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Reducing the environmental impact of buildings through stone masonry structures

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Abstract

Slabs represent the largest part of building structures environmental burden. Optimising shape and using less carbon intensive materials are significant levers to improve the environmental performance when designing a structure. For this purpose, the study focuses on stone masonry structures. Three structure typologies are considered: Abeille vault, groin vault and post-stressed stone beams. While groin vault shape allows for an effective use of material, prestressed stone beams and Abeille vault present flat surfaces close to contemporary slab typologies. Every structural system is studied considering a 6m by 6m grid and three different alternatives for each typology. Design is carried out using limit analysis for groin and Abeille vaults. Post-stressed stone beams are designed similarly to prestressed concrete considering the material specificities. Life cycle assessment is applied in a cradle to grave approach including construction processes. Uncertainties are estimated using Monte-Carlo simulations. Masonry systems are finally compared to concrete, steel and wood building structure systems. Results show that masonry structures emit less greenhouse gases than concrete and steel typologies and are comparable to wood structures. The study also highlights the importance of considering other environmental indicators since a low carbon system may lead to increased damages to ecosystems and human health.

Keywords: life cycle assessment, masonry, stone, multicriteria, vault, uncertainty

Figure 1: Abeille vault by AAU in Jerusalem © Mikaela Burstow ; post-stressed stone system by the Stone masonry company in London, retrieved from [1] ; groin vault in Santa Maria dei Carmini, Venice CC BY-SA 4.0 Didier Descouens

1. Introduction

Reducing greenhouse gases (GHG) emissions of buildings is a major concern for the sector as it represents 38% of worldwide emissions (Global Alliance for building and Construction 2020 [2]). Two types of emissions are distinguished: operational emissions related to the use of the building and its energy consumption (for heating, cooling, equipment operation...) ; and embodied emissions, linked to the construction materials. As energy performances of new buildings increase, the share of embodied emissions in the building whole GHG balance increases too (Blengini and Di Carlo 2010 [3] ; Ferreira et al. 2023 [4] ; Karimpour et al. 2014 [5]).

Building structure represents a large part of the embodied emissions because of the material quantities involved and the use of carbon intensive materials such as concrete and steel (Kaethner and Burridge 2012 [6]). A building structure is composed of different elements: slabs, columns, walls and beams. Of all those structural elements, many studies point out that slab systems have the greatest impact (Hart et al. 2021 [7] ; Navaro Auburtin et al. 2023 [8] ; De Wolf et al. 2016 [9]).

Greenhouse gases emissions are not the only damage building structure can do to the environment. Production of materials emits different types of pollutants depending on the material and manufacturing process. For instance, the use of polyurethane adhesive in timber can have an impact on marine eutrophication. Without considering the direct destruction of an ecosystem due to a new building, structures have an impact on biodiversity since they require the exploitation of resources and emit pollutants, mostly indirectly. As many scientific reports inform of the urgency of the situation (IPBES 2019 [10]), it is time for designers to take those damages into account.

Compared to concrete and steel, stone material consume less energy for its manufacturing. It is then seen as a potential low carbon material (Ioannidou et al. 2014 [11]). Due to its mechanical characteristics, stone needs special systems to be erected and stand. Historically, horizontal structural systems in stone are vaults such as in religious buildings, cellars, or monumental administrative buildings (Choisy 1883 [12]). However, with technological advances, other typologies and geometries emerge, such as post-stressed stone structures.

1.1. Literature

Various solutions exist to reduce the environmental impact of structures (Fang et al. 2023 [13]). They focus on different aspects: material choice, efficiency (Jayasinghe et al. 2021 [14]), and reuse (Brütting et al 2021 [15]). This article examines stone as a low carbon solution for slab, setting the focus on material choice and efficiency. Due to its characteristics, stone can be used in efficient structural configurations in order to design durable structures. Calculation methods for masonry structures are also getting more accurate (Parent et al. 2023 [16]), allowing to design more optimised stone structures. This article studies three of them: Abeille vault, post-stressed stone and groin vault, illustrated in Figure 1.

