 2
Material Pyramid

Source: https://www.materialepyramiden.dk/

Relation of Lifespan and EC footprint

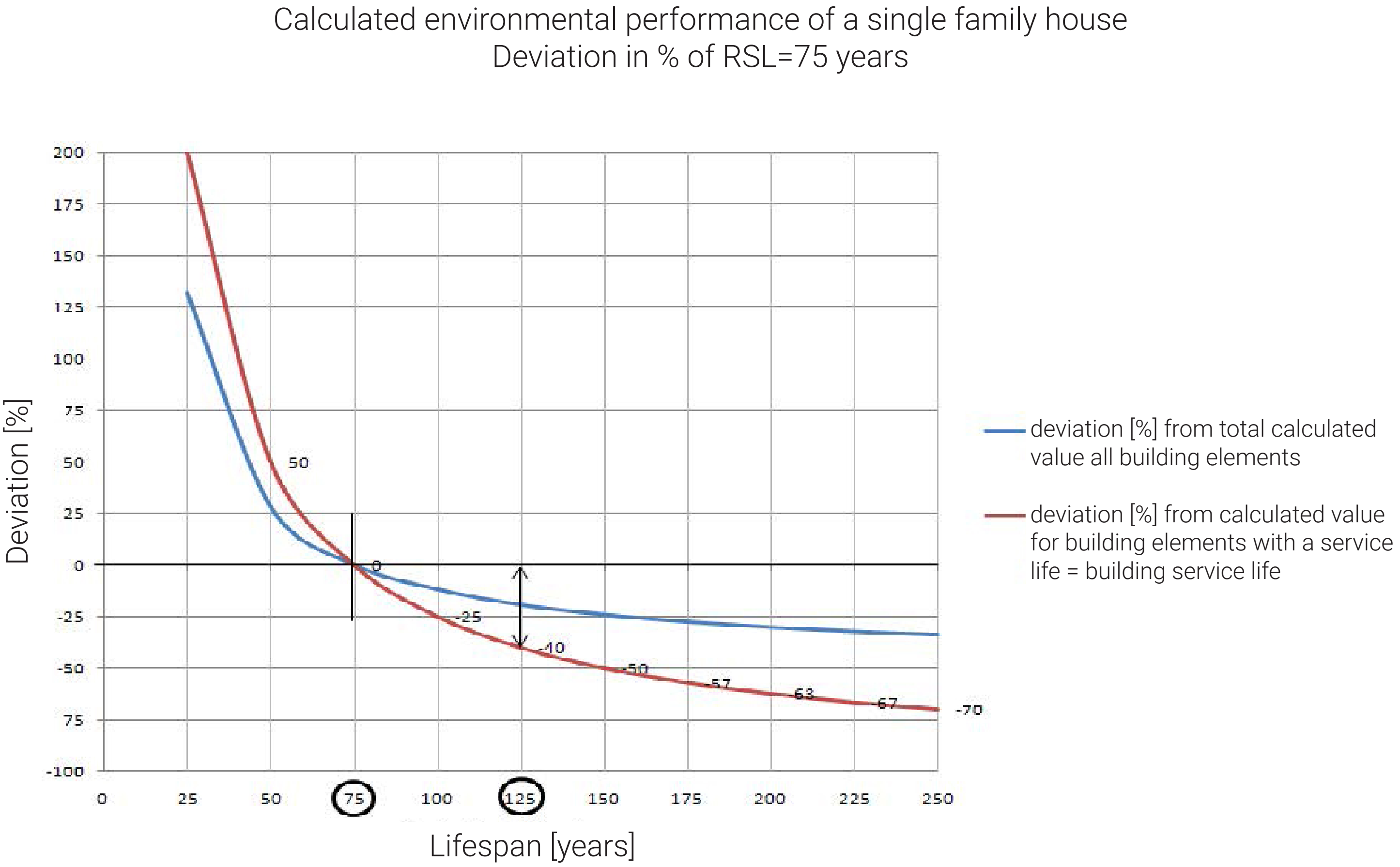


Fig. 3
Environmental Performance over Time

Source: (Mooiman & Van Nunen, 2012).

Embodied Carbon (EC) per Building Element

Case Study 1 - Office Building

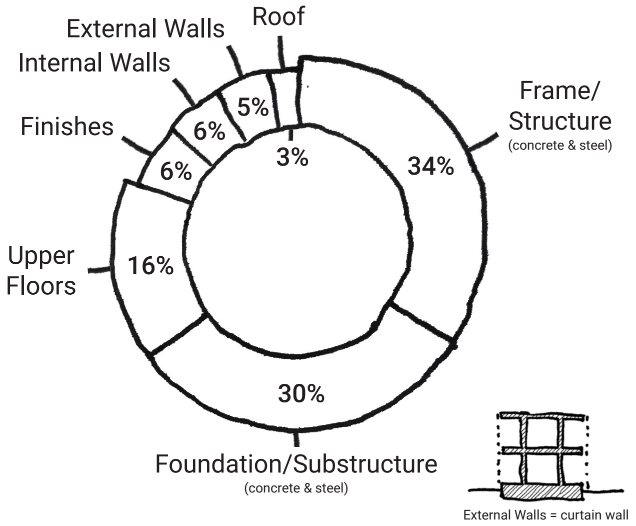


Fig. 4
Case Study Office Building
Source: (Fernando et al., 2018)

