Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

Search for an Equilibrium in Multimodal Performance New Variations of Traditional Cap Ceilings

Emil BRECHENMACHER*, Christoph GENGNAGEL*

* Universität der Künste Berlin, KET Fachgebiet für Konstruktives Entwerfen und Tragwerksplanung
Hardenbergstr. 33 10623 Berlin
e.brechenmacher@udk-berlin.de

Abstract

In In the pursuit of resource-conserving and cycle-orientated construction, ceiling systems are becoming decisive parameters in building planning alongside the foundations, driven by their significant volume share of the primary structure, the constantly increasing comfort requirements in acoustic and thermal terms and the demands for high adaptability to a wide range of uses. This catalogue of requirements has led to a worldwide monoculture of reinforced concrete ceilings, especially point-supported flat ceilings in Europe, and thus to a significant source of embodied carbon emissions. The reintroduction of vault and shell constructions harbours considerable potential for significant material savings. Various research and development projects in recent years have shown that digital design and fabrication tools can address the challenges of these construction methods, such as high formwork costs and the need for skilled labour. So far, these projects have mainly focused on optimising the construction weight in terms of load transfer. In multi-storey buildings, regulations for comfort, encompassing thermal and acoustic physics, along with vibration limits, restrict the application of lightweight constructions. The need for a minimum mass for sound insulation frequently contradicts optimization goals in structural design. This research aims to strike a balance between building requirements and the imperative for radical sustainability. An initial investigation reveals that the traditional Prussian cap ceiling demonstrates robustness with 50% lower embodied carbon compared to equivalent reinforced concrete slabs. In this study, various transformations of historic flat vaulted ceilings (cap ceilings) are analysed. It also discusses the correct mass distribution to fulfil the multimodal requirements described. The developed design system retains the potential of the historical model in terms of a circular design. The paper evaluates the most important standards in the areas of sound insulation, acoustics, thermal properties, and vibrations that are relevant for the D-A-CH region. The aim of the project is to present an immediately applicable vault system for contemporary multi-storey construction by transforming the Prussian cap ceilings, emphasising their potential to meet stringent standards and as a sustainable alternative to conventional systems.

Keywords: Capped Vaults, Preußische Kappendecke, Historic Construction Forms, Transformation, LCA, Sound Insulation, Acoustics, Standardization, Circularity, Digital Design

1. Introduction

The construction of tomorrow must pursue three fundamental goals: conserving natural resources, reducing emissions both in the construction and operation of buildings and designing in a circular way. In building construction, two elements of primary construction play a decisive role due to their high-volume share and their materiality: ceilings and foundations (Gengnagel, Appelaniz [1)]. Ceilings in particular offer great potential for a decisive step towards achieving a radical reduction in climate-damaging emissions and the consumption of material resources. Currently, the requirements for ceiling constructions such as high flexibility of use, permanently increasing comfort requirements in acoustic and thermal terms as well as fire protection regulations are causing a monoculture in construction with

Copyright © 2024 by Emil Brechenmacher, Christoph Gengnagel
Published by the International Association for Shell and Spatial Structures (IASS) with permission.

excessive material consumption. In Europe, this effect is further exacerbated by the mass realisation of point-supported flat slabs.

The reintroduction of vault and shell constructions offers a variety of answers to this situation. The art of vaulting (Hart [2]) is not only associated with the simple mechanical principle of transferring external loads in a material-saving manner exclusively via normal forces, but also with a multitude of design possibilities that affect the performance of the entire space. The development of a multimodal spatial effect of ceiling systems is one of the fundamental ideas behind our research. This new perspective arises from the realisation that the search for equilibrium is not only a question of mechanics but of all physical requirements of a construction element. Only from this approach can we succeed in finding our way back to a technically uncomplicated and therefore circular design.

The fascination of structural engineers for the shell was primarily linked to the premise of developing very light, long-span constructions according to this operating principle. In multi-storey residential buildings, thermal and acoustic comfort regulations as well as vibration limits restrict the use of lightweight constructions. The requirements to provide ceiling constructions with a minimum mass for sound insulation and a sufficient thermal storage mass are often at odds with the optimisation goals of the structural design of a material-saving construction. This paper is therefore not concerned with a new type of high-performance system development, but with a transformation of a historical ceiling system that has already proven its applicability and advantages, the Prussian capped ceilings (Preußische Kappendecke). It is based on flat arched, mostly brick vaults between parallel beams. This system promises very good life cycle values, incorporates principles of the circular economy, and can be transformed with additional properties using new digital tools.