Abeille vaults are a well studied structural system (Brocato and Mondardini 2015 [17]). Conceived in 1699, it presents a mixed behaviour as it functions as a vault and as nexorade. It is based on a module which is repeated along both axis. Such vault has already been erected for instance in Jerusalem by the studio AAU. Recently, the number of studies on post-stressed stone has drastically increased (Boote and Lynes 2020 [18] ; Bagnéris et al. 2019 [19]). Similarly to concrete, stone is weak in tension and strong in compression. Following the same principles as prestressed concrete, post-stressed stone can reduce material quantities required for the system.

Life cycle assessment (LCA) of stone has been conducted in different works to understand the environmental performances of such system (Pestre 2021 [20] ; Bianco et al. 2019 [21]). These global studies develop life cycle models and inventories. Further studies compare stone solution for façade with concrete or wood solutions (Toldi and Pestre 2023 [22] ; Ioannidou et al. 2014 [11]). They show the influence of transport on GHG emissions of a stone product. Most LCA studies focus on GHG emissions (Hart et al. 2021 [7] ; Saade et al. 2020 [23] ; Kaethner and Burridge 2012[6]), missing the other environmental impacts of structure.

1.2. Overview

This article aims to show the potential of stone spatial structures for low environmental impact buildings, as well as providing a rigorous method to conduct LCA of structures. For this purpose, it proposes an approach combining parametric design of stone structures with LCA, including uncertainties on the environmental data.

First, the methodology is described. Then results on the parametric stone structures are given. Finally, the results are compared to more typical slab solutions in steel, wood and concrete considering a multi-criteria analysis.

2. Methodology

The methodology combines structural parametric design (Figure 2) of stone structures with LCA.