Case Study 2 - Apartment Building

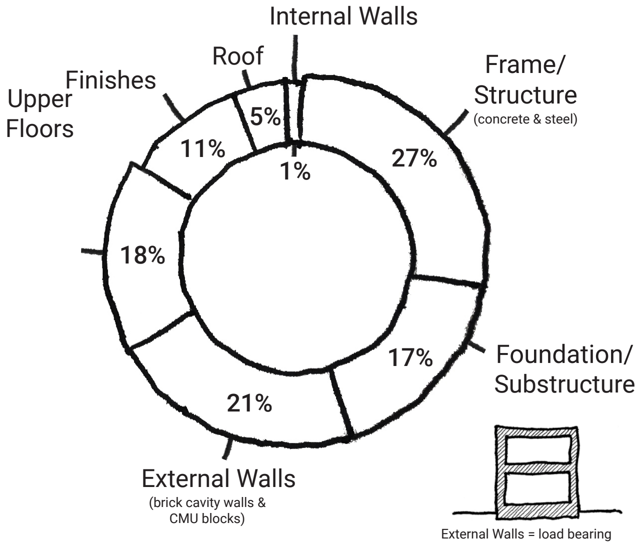


Fig. 5
Case Study Apartment Building
Source: (Fernando et al., 2018)

Case Study 3 - 41 Office Buildings

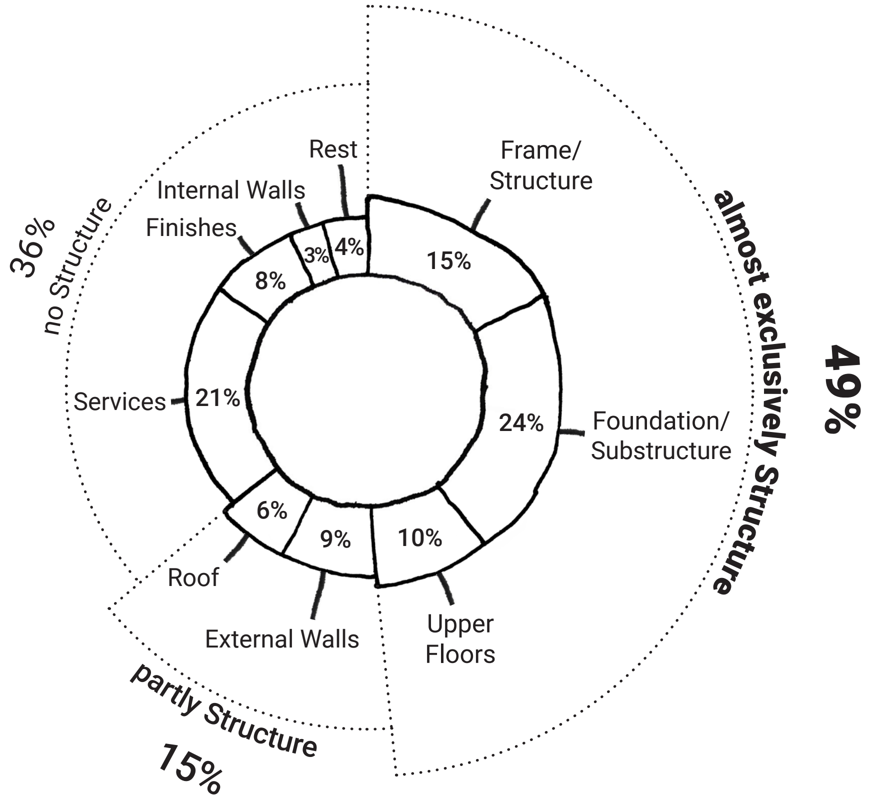


Fig. 6
Case Study Office Buildings
Source: (Victoria et al., 2018)