2. LCA in building design

The theory and meta-study of LCA helps us to identify the decisive components on the way to a rapid decarbonization of building construction. an isolated comparison of components should help planners to make the right intuitive decisions in the early (decisive) design phases. To select the appropriate assessment categories, the methodological principles of LCA in building design must be briefly discussed. The energy associated with the construction and operation of buildings is basically divided into two components: embodied energy and operational energy. In an energy-efficient new building, embodied energy accounts for around 50% of energy consumption over the life cycle of a building (see Fig. 1). Due to the currently very high proportion of fossil fuels in energy generation, embodied energy and operational energy are directly linked to the CO_2 emissions that are largely responsible for the climate emergency. Added to this are carbon emissions caused by chemical processes in the production of building materials such as cement. In line with the differentiation between embodied energy and operational energy, greenhouse gas emissions are also divided into two groups. The term "embodied carbon" covers all emissions that are released during material extraction, production, transport to the construction site, construction, etc. The term "operational carbon" covers all emissions that are released during the operation of buildings and infrastructure. Embodied carbon differs from embodied energy and operational energy as, for example, the consumption of renewable energy does not lead to the release of greenhouse gases, and the chemical processes of manufacturing or recycling materials as a source of greenhouse gases are not included. To influence the exponential development of the climate crisis in the construction industry, the rapid reduction of greenhouse gas emissions in the production and operation of infrastructure and buildings is a top priority. Greenhouse gases have different global warming potentials (GWP). The GWP is expressed in CO_2 equivalents.

2.1. Objectives of LCA in the planning process

The integration of sustainability aspects and life cycle analyses (LCA) into building and urban planning is still in the development phase and, in the conventional planning process, is essentially focused on the phases that involve more precise quantity calculations. This is problematic, as fundamental changes to the design can hardly be implemented at this stage.

The supporting structure with its high mass proportions and ultimately manageable catalogue of materials generates up to 70% of the CO_2 share of a building's embodied energy and therefore offers a simple and effective lever for reducing CO_2 in construction (Figure 1a). Of course, the focus should be on the construction elements with high mass fractions (Figure 1b).

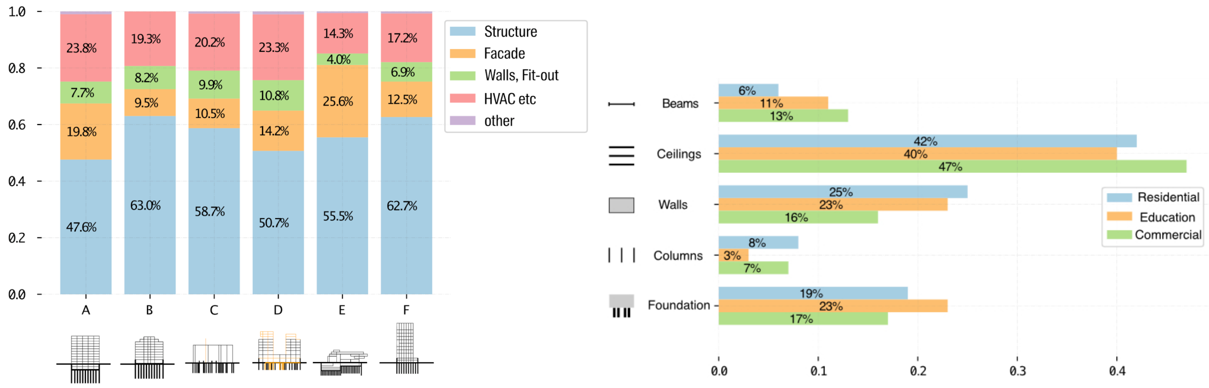

Figure 1a: GWP of buildings differentiated by component. Data basis of the graphic (Carroll [3]) assuming *cradle to gate*. 1b: GWP of a building depending on the structural element and building utilization (Watson [4]).