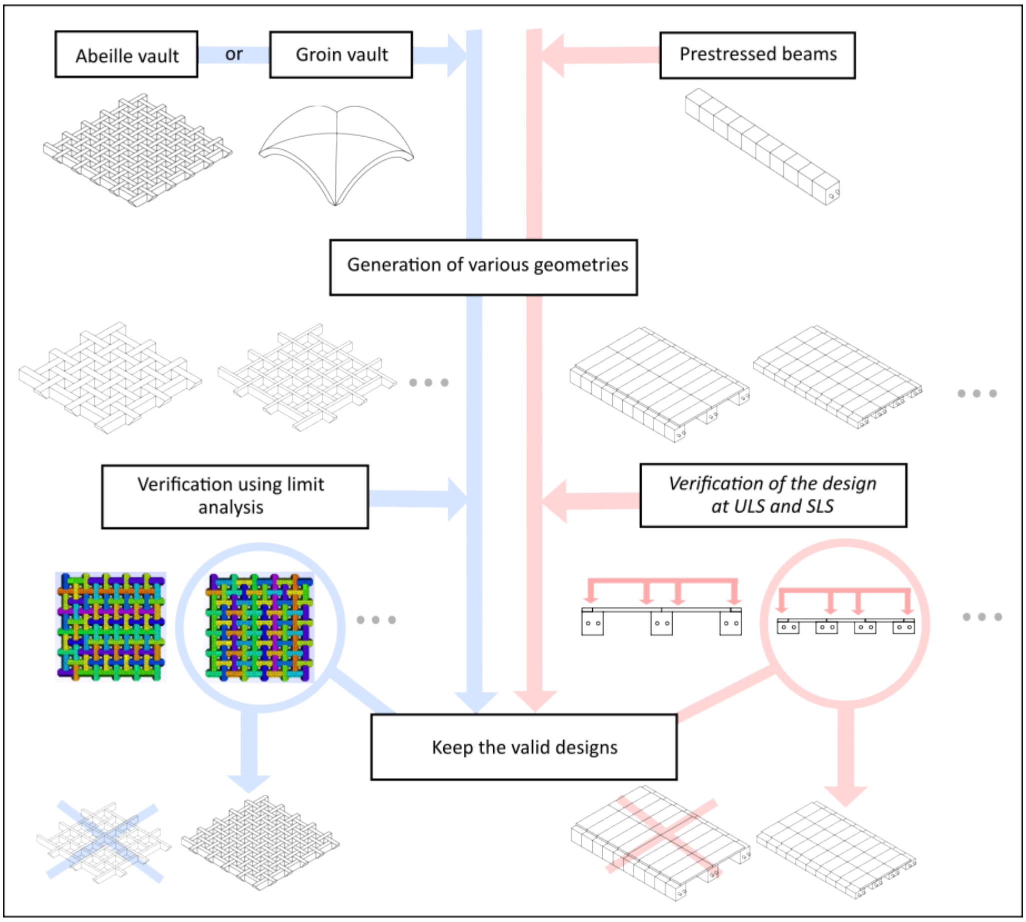

Figure 2: Stone structures calculation methods.

2.1. Parametric design of stone structure

Three typologies of stone structures are selected: Abeille vault, groin vault and post-stressed beams. Each typology represents a different spatial structure. Groin vaults are an historic way to do horizontal structures. Abeille vaults are relevant for floor systems as they are flat. Finally, post-stressed beams represent a more recent approach to the material taking advantages of technological progress as well as using the advantages of the stone material. Each typology is calculated for a grid of 6 meters by 6 meters. For each typology, different structures are considered by geometrical variations using the design parameters. Because of the stone quarry or the project constraints, an optimal design cannot always be chosen. Having different options in the same typology allows to cover for such issues. As each system has a different structural behaviour, calculation methods vary from typology to typology. A synthesis is presented in Figure 2. The detailed methods are presented in the following subsections.

Different structural performance can be achieved depending on the stone characteristics. This study focuses on Valanges stone, which is a limestone found in Bourgogne (France) with a compressive strength of 73 MPa and a bending strength of 6 MPa.

2.1.1. Post-stressed stone structure

Post-stressed stone systems are composed of three elements: unreinforced floor stone block, with span on p distance ranging from 0.5 to 1.5 meters. The blocks are fixed using steel dowels to the main beams that are parallel to the longest side of the grid. Two border beams are connected to the principal beams and redirect the forces from the principal interior beams to the columns. A thin mortar joint (5mm) is placed between each stone elements. The three selected geometries are shown in Figure 3 and named PS05, PS1, PS15.

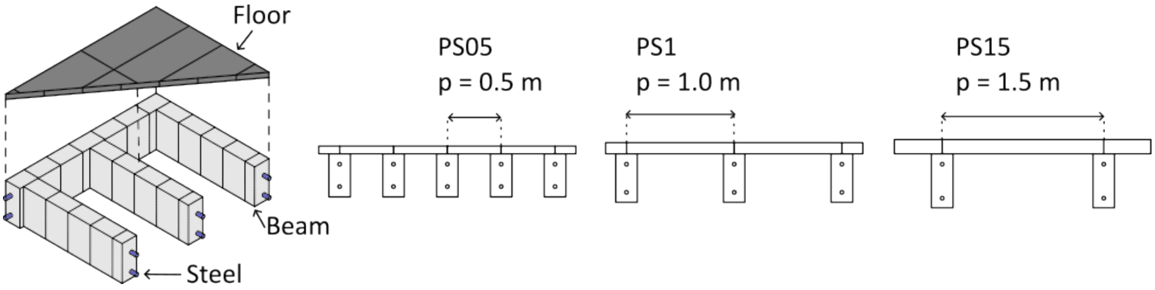

Figure 3: post-stressed stone typology elements ; parametric structures chosen with side view

Calculation of the floor blocks have been handled following Eurocode 6 (AFNOR 2006 [24]) considering compression and tensile strength. For the post-stressed beams, stone characteristics and resistances have been considered following AFNOR 2006 [24]. The calculation of post-stressed stone elements have been made with a similar method as for prestressed concrete in BPEL 1999 [25].

First the floor blocks are calculated. It provides the dead loads to the principal beams which can then be designed. Finally, the border beams are designed taking into account the dead loads of the other elements.