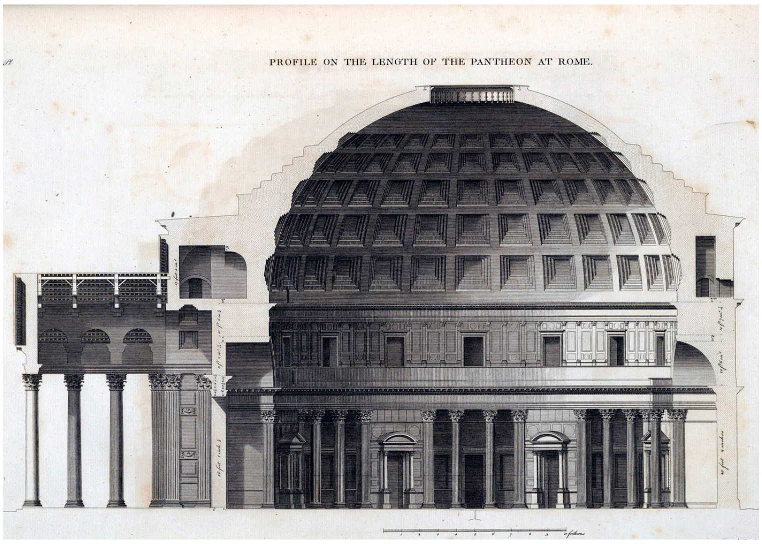


Fig. 7
Pantheon Section

Source: https://driskulin.github.io/posts/pantheon-section-drawing/

Fig. 8
Pantheon, Rome, Italy

Source: https://blog.ansharphoto.com/city/pantheon-in-the-morning-rome/

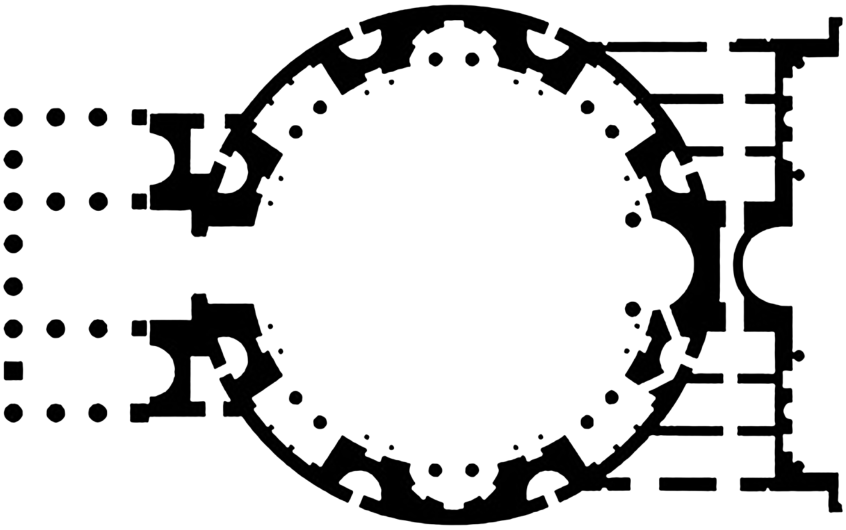


Fig. 9
Pantheon Floor Plan

Source: https://www.pinterest.de/pin/362891682469263717/

Fig. 10
Pantheon Dome

Source: https://monolithicdome.com/pantheon-a-temple-to-all-gods

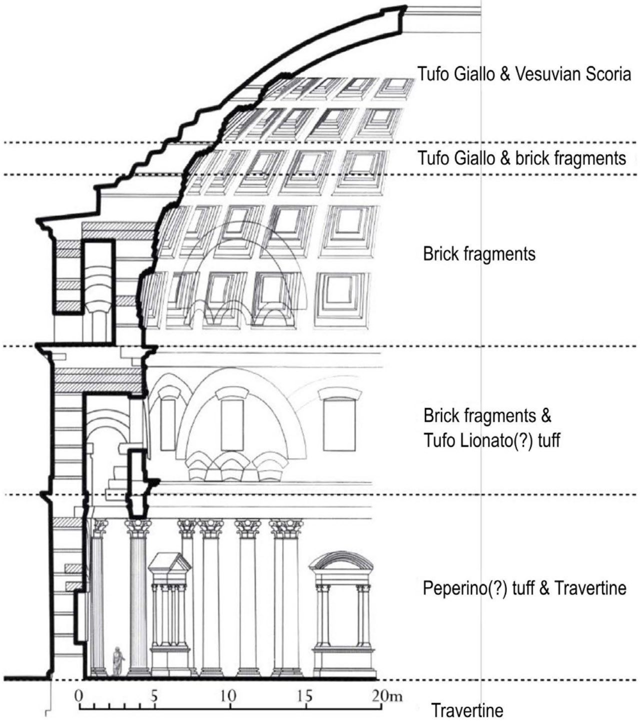


Fig. 11
Pantheon Concrete Aggregates

Source: (Lancaster, 2005)