2.2. Methodological approach - considerations of construction masses

In the early design phases, very different design variants are often compared for orientation purposes to achieve structures with the lowest possible global warming potential. These comparisons can be made at component or building level. When comparing ceilings, walls, columns or construction systems, attention should be paid to the same structural properties, fire protection, sound and thermal insulation requirements and service life. A simplified analysis of the life cycle A1-A3 (cradle to gate) is recommended to determine the GWP of the design alternatives. Alternatively, a more complex analysis can also consider the emissions during production, use and at the end of the life cycle A1-A3, B4, C4/C4 optionally D (Cradle to Life). In both cases, the masses of components or construction systems are linked to the carbon factors of the materials used from databases. Generic EPDs should be used as far as possible and product-specific EPDs should be avoided. The ÖKOBAUDAT platform of the Federal Ministry of Housing, Urban Development and Building (BMWSB), for example, offers a sufficient range of data sets. A simple spreadsheet program is sufficient for this approach.

This approach involves an isolated comparative analysis of ordinary building components in terms of their life cycle assessment and their circularity. the Prussian cap ceiling serves as an example. Similar work would have to be carried out for all possible building components in order to arrive at a catalog that would allow architects and planners to make well-founded design decisions regarding their environmental impact at an early design stage, without having to carry out separate life cycle analyses. There are certainly still numerous forgotten forms of construction that could contribute to a new constructive diversity.

3. Analysis and Transformations of the Prussian vaulted ceiling

With the increasing industrialization of construction at the end of the 19th century, floor ceilings began to be designed as flat-arched caps made of masonry between steel beams (Maier et al. [5]). The shortage of materials after the Second World War gave the vaulted ceiling systems a brief renaissance The simplicity and effectiveness of the purely pressure-loaded caps enabled rapid reconstruction with the available material and rubble – characteristics which, in the light of today's debates on resource scarcity and circularity, call for the system to be reconsidered. The curved geometry increases material efficiency. Each component of the construction system has a specific task in the structure. All materials are clearly separated from each other and are put together in a simple and logical manner.

3.1. Construction method and load-bearing behavior

Barrel vaults have been a common way of covering space since ancient times. If the radius of the arch line corresponds to half its span, it is a pure barrel vault. This type of vault has the advantage that almost exclusively vertical loads are transferred at the support point. If the semi-circular segment is shortened, so-called compressed barrel vaults are created. The flatter the vault, the greater the horizontal load component at the support. The particularly flat forms of barrel vaults are also known as cap vaults and have a common pitch height of between 1/8 and 1/12 of their span. The term "Prussian caps", which is commonly used in Germany, should not obscure the fact that this type of construction was also used in other parts of the world. However, it does indicate the widespread use of the cap system from the second half of the 19th century and its semi-industrialised production in Prussia.
A major advantage of historic capped ceilings is that they can be calculated using simple approximation formulae (Fischer [6]). Recalculations and new measurements of historic vaults show that the simple calculation methods contain large reserves and safety margins. Both for masonry cap ceilings (Göstl [7]) and concrete caps (Marwede [8]), the examples used are very generously dimensioned. Their actual load-bearing capacity significantly exceeds that of the simplified calculation methods. The simple and abstract approximation methods ignore any side effects such as composite and shell load-bearing effects by focussing only on the axial forces in the vault. However, it is this abstraction that leads to the great resilience and long-term robustness of the historic cap vaults.

Approximation formulae (Maier [5]):

$$Fv = \frac{q \cdot l}{2} \qquad Fh = \frac{q \cdot l^2}{8 \cdot f}$$

q	Total load (dead load + imposed load)
l	Span
f	Height of the vault
d	Thickness of the vault

3.2 LCA comparison of ceiling systems

To make a statement about the GWP of the cap ceiling construction, a detailed series of comparisons was carried out. Six different systems for office or school use were pre-dimensioned in a uniformly defined framework. The systems compared are a reinforced concrete flat slab, a prestressed concrete hollow core, a timber-concrete composite system, a timber hybrid system and two forms of cap ceiling. A life cycle analysis was carried out for these constructions, which are all built on the same axial grid and have a uniform span length of 8.10m. The analysis is based exclusively on Ökobaudat. To maintain the abstract character of the comparison, generic EPDs were used for the material groups where possible. For specific products, such as the hollow planks from DW Systembau, manufacturer data was used (Institut Bauen und Umwelt [9]).

The results of this analysis are shown in Figure 2. While the conventional concrete flat ceiling has a global-warming potential of 136 kgCO2e/m2, the cap ceiling achieves a value of only 64 kgCO2e/m2 at best. It thus has a savings potential of approx. 53%. The examined cap ceilings are on a par with the timber-hybrid systems or are even slightly better than them. Under the same general conditions, masonry cap ceilings are thus a system that embodies less than half as much grey emissions as a conventional reinforced concrete ceiling. Where there are still open questions regarding the end-of-life scenario of timber construction, clear circularity characteristics can be demonstrated for cap ceilings (Aziz et al. [10]).