2.1.2. Abeille vault

The structural system is composed of unreinforced floor stone elements which serves the acoustic purposes as well as a resulting flat surface on top of the vault. The Abeille vault stands on four post-stressed stone beams for each side of the grid considered. For Abeille vaults, changing the base module leads to a different overall vaults geometries. This allows to generate different floor solutions for one typology. The three selected geometries are shown in Figure 4 and named AV1, AV2 and AV3.

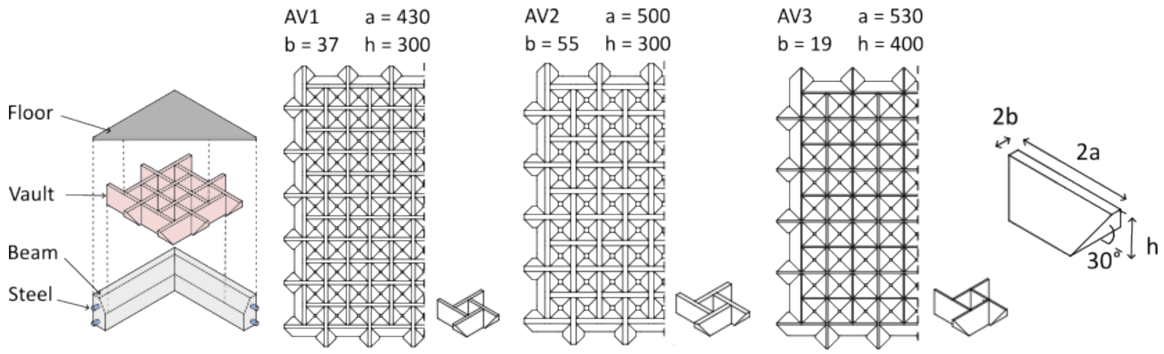

Figure 4: Abeille vault typology elements ; parametric structures chosen with top view of half the structure and axonometry of 4 modules

For both groin and Abeille vaults, the mechanical verification are conducted using limit analysis with the fenics software (Bleyer and Hassen 2021 [26]) along with fenics_optim (Bleyer 2022 [27]). This methodology is efficient to calculate the ultimate load of a structure. This verification has the advantage of a reduced calculation time. Results for the AV2 structure are presented in Figure 5. This resulted in a cracking pattern following the diagonals. It is similar to plates structure and consistent with the bending behaviour described by Brocato and Mondardini 2015 [17].

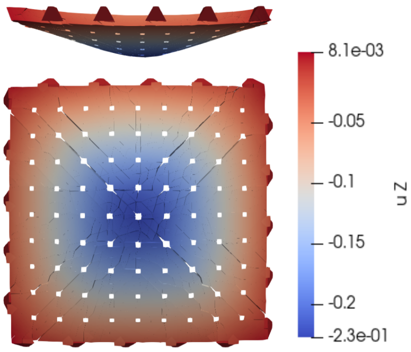

Figure 5: Failure mode of the Abeille vault AV2 ; side view ; view from the downward ; uz is the vertical displacement

2.1.3. Groin vault

Groin vaults are composed of two main elements: stone blocks to make the vault, and steel bars to take the horizontal loads from the vault. Thin mortar joints are considered between each stone block. The height of the vault h and the thickness on top of the vault $h - f$ are the parameters considered. The three selected geometries are shown in Figure 6 and named GV1, GV2 and GV3.

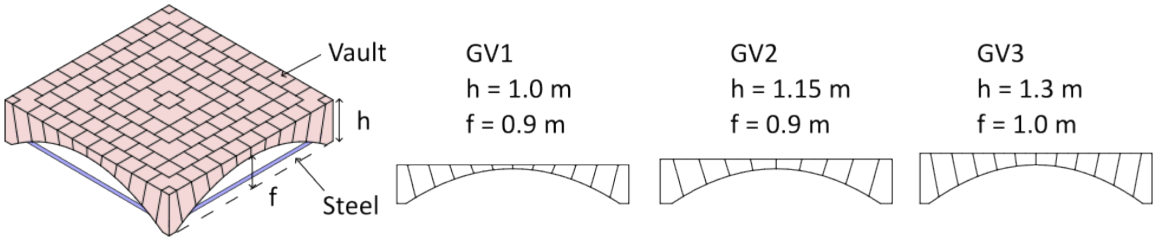

Figure 6: Groin vault typology elements ; parametric structures chosen with side view