Fig. 12
Pantheon external Wall *Source: Google Streetview*

Fig. 13
Pantheon external Wall Zoom *Source: Google Streetview*

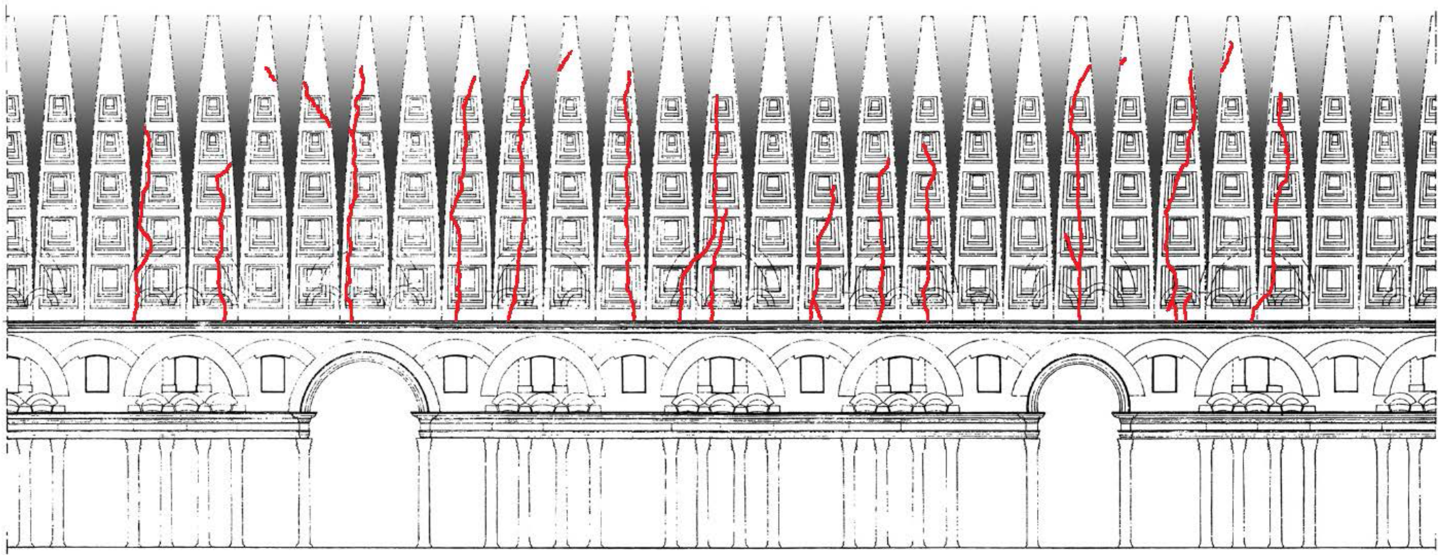


Fig. 14
Display of Cracks in Pantheons Dome *Source: (Masi et al., 2018)*

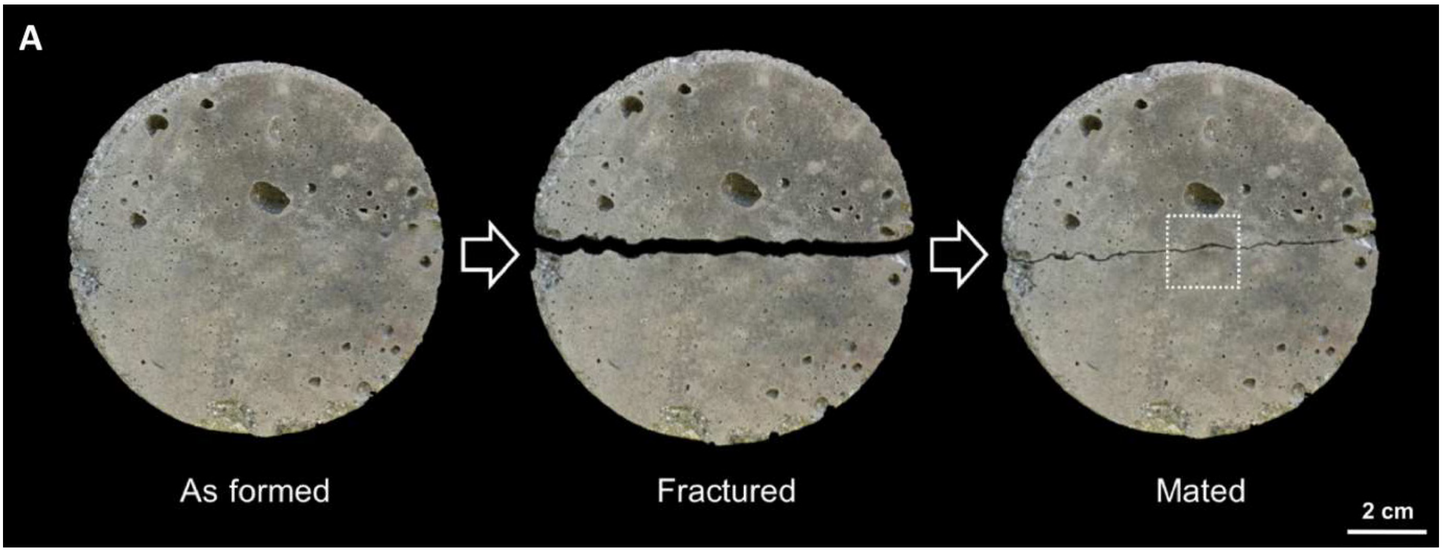


Fig. 15
Self-healing Concrete *Source: (Maragh et al., 2023)*

Fig. 16
Aula Palatina, Trier, Germany

Source: https://en.wikipedia.org/wiki/Aula_Palatina#

Fig. 17
Aula Palatina Interior

Source: https://trier.ekir.de/inhalt/konstantin-basilika-kirche-zum-erloeser/

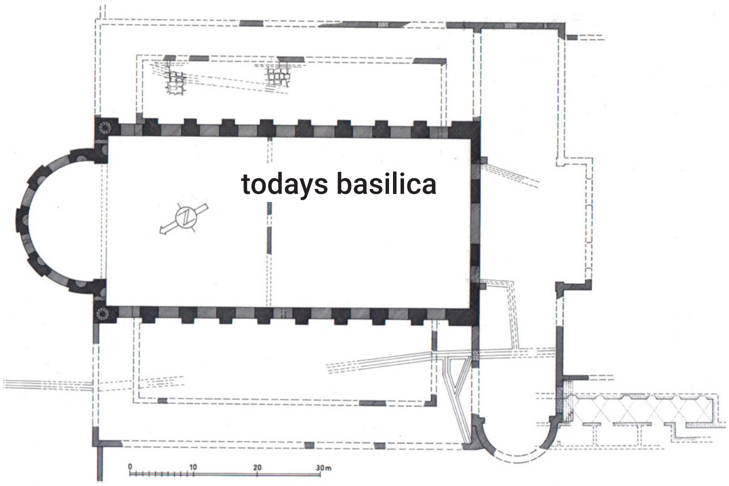


Fig. 18
Floor Plan of ancient Complex

Source: https://www.trierer-original.de/Uns-Trier/spektakulaere-Bauwerke/Konstantinbasilika-51628.html