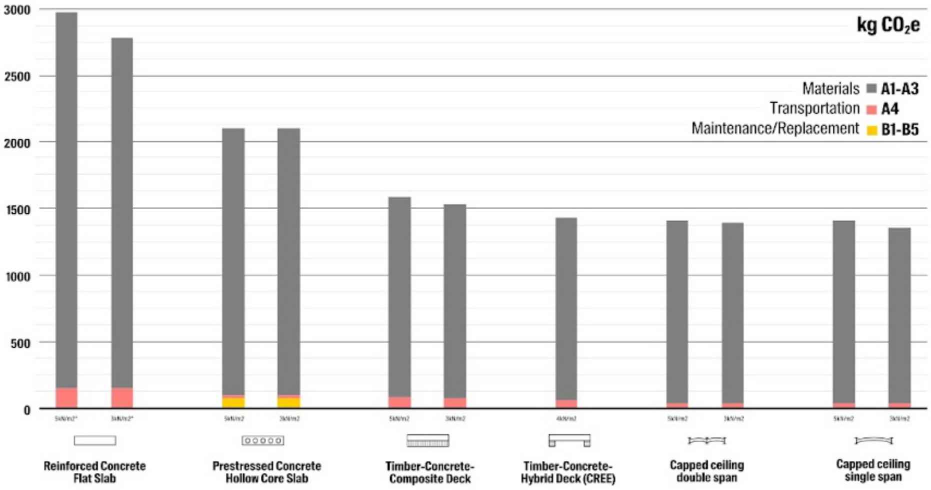

Figure 2: Results of the LCA-Comparison.

To further improve the ecological footprint of the historic system, the masonry of flat-arched caps between modern glulam beams was tested. A special beam geometry was developed for this purpose. The system was tested in an initial trial at the Zukunftbau Pop-up Campus Aachen using a 1:1 demonstrator (Brechenmacher [11]).


Figure 3: 1:1 Demonstrator of a transformed Prussian capped ceiling between specially milled timber beams at ZukunftBau Pop-up-Campus Aachen, 2022.

3.3 Sound insulation and the equilibrium of the masses

Materiality, geometry and mass play an important role in structural sound insulation. It is therefore necessary to analyse the sound insulation properties of the masonry cap ceiling to be able to make a statement as to whether the cap ceiling system is suitable in practice. The predominance of reinforced concrete ceilings is also due to increased sound insulation requirements. While other components, such as façades or interior wall systems, are becoming lighter and lighter thanks to technical innovation, the opposite trend can be observed for storey ceilings. The diversity of ceiling systems is steadily decreasing, while the installed mass is increasing (Sälzer, 1990 [12]). In Germany the minimum requirements are regulated in DIN 4109-1:2018-01 Sound insulation in buildings [13]. As a rule, historic capped ceilings achieve surface weights of between 200 and 300 kg/m2 and thus weighted sound insulation values of 44 to 49 dB. For this reason, building acoustics improvement measures are also regularly required for existing refurbishments to retrofit the ceiling systems to meet today's requirements (Küstner, 2008 [14]).

The sound reduction index R_w for the systems assessed is calculated for classification purposes. As the ceiling component is considered in isolation here, only the weighted sound reduction index R_w can be calculated and not the weighted construction sound reduction index R'_w, which considers the flanking transmission. Only the components of the supporting structure are considered. Screeds and superstructures are not included in the value. The following applies to the weighted sound reduction index R_w for solid ceilings:

$$Rw = 30,9 * \log(m) - 22,2$$

m Surface-related mass of the ceiling in [kg/m2]

	g	R_w
Reinforced concrete flat slab	800 kg/m²	67,5 db
Prestressed concrete hollow core	351 kg/m²	56,5 db
Timber-concrete composite system	396 kg/m²	58,0 db
Timber-concrete hybrid system CREE	297 kg/m²	53,3 db*
Capped vault, double span	282 kg/m²	49,9 db*
Capped vault, single span	306 kg/m²	50,4 db*

*Resulting sound reduction index from the overall cross-section

To determine the resulting sound reduction index of non-uniform layers, the cross-section is divided into small sections, for each of which the specific weight per unit area and the sound reduction index are calculated individually. The resulting sound reduction index is obtained by summarising the values in the formula:

$$Rw_{res} = -10log*(\frac{1}{l*\Sigma(n*(10^{-\frac{Rw}{10}})})$$

l = Section length of divided crosssection [m]
n = l/number of individual sections [m]
R_w = Sound insulation values of the individual sections

The comparison clearly shows the correlation between the mass per unit area and the sound reduction index of a construction. If this finding is superimposed with the previous results from the life cycle assessment, a mirror image emerges: the higher the mass and the global warming potential of a construction, the higher its sound reduction index.

