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The central role played by structural design in enabling the construction of buildings that advanced and revolutionized architecture

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HIGHLIGHTS

- Built architecture, paper architecture, imitative architecture.
- Structural design is all-pervading in architecture and underpins architectural design.
- Reading and interpreting a historical piece of architecture needs structural engineering.
- The Renaissance was triggered when architecture embraced structural design.
- Paper architecture and imitative architecture ignore structural design.

GRAPHICAL ABSTRACT

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ABSTRACT

The paper draws a parallel between the Italian domes of the *Santa Maria del Fiore* cathedral by Brunelleschi, the *Villa Barbaro* temple by Palladio, and the *Umiltà* sanctuary by Vasari, which covers all structural aspects concerned with their whole life cycle; from the concept and design through to construction, performance, damage and safety assessment.

The first dome promoted greater knowledge of the capabilities of materials and structural design: although Brunelleschi's dome was Gothic, it started the Renaissance.

The second and third domes referred to existing buildings; Palladio imitated the image whereas Vasari also imitated the structure; while Palladio's dome was stable and is still safe, Vasari's dome was unstable and needed retrofitting.

This interdisciplinary study offers new insights into and knowledge about those historical buildings, which are relevant to researchers, teachers, and practitioners alike, because they show that structural design is crucial in every aspect of architecture and underpins the architectural design process. Moreover, the study proves that reading and interpreting a historical piece of architecture needs structural engineering.

1. Introduction

In new works and repair practice, a successful building needs the judicious selection of the best materials, coupled with a structural design that takes full advantage of their properties [1,2]. Thus, architecture should promote a greater knowledge and understanding of the attributes and capabilities of all types of building materials in the context of structural design, and structural design should be a facet of architectural design [3,4].

Moreover, at a time when the pressure is on all architects, engineers and contractors to optimize use of new materials and up-to-date technologies [5–8], architecture should encourage developments in the field of construction and building materials, and their application in new works and repair practice, as well as should support developments in the field of structural design in the context of architectural design [9–17].

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Conversely, a rising trend in architectural education, critique, and commentary of the last decades is to focus on image and formalism, to exclude the practical from the aesthetic, to consider architectural drawings as pictures, to ignore the separation between 'project' and 'design', to establish inadequate links between architectural styles and structural behavior, as well as between history of architecture and structural area or allied areas. That trend is tantamount to ignore the role played by materials and structural design in architecture.

In order to oppose that trend, some schools of architecture coined the collocation 'paper architecture', which is a recent term for the buildings developed in drawings but never built. Paper architecture includes projects that were never meant to be built and projects that, although intended to be built, were unbuildable or remained unbuilt for reasons that did not depend on the mere project.

Projects that never meant to be built are different than projects that were unbuildable, since the former suggest the idea of an idealistic, impractical or Utopian architecture, while the latter suggest the idea of architectures with flaws. Hence, the former belong to visionary architecture (which depicts mental pictures produced by the imagination or abstract aesthetic experiments of an architectural elite, sometimes out of touch with the practical needs of the populace), while the latter belong to unrealistic and impossible architecture (which suffers from wrong technical or economical approaches). Also what remained unbuilt for reasons that did not depend directly on the project suffers from flaws, which derive from bad interpretation of the client's needs or budget; other sources of flaws may be the availability of structural technology or a project not appropriate to the building's site.

Working on abstract architecture, projects, and concepts is important, and the so-called paper architecture is essential, as a measure of our aspirations or to express our ideas and imagination. The allure and influence of paper architecture on built architecture prompt the latter to explore new solutions instead of choosing automatically the usual solutions. That paper architecture focuses on alternative futures and although it remains largely within the realm of provocation rather than practice, it greatly influences built architecture [1,18].