Fig. 19
Roman Times

Source: https://trier.ekir.de/inhalt/konstantin-basilika/

Fig. 20
Middle Ages

Source: https://trier.ekir.de/inhalt/konstantin-basilika/

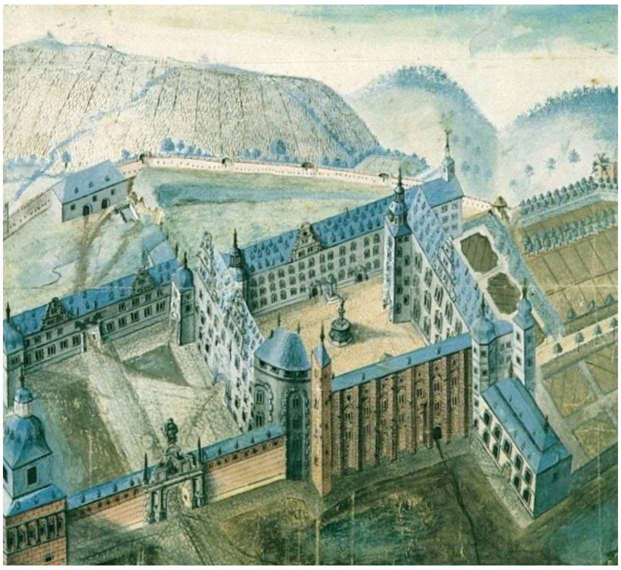


Fig. 21
Renaissance

Source: https://trier.ekir.de/inhalt/konstantin-basilika/

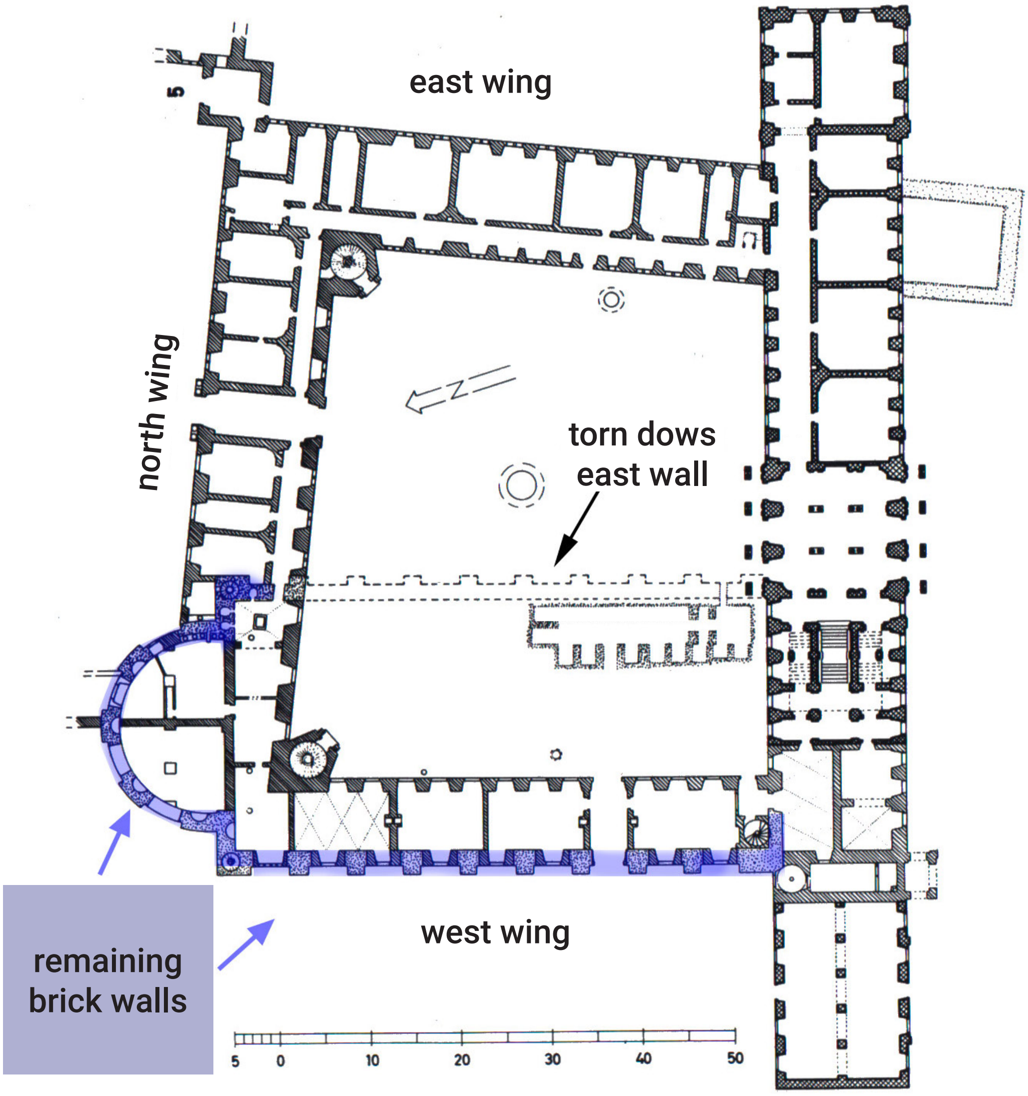


Fig. 22
Remaining Walls

Source: https://trier.ekir.de/inhalt/konstantin-basilika/

Fig. 23
Destruction by the Bomb Raid

Source: https://www.wochenspiegellive.de/stadt-trier/artikel/75-jahre-kriegsende-mehrere-veranstaltungen-in-trier