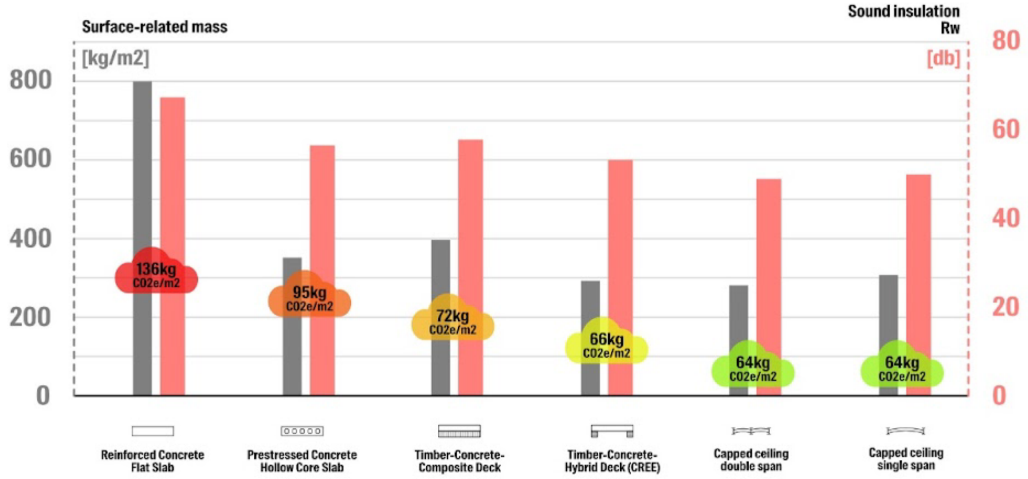

Figure 4: Correlation of mass, Global Warming Potential and Sound Insulation Coefficient in comparison matrix of six ceiling systems.

With its low weight per unit area, the cap ceiling performs worst in terms of sound insulation. The results are consistent with the data from historical building research. A closer look at the sound reduction index over the entire cross-section of the cap reveals that the weak point is at the apex of the vault. The large concentration of mass around the support areas can only compensate for the weak points of the cross-section, which tapers towards the center, to a very limited extent.

The pivotal inquiry lies in how sound insulation has emerged as a paramount factor determining the grey energy footprint within load-bearing structures. Our research unequivocally illustrates the nexus between mass, embodied carbon in construction, and resultant sound insulation coefficients. Despite identical load-bearing capacities among compared ceiling systems, they markedly diverge in material composition, geometric efficiency, and resultant grey energy expenditure during construction. Standardization assumes a pivotal role herein. In Germany, the integration of comfort standards, particularly in sound insulation, into building legislation via DIN standards, has rendered the realization of lighter ceiling systems nearly impracticable. Yet, the comprehension of this consequence among decision-makers and regulatory bodies remains dubious. Our correlation conspicuously highlights this issue, fostering discourse beyond structural design confines.

But also, in locales where comfort standards are not enshrined in building codes, developer-specific sound insulation requirements can inadvertently breed unnoticed conflicts. For instance, under its current "Schulraumstandard," which mandates the construction of new school facilities, the city of Zurich imposes exceedingly stringent sound insulation criteria between various spaces (IMMO Stadt Zürich [15]). This frequently necessitates the use of heavy, costly, and often CO2-intensive components. Such practices run counter to the city's parallel aspirations to curtail grey energy in new constructions and its political aim of achieving net-zero emissions [16]. The two cases of Germany and Switzerland vividly depict the inherent conflict in advanced construction contexts, wherein burgeoning standards impede the pursuit of innovative, sufficient, and low-carbon construction methodologies.