Thus, on one hand, paper architecture deserves to be studied and should be encouraged. On the other hand, however, paper architecture should be dealt with as something different than built architecture – real buildings and their designs – since the former is abstract whereas the latter is concrete. Abstract-concrete dichotomy entails that paper architecture cannot even be considered as the preliminary design of built architecture; as a consequence, built architecture includes the entire design process, from preliminary design to detailed design, and nothing else. Conversely, modern architectural education, critique, and commentary sometimes do not distinguish paper architecture from built architecture, which leads to a lot of problems in the world of architecture and in academia. Moreover, the paper architecture that seems to be gaining traction during this downturn is focused less on architecture as a self-referential discipline and more on the imperatives of the deepening environmental and economic crises. Therefore, present paper architecture has less capacity of directing built architecture towards advanced solutions.

This research has analyzed three masonry domes. The study's statement of purpose was to emphasize and address the differences between built architecture and paper architecture, and to show the central role of structural design in architecture. The study was also devoted to reflecting the multidisciplinary nature of architectural history, whereas historians often neglect it, in particular they ignore structural design. Furthermore, this paper aims at establishing appropriate links between architecture and structural form as well as materials.

2. Summary of masonry dome behavior

The theoretical framework used for analyzing the masonry domes of this study can be built from the papers cited in the references. In particular, basic research on the behavior of masonry structures can be found in [10,16,19–30], including the masonry dome [28]; the cracking pattern of masonry structures can be found in [31–37], including masonry domes due to the own weight (meridional cracks); the behavior of the dome with meridional cracks can be found in [22,24,38–40]; advanced research on specific topics related to the load-carrying capacity of masonry structures can be found in [41–47].

The structural behavior of a masonry dome can be summarized as follows. Typically, the own weight is sufficient to induce hoop (circumferential) tensile stresses at the springing that are greater than masonry tensile strength. Thus, immediately after the construction, a dome usually cracks at some points of the springing, in the vertical direction (sometimes even during the construction; other times due to a vibration some years after the completion). Those cracks cut the entire masonry thickness, from the external surface (extrados) to the internal surface (intrados).

Those cracks propagate in a quasi-meridional direction along the shell and in the vertical direction into the drum. After cracking, thus, a masonry shell is split into wedge-shaped portions, i.e. pie-shaped segments, and the drum into annular portions, i.e. arc-shaped segments. Thus, the resisting system of the cracked dome consists of the shell split into variable-depth semi-arches plus the drum split into arc-blocks. The semi-arches meet each other at the crown (i.e., the oculus) and give rise to a system of arches, which exchanges a thrust between each of the arch-blocks and each of the drum's blocks, through the springing section. Hence, a drum's block is the abutment of the arch-block that rests on it.

The load-carrying capacity of the dome split into an arch-abutment system is lower than that of the uncracked dome. Therefore, the structural perspective considers only the cracked dome. However, almost all the life cycle of a masonry dome includes meridional cracks and, therefore, typically the dome is split into an arch-abutment system, while the shell structure exists only for a short period of time.

It follows that the load-carrying capacity of the masonry dome coincides with that of the masonry arch. Thus, the behavior of a masonry dome is represented by the diagrams of Figs. 1–4, which show the possible failure modes of the masonry arch. Each arch of

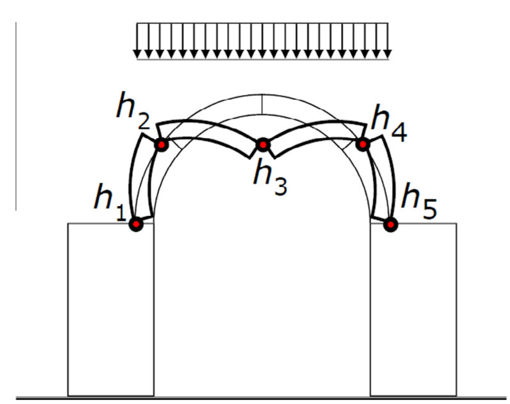

Fig. 1. Masonry arch and abutments. Kinematic mechanism that does not involve the abutments: the springing sections do not move while the crown moves downwards. In the figure, both the structure and load are symmetric. In reality, structures and loads are not symmetric. Thus, the hinge h_5 (or h_1) does not form and h_3 is not exactly at the crown; moreover, h_2 and h_4 are not symmetric. Hence, the actual mode is that of Fig. 4, which however, in practice, differs marginally from this mode.