Fig. 24
Destruction by the Bomb Raid

Source: https://trier.ekir.de/inhalt/konstantin-basilika/

Fig. 25
West Wall today

Source: https://www.youtube.com/watch?v=HJ6SDufa7ow

Fig. 26
External Wall - highlighted Repairs

Source: https://www.youtube.com/watch?v=HJ6SDufa7ow

Fig. 27
Apse - highlighted Repairs

Source: https://www.youtube.com/watch?v=HJ6SDufa7ow

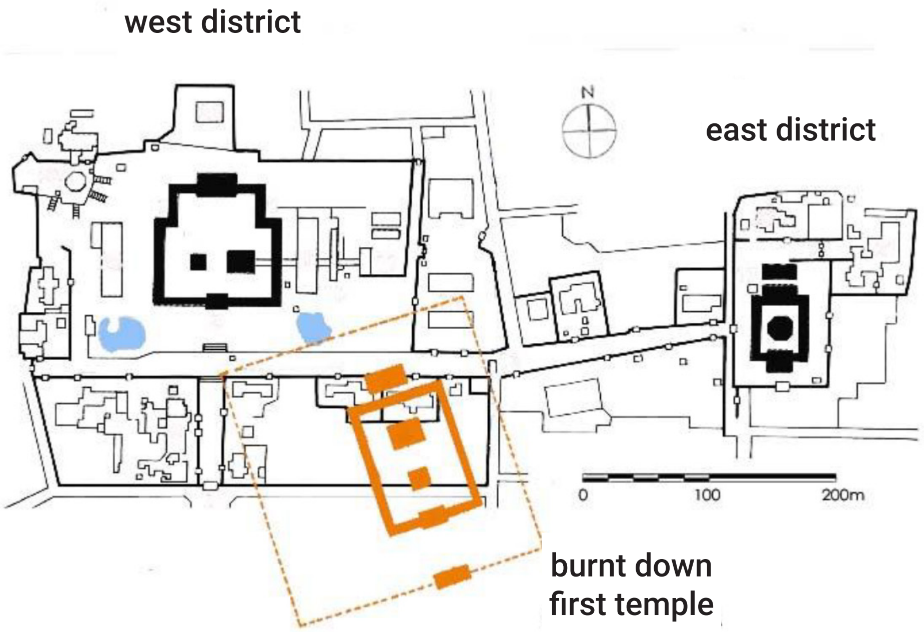


Fig. 28
Horyuji Temple Overview

Source: (Lan, 2010)

Fig. 29
Horyuji Temple, Ikaruga, Japan

Source: https://www.pinterest.de/pin/106397609934241478/

Fig. 30
Pagoda

Source: https://de.wikipedia.org/ wiki/H%C5%8Dry%C5%AB-ji

Fig. 31
Pagoda Structure

Source: (Lan, 2010)

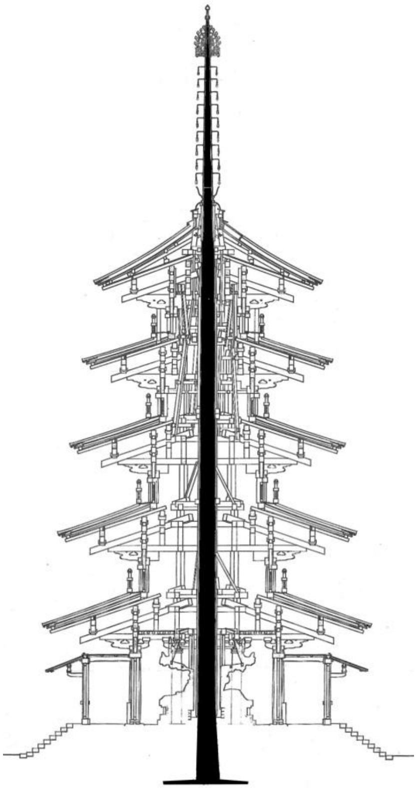


Fig. 32
Wrong Assumption of Trunk

Source: (Lan, 2010)

Fig. 33
Acarde

Source: https://www.gltjp. com/en/article/item/11254/

Fig. 34
Buidling Simply Houses

Source: https://www.baunetzwissen.de/beton/objekte/wohnen-mfh/forschungshaeuser-in-bad-aibling-7597304

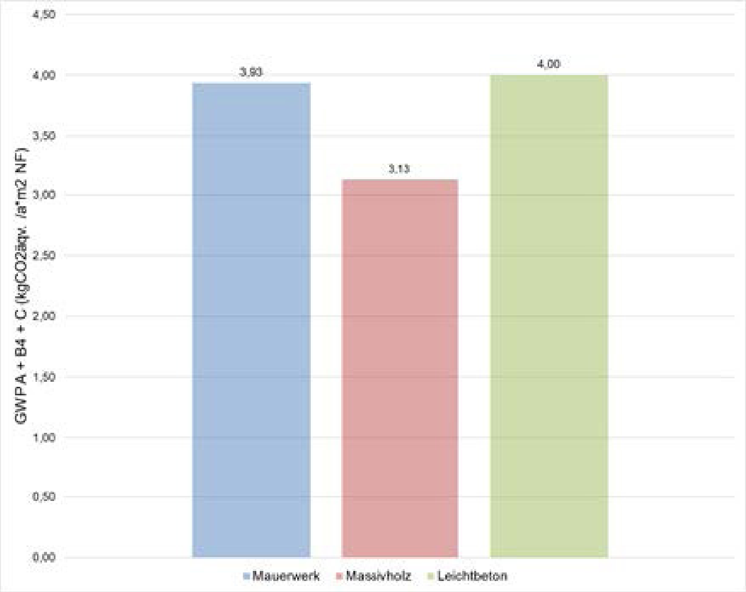


Fig. 35
total GWP/m²

Source: (Jarmer et a., 2021)