2.2. Life Cycle Assessment

LCA of structures is applied in compliance with the ISO 14040-14044 standards 2006 [28]. LCA allows to quantify the environmental impacts of a system over its whole life cycle, from extraction of the primary resources to its disposal or reuse. According to EN15804, the life cycle is decomposed in four modules: production and construction stages (A), usage phase (B), end of life (C), benefits and loads beyond the system boundaries (D).

In this study, D module is excluded, the LCA is carried on A to C modules. To carry out a LCA, four phases must be followed. First phase is the definition on the functional unit and system boundaries. In this study the functional unit is defined as:

> *a floor structure covering the chosen span in a housing situation designed with a superimposed deadload of* $1.2kN/m^2$*, a live load of* $1.5kN/m^2$ *and an acoustic insulation of 53dB*

The second phase is the inventory of emissions and extractions calculation. It provides the quantity of substances exchanged by the process (the structure element) and the environment. At this point, it is called life cycle inventory. The third phase consists in the calculation of environmental impacts associated to the process using specific method of impacts. Those methods quantify global warming as well as other impacts such as eutrophication or acidification. Finally, the fourth phase is the interpretation of the results. Uncertainties evaluation playing an important role in this phase as it nuances the results.

LCA is conducted using the Python based software Brightway2 and the ecoinvent 3.9.1 database. The methods chosen are the ReCiPe 2016 hierarchist (Huijbregts et al. 2016 [29]).

Having Life Cycle Inventories of materials instead of only carbon factors allows to evaluate the structure impacts on others indicators such as ecotoxicity, human toxicity, euthrophication etc. This allows to compute uncertainties on the impact calculation. Following the production site, transport distance or other hypothesis, the Life Cycle Impact of a material can drastically change. For this purpose, uncertainties are calculated and enable to capture the dispersion on such data.

The stone life cycle inventory is based on Pestre et al. 2021 [20]. This inventory provides mean values of process exchanges considering 450 different french limestones.

Cement mortar is considered for joints. For stone masonry, mortar are made on the construction site by experienced workers. Proportions then vary depending on the worker. From discussion with stonemasons, this study considers 1 volume of cement for 3 volumes of sand and half volume of water.

Life cycle inventory for steel is established from French environmental product declaration from the French technical center for steel (CTICM) found in the INIES database (Inies 2022 [30]).

3. Results

3.1. Life Cycle Assessment of parametric stone structures

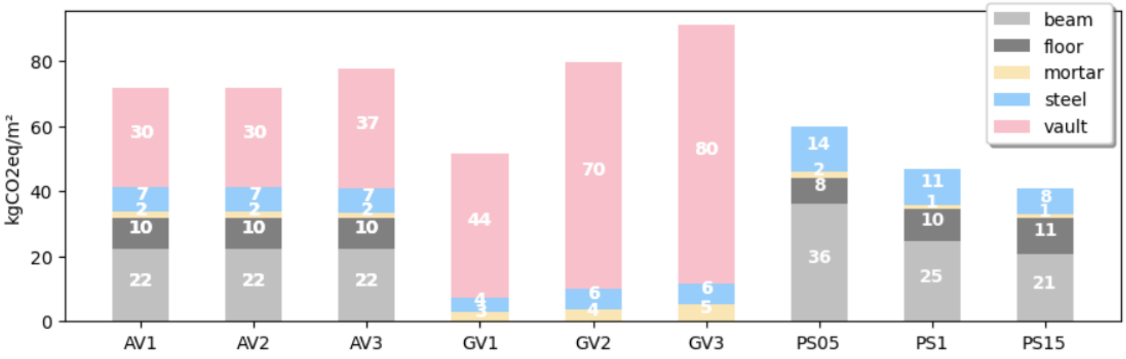

Figure 7: Global warming scores of stone floor solutions ; AV: Abeille vault ; GV: groin vault ; PS: post-stressed stone

For the considered stone structures, Global Warming (GW) is calculated taking into account the contribution of the different structural elements (beam, floor, mortar, steel and vault). The results for Abeille vault (AV), Groin vault (GV) and post-stressed stone (PS) are presented in Figure 7.