3.4 Heavy Vaults

The need to increase the mass of a ceiling for sound insulation reasons is generally at odds with the basic idea of a lightweight construction optimised in terms of its load-bearing effect and material effectiveness or a construction with a low CO2 content. This dilemma is illustrated by the current strategy often used in this case of upgrading lightweight ceiling structures such as timber or brick ceilings by adding loads to improve sound insulation - which also increases the overall height of the ceiling structure and thus the building volume with the corresponding economic disadvantages. If the use of heavy, resource- and energy-intensive constructions is to be avoided, there is a conflict of objectives between health and comfort standards and ecological challenges. In the case of capped ceilings, the attempt to achieve higher construction weights without adding additional layers on top of the vault the options are limited to the use of heavier bricks. In the past, attempts were made to make the vaults as light as possible for practical and constructive reasons. The idea of particularly heavy vaults contradicts the basic idea of the art of vaulting. Up to now, the masonry bricks in the system have been estimated to have a bulk density of 1500 kg/m3. If heavy masonry blocks made of concrete or sand-lime bricks, with bulk densities of up to 2600 kg/m3, the dead weight of the construction is significantly increased, causing a significantly higher stress on the bending beams, which can also only be compensated for by the overall height and the use of high-strength and thus energy-intensive materials. Thus, the use of these vault stones can quickly not cancel out the advantages of the system in the life cycle assessment. The use of masonry bricks made from recycled materials could compensate for this. However, since the weight is not quadratically included in the formula for calculating the maximum bending moment in the beam, in contrast to the span, the use of heavy materials for the vault still appears justifiable ($m=(q*l^2/8)$).

The use of concrete elements from existing buildings could offer great potential. Instead of completely downcycling the concrete as an aggregate, brick-sized blocks could also be cut from the demolished reinforced concrete parts. The sound insulation of such a heavy vault made of reused concrete blocks with a characteristic density of 2500 kg/m^3 is quite competitive with reinforced concrete ceilings.

The example (Fig. 07) shows the construction of a 20 cm thick vault with a mass per unit area of 500 kg/m^2; this achieves a sound reduction index Rw of 61.2 db. Such heavy vaults based on cut-up old concrete parts can be an exciting new approach to circular load-bearing reuse in line with the idea of unreinforced concrete masonry (URCM) as demonstrated by Bhooshan et al [17].

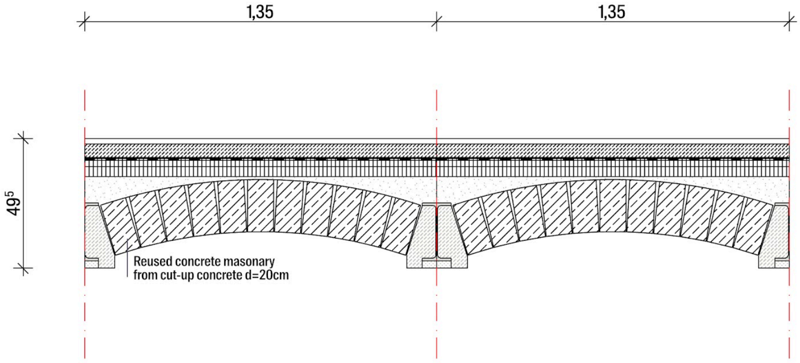

Figure 5: Scheme – Heavy vault from cut re-used concrete parts

3.5 Room acoustics and modification of surfaces

Multimodal design denotes the seamless integration of all design, physical, and technical parameters within the architectural process. Specifically, for the supporting structure enveloping a space, this entails meticulous consideration of mechanical properties, room acoustics, and ambient climate factors. The objective is to attain optimal functionality through geometric properties via hybrid form-finding techniques, thereby crafting straightforward yet efficient structures employing minimal material components. An important concern here was the symbiosis of load-bearing effect and acoustic room effect with minimal design effort. The sound field of the room is controlled by porous absorption via trapped air volumes (Helmholtz resonance) on the underside of the ceiling. The micro-geometries required for this can be created using additive manufacturing processes. The pressure path required for this is generated in the same software environment in which the geometry was previously optimised. For the Prussian cap ceiling, this approach means integrating acoustic properties into the module of the individual brick.