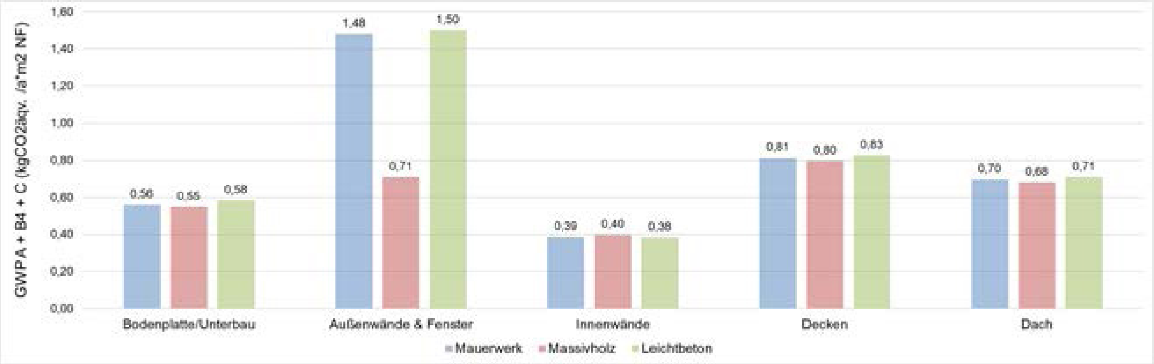


Fig. 36
Single Component GWP/m²

Source: (Jarmer et a., 2021)

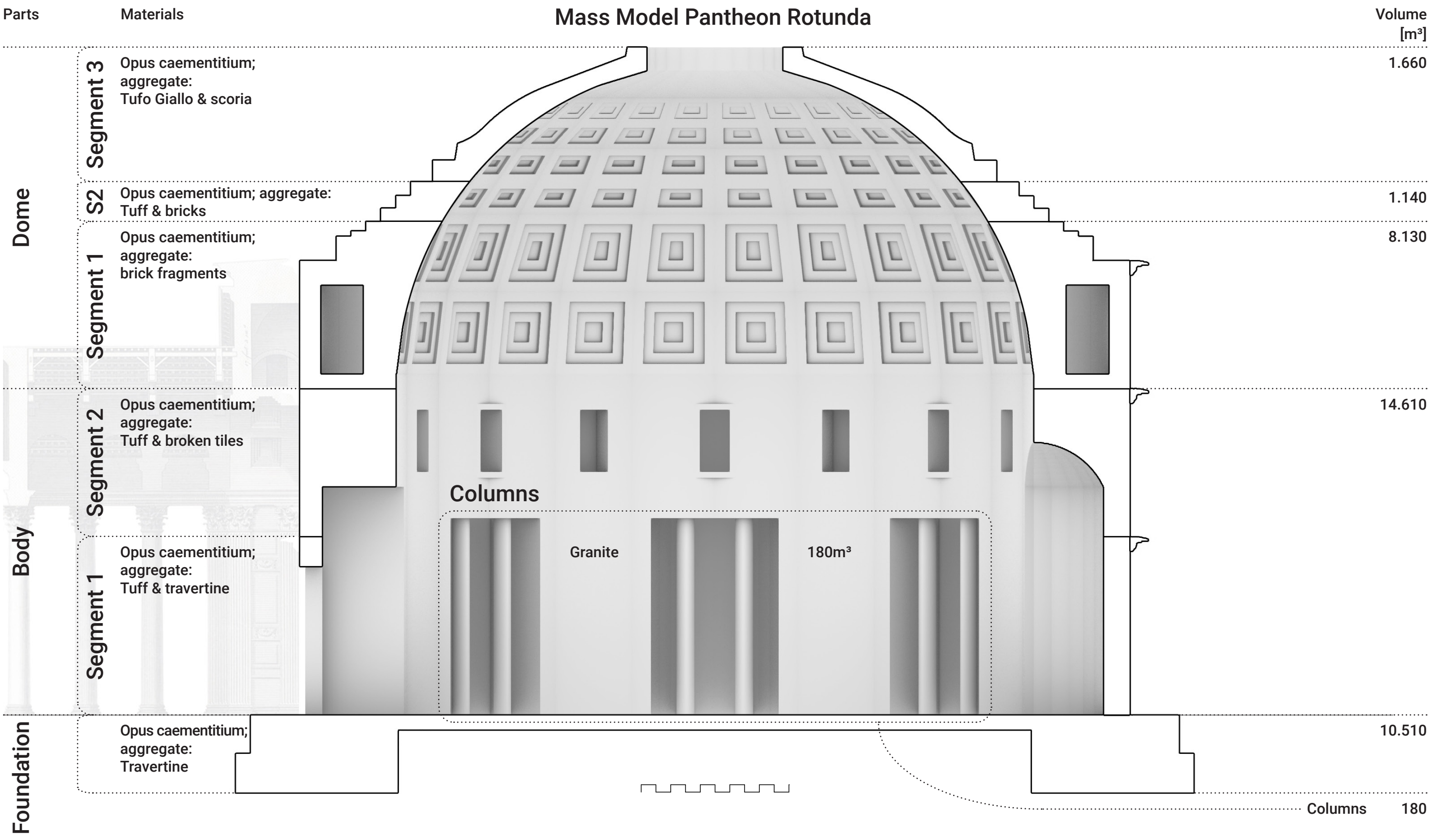
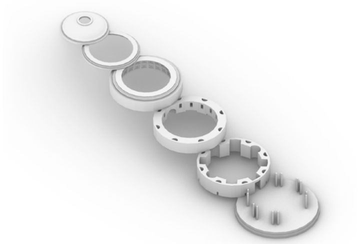
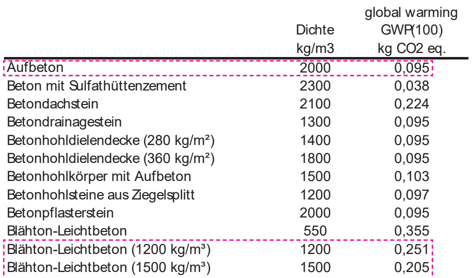