For Abeille vault, the highest contributors are vault elements (from 42% to 47%), closely followed by the post-stressed stone beams (from 37% to 40%). The stone vault elements take most of the impact in the groin vault typology. For post-stressed stone, results show that the higher the span of the floor element, the lower the impact. Stone in the beams are the main contributor to GW ranging from 51% to 60% of the total impact. On every typology, mortar accounts for a small part of the GWP of the structure. This is due to the use of thin joints (5mm) considered in this study.

Those results highlight the fact that there is no absolute best stone typology. Depending on the choice of parameters, each vault can perform better on GW. However, on average, post-stressed stone performs better than Abeille and groin vaults. Abeille and groin vaults have similar impacts.

3.2. Comparison to typical building slabs

The stone floor systems can be compared to more typical building floors. For this study, concrete cast-in-place slab (CIP), composite concrete-steel deck with steel beams (CCS), and cross laminated timber (CLT) floors are considered. The design of those floor systems is taken from Navaro Auburtin et al. 2023 [8]. For stone solutions, the solutions with the lowest GW impact have been selected: PS15, AV1 and GV1.

Figure 8 shows the comparison of slabs considering uncertainties of the LCA models. Uncertainties are based on the LCA processes. Each exchange between processes is modelled as a distribution. For instance, transport of stone from the workshop to the construction site is modelled as a log-normal distribution centered on a chosen value. Based on those distributions, a Monte-Carlo simulation with a sample of size 100 is run. Running a Monte Carlo simulation consists of making a random sample on each of the exchanges based on the distributions. This provides the boxplot in the Figure 8 and enables to take into account the uncertainties in the mean of production of the different materials. In Figure 8, the outliers are not shown.

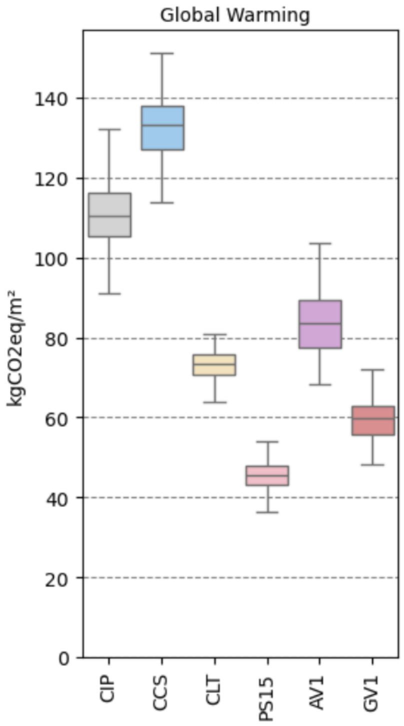

Figure 8: Comparison of stone structures to typical structures, considering uncertainties, on the GW ; CIP: cast-in-place concrete ; CCS: composite concrete-steel deck ; CLT: cross-laminated timber ; PS: post-stressed stone ; AV: Abeille vault ; GV: groin vault

Considering median values, results show that stone structures emit 45 $kgCO2/m^2$, 83 $kgCO2/m^2$ and 59 $kgCO2/m^2$ for, respectively, post-stressed stone, Abeille vault and groin vault. This is lower than cast-in-place and composite concrete-steel floors which emit 110 $kgCO2/m^2$ and 133 $kgCO2/m^2$. Post-stressed stone systems have lower impact than CLT floor (74 $kgCO2/m^2$). Taking into account the uncertainties, CLT, Abeille vault and groin vault behave similarly concerning GW. This calculation is handled without taking into consideration the sequestration of

CO2 by wooden elements as this approach is debated (Cordier et al. 2022 [31]). However, taking into account this sequestration could lead to lower values for CLT floor.