Acoustically, the curved caps initially offer no advantage over flat solid ceilings, despite an increase in surface area of approx. 20%. In office and school construction, room acoustics often play a decisive role in the interior design of rooms. Good acoustic design is essential for the quality of rooms. This often must be ensured by installing elaborate additional absorber systems on walls, ceilings, or floors. Integrating acoustic absorption properties into the building shell follows the concept of simple construction by reducing work steps, technical measures, and the general number of construction elements. For the functional integration of the supporting structure and acoustic system, the initially sound-reflecting surface of the cap ceiling must be converted into a sound-absorbing surface. An approach already tried and tested in earlier research work is the integration of so-called Helmholtz resonators into the geometry of the ceiling soffit (Aziz et al. [18]). For capped ceilings, this can be achieved by integrating the resonators into the masonry blocks. The production of the bricks using mineral 3D printing processes enables the precise realisation of the simulated geometry for different frequency ranges. In this case, four different bricks were developed for four frequency ranges. By spreading the number and distribution of certain bricks and frequency ranges, it is possible to respond very precisely to the respective acoustic properties of the covered rooms.

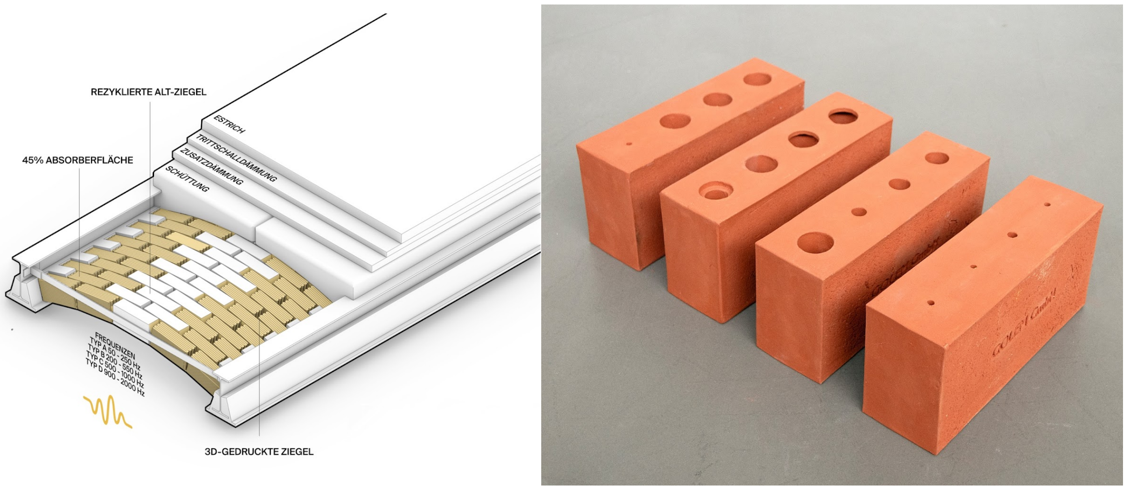

Figure 6a: Scheme of an acoustically activated cap ceiling using acoustic bricks.
6b: Prototypes of the acoustic bricks in traditional fabrication method.

Prototypes for the acoustic bricks were produced using both 3D printing and traditional manufacturing methods. Together with an established craftsman construction specialist, a series of precisely manufactured bricks were tested for their acoustic and structural performance. The bricks achieve their simulated properties in both categories. The next step will be to test the acoustic properties of the entire component.

4. Conclusion and Outlook

Our research project and practical experiments sought to explore whether the historical system of masonry cap ceilings could regain relevance in contemporary construction practices. This inquiry stemmed from both a curiosity about historical technology and a pressing need for practical solutions to reduce emissions and promote circularity in construction. While discussions on sustainable building often encompass broad concepts, our approach deliberately focused on a single building component to address the significant emission drivers in the industry. Ceiling systems present a promising avenue for reducing the prevalent use of reinforced concrete, and our aim is to contribute to this by revitalizing masonry cap ceilings. The studies on sound insulation in ceiling systems revealed a clear correlation between mass, embodied carbon in construction, and the resulting sound insulation. Sound insulation requirements in floor slabs emerges as a major driver of GHG emission, often hindering lighter and more efficient construction systems, particularly in highly regulated industries like those in D-A-CH. However, our research underscores the importance of considering all building physics parameters when developing new building components for the future. Multimodal design, exemplified by surface activation for acoustic properties and extending to thermal properties and storage capacity, ensures practical applicability and potential emissions reduction. Our approach diverges from pure engineering fascination with highly efficient, lightweight structural shells by advocating for the revitalization of proven construction methods with modern adaptations. Furthermore, it necessitates a dialogue about scaling back certain comfort standards to realize the vision of lighter, more efficient, and environmentally responsible constructions in the years to come.