Fig. 37
3D-Model Pantheon



(Masi et al., 2018)

Table 1.1
Lightweight Concretes



	Dichte kg/m3	global warming GWP(100) kg CO2 eq.
Aufbeton	2000	0,095
Beton mit Sulfathüttenzement	2300	0,038
Betondachstein	2100	0,224
Betondrainagestein	1300	0,095
Betonhohldielendecke (280 kg/m²)	1400	0,095
Betonhohldielendecke (360 kg/m²)	1800	0,095
Betonhohlkörper mit Aufbeton	1500	0,103
Betonhohlsteine aus Ziegelsplitt	1200	0,097
Betonpflasterstein	2000	0,095
Blähton-Leichtbeton	550	0,355
Blähton-Leichtbeton (1200 kg/m³)	1200	0,251
Blähton-Leichtbeton (1500 kg/m³)	1500	0,205
Blähton-Leichtbeton (1700 kg/m³)	1700	0,170

Source: (IBO, n.d.)

Material	Part	Density ρ [kg/m^3]	Volume [m^3]	total Mass [kg]	assumed Material	GWP/mass [kg CO$_2$eq/kg]	total GWP [kg CO$_2$eq]
Granite	Columns	2500	180	450.000	Granite	estimated 0,020	9.000
Concrete 1	Foundations	2000	10.510	21.020.000	concrete (2000 kg/m^3)	0,095	1.996.900
Concrete 2	Cylindrical wall	1750	14.610	25.567.500	Expanded clay lightweight concrete (1700 kg/m^3)	0,170	4.346.475
Concrete 3	Lower dome	1600	8.130	13.008.000	Expanded clay lightweight concrete (1500 kg/m^3)	0,205	2.666.640
Concrete 4	Intermediate dome	1500	1.140	1.710.000	Expanded clay lightweight concrete (1500 kg/m^3)	0,205	350.550
Concrete 5	Upper dome	1350	1.660	2.241.000	Expanded clay lightweight concrete (1200 kg/m^3)	0,251	562.491
							9.932.056 total kg CO$_2$eq

Table 2
GWP Calculation Pantheon

Material	[-]	Pantheon diff. Concretes	Reference norm. Concrete
Mass of structure	[kg]	63.996.599	130.800
Service life (so far)	[years]	1.896	75
Surface area	[m^2]	1.745	(2 floors) 140
Volume	[m^3]	63.560	560
GWP total	[kg CO$_2$eq]	9.932.056	12.426
GWP/year	[kg CO$_2$eq/year]	5.240	165
GWP/surface area	[kg CO$_2$eq/m^2]	5690	89
GWP/volume	[kg CO$_2$eq/m^3]	156	22
GWP/volume/year	[kg CO$_2$eq/m^3/year]	0,082	0,3

Table 3
Comparison with Case Study

Type of obsolescence	**Reason**
Physical	- Unexpected defects in the building due to the method of construction or materials used so that repair or replacement is not economic - Catastrophic failure due to an external event, such as an earthquake or tsunami, requiring major works that may not be economic - Spare parts, materials, or craftsmen becoming unavailable before planned scrappage so that repairs and maintenance are impossible or uneconomic
Environmental or sustainable	- Acceptable emission levels cannot be met economically - Hazardous components incorporated in construction, e.g. asbestos, which may not be economical to be dealt with - Tenant corporate responsibility expectations cannot be met in a financially tenable manner - Environmental impact does not match up to alternative accommodation

Table 4
Types of Obsolencense + Reasons

Source: (Grover & Grover, 2015)

Building component	**Definition**
Frame	To provide a full or partial system of structural support, where this is not provided by other Elements. = part of structure
Substructure	To transfer the load of the building to the ground and to isolate it horizontally from the ground. = foundation + ground insulation layer
External Walls	To provide the vertical component of the external enclosing envelope in conjunction with Windows and External Doors. = external wall construction layers including structure, insulation and outer shell
Upper Floors	To provide floor space on upper levels (i.e. above the lowest floor level). = structural floor slabs, balconies etc.
Roof	To provide the horizontal component of the external enclosing envelope. = all roof elements including roof structure
Internal Walls	To divide the floor space.
Finishes	Wall-, floor- or ceiling finishes

Table 5
Definition of Terms

Source: (RICS, 2012)