3.3. Considering other indicators than GW

GW is a major concern, but it is not the only impact a building structure has on the environment. The production of structure material can lead to other types of impact. For instance, marine eutrophication, which leads to an excessive plant and algae growth destroying ecosystems, can be generated by the production of polyurethane adhesive in the glue for timber elements.

Practitioners should start taking into account damages to the ecosystems and human health. For this purpose, Figure 9 shows five other indicators including marine eutrophication. Those have been selected as they show different types of impact on ecosystems and human health.

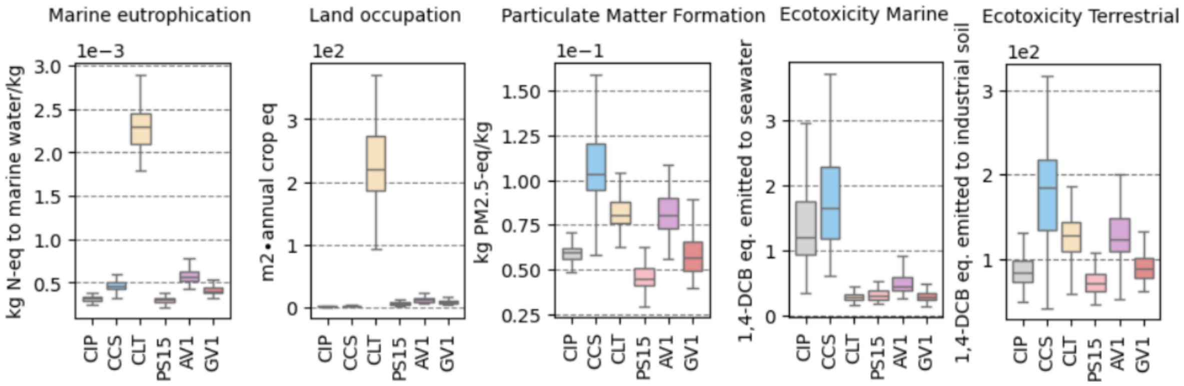

Figure 9: Comparison of stone structures to typical structures, considering uncertainties, on other indicators ; CIP: cast-in-place concrete ; CCS: composite concrete-steel deck ; CLT: cross-laminated timber ; PS: post-stressed stone ; AV: Abeille vault ; GV: groin vault

Land occupation indicates the square meters occupied to produce such structure. The value is high for CLT as large spaces are needed to grow a timber exploitation. Particulate matter formation indicates the emission of organic and inorganic substances creating air pollution and leading to damages to human health. Productions of steel and timber generate such matter. Ecotoxicity (terrestrial and marine) is related to ecosystem damages. It relies heavily on the input of metals in soil and marine environment, hence the high values on this indicator for steel based solutions.

Figure 9 shows the high uncertainties attached to the results. There is a need for more robust dataset on the environmental impact of structure materials. Depending on the indicator, the ranking of structural floor is different meaning designers need tools to navigate through multicriteria analysis or prioritize specific indicators according to relevance.

4. Conclusion

Stone floor systems represent a potential lever to reduce the impact on global warming of building structures, with GHG emissions between 42 (PS15) and 91 $kgCO2/m^2$ (GV3) which is far less than concrete and steel floors and comparable to timber solutions.

Uncertainty analysis shows a great dispersion in the values that relies on the quality of environmental data and of the diversity in the mean of production of a same material. Environmental evaluations of structure can have high uncertainties and designers should be cautious when taking them into account. A collaboration between designers and environmental impact experts is necessary to assess the quality of the data and refine the design process.

Even if global warming is a major concern, other environmental indicators should be considered by designers, such as damages to ecosystems and to human health. Results show that even low carbon systems can have higher impact on other type of damages. Practitioners should find tools to navigate through this multicriteria analysis or take decisions on which indicators to prioritize in their designs.

Future work should focus on sensitivity analysis on the stone LCA. Various other typologies of stone structure such as mixing barrel vault with post-stressed stone could lead to low-carbon solutions.

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