References

[1]D. Appelaniz and C. Gengnagel, “LCA im Konstruktiven Entwurf – aktuelle Praxis und Ausblick,” *nbau - Nachhaltig Bauen*, vol. 3, no. 2023, pp. 23–31, 2023.
[2]F. Hart, *Kunst und Technik der Wölbung*. Georg D. W. Callwey, 1965.
[3]C. Carroll, “Net-zero buildings Where do we stand?,” 2021. Accessed: Apr. 13, 2024. [Online]. Available: https://www.wbcsd.org/contentwbc/download/12446/185553/1

[4]N. Watson, “Lean design: 10 things to do now,” *The Structural Engineer*, vol. 98, no. 8, pp. 12–14, Aug. 2020, doi: https://doi.org/10.56330/cdja1258.
[5]R. Ahnert and K.-H. Krause, *Typische Baukonstruktionen von 1860 Bis 1960*. Berlin: Verlag für Bauwesen, 1987.
[6]M. Fischer, *Steineisendecken im Deutschen Reich: 1892-1925. Bd. 1.* Fakultät Architektur, Bauingenieurwesen und Stadtplanung der BTU Cottbus, 2008.
[7]S. Göstl, “Bemessung von Gewölben aus Mauerwerk,” *repositum.tuwien.at*, 2014. https://resolver.obvsg.at/urn:nbn:at:at-ubtuw:1-63448 (accessed Apr. 13, 2024).
[8]H. Marwede, “Preußische Kappendecken Analyse der Tragstruktur auf Grundlage von Belastungstests im Rahmen des Projekts Stadthöfe Hamburg,” *diglib.tugraz.at*, 2016.
[9]Institut Bauen und Umwelt e.V. (IBU), “Umwelt-Produktdeklaration Spannbeton-Fertigteildecken DW-Systembau,” *dw-systembau.de*, 2020. (accessed Apr. 13, 2024).
[10]S. Aziz, E. Brechenmacher, B. Alexander, J. Loutfi, and C. Gengnagel, “Cap Ceilings Revisited: A Fabrication Future for a Material-Efficient Historic Ceiling System,” *Sustainable development goals series*, pp. 393–408, Nov. 2023, doi: https://doi.org/10.1007/978-3-031-36554-6_25.
[11]E. Brechenmacher, “Demonstrator eines neuartigen Kappendeckensystems ,” in *Zukunft Bau Pop-up Campus Aachen*, Bonn: BBSR, 2023, pp. 164–169.
[12]E. Sälzer, *Schalschutz im Massivbau, Grundbegriffe, Anforderungen, Konstruktionsbeispiele*. Wiesbaden, Berlin: Bauverlag GmbH, 1990.
[13]DIN Deutsches Institut für Normung, “DIN 4109-1:2018-01, Schallschutz im Hochbau - Teil 1: Mindestanforderungen,” 2019, doi: https://doi.org/10.31030/2764537.
[14]E. Küstner, “Bauakustik Bauakustische Maßnahmen bei der Modernisierung von Altbauschulen,” Kultusministerkonferenz, 2008.
[15]IMMO Stadt Zürich, “Raumstandards für den Bau von Volksschulanlagen der Stadt Zürich,” 2022. Accessed: Apr. 13, 2024. [Online]. Available: https://www.stadt-zuerich.ch/content/dam/stzh/hbd/Deutsch/Immobilienbewirtschaftung/Weitere%20Dokumente/Zbgg/immo_raumstandards_RGB_online_20221207.pdf
[16]Stadt Zürich UGZ, “Klimaschutzplan, Ziele und Massnahmen zur Reduktion der direkten Treibhausgasemissionen auf netto null bis 2040,” *stadt-zuerich.ch*, 2023.
[17]S. Bhooshan, A. Dell’Endice, F. Ranaudo, T. Van Mele, and P. Block, “Unreinforced concrete masonry for circular construction,” *Architectural intelligence*, vol. 3, no. 1, 2024, doi: https://doi.org/10.1007/s44223-023-00043-y.
[18]S. Aziz, B. Alexander, C. Gengnagel, and S. Weinzierl, “Generative Design of Acoustical Diffuser and Absorber Elements Using Large-Scale Additive Manufacturing,” *Proceedings of the 16. International Conference on Architectural Acoustics and Sound*, 2022.