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Connecting architecture and engineering through structural topology optimization

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ABSTRACT

One of the prevalent issues facing the construction industry in today's world is the balance between engineering and architecture: traditionally, the goal of the architect has focused more on the aesthetics, or "form" of a structure, while the goal of the engineer has been focused on stability and efficiency, or its "function". In this work, we discuss the importance of a close collaboration between these disciplines, and offer an alternative approach to generate new, integrated design ideas by means of a tailored structural topology optimization framework, which can potentially be of benefit to both the architectural and structural engineering communities. Several practical case studies, from actual collaborative design projects, are given to illustrate the successes and limitations of such techniques.

1. Introduction

Design professionals (such as architects and engineers) strive for a balance between different and sometimes conflicting goals for any particular project. Traditionally (at least in recent tradition) we can perhaps generalize that the goal of the architect has been leaning towards aesthetics and the goal of the engineer has been focused on stability and efficiency. In the more distant past (say, in medieval times during which great cathedrals were being built) the specialization of *architecture* and *engineering* that exists today did not.

In many instances there is a chasm between the vision of the architect and the sensibility of the engineer, between the aesthetics or appearance of a structure and its corresponding skeleton. We can argue that the distinction is between form and function – the form being the domain of the architect and the function of the engineer, but often the architect is as much concerned with "function" as the engineer, perhaps in a very different sense, and the engineer is as concerned with "form" as the architect, but perhaps differently than the architect.

The architect might speak of the building in ethereal terms and dealing with how people may experience the building and the philosophy of the design. The engineer might speak in more explicit and quantitative terms. They, of course, talk about the same building, yet not they only have different ways of describing it, but different ideas about what it should be. Since both architects and engineers are critical in the design of a building, the result can be (at worst) a compromise (neither the architect nor the engineer is completely happy) or (ideally) a synergistic result (where both are happy and proud, and the result is a sum even greater than the contributions of both participants).

Vitruvius (a Roman architect of the 1st century AD) wrote that a good building should satisfy the three principles of strength, utility and beauty (*firmitas*, *utilitas*, *venustas*). A building designed with aesthetics but without enough engineering to stand is unacceptable. A building designed only to stand but without regard for how it will be used or how people will respond to it is equally unacceptable.

Just as cathedrals "pushed the envelope" of design and technology, we are continuing to stretch limits with what we are designing. Innovations in design tools and philosophies about design, as well as innovations in fabrication and construction, are enabling designs to be realized which recently would not have been able to be built. In some instances, an architect is able to design something which would have been impossible to an engineer before. In an (unfortunate, we think) environment where an architect will envision a building without any regard or sense for engineering principles but can instruct the engineer to "make it work" more things are now possible. In a more collaborative environment architects and engineers work together to envision and realize incredible structures. Super-tall skyscrapers are one example of buildings requiring such close collaboration.

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Architects and engineers specialize in their disciplines, and even people within a discipline may specialize in a particular aspect of it. But, the process of design is extremely collaborative from the very start of a project. This reduces the problem of going too far in a design direction without considering several aspects. Architects inspire engineers and engineers inspire architects in all of our designs (even if it may be difficult to pin-point the origin of a particular idea, and even if some might be reluctant to admit it).

Historically, there are architects whose visions of aesthetics produce designs with very strong structural sensibility and innovative ideas. Such buildings have influenced the fields of architecture and engineering tremendously. Examples of these architects include: *Antonio Gaudi*, who used physical models to calculate sophisticated structures; *Buckminster Fuller*, whose philosophical ideas about holistic design, synergetics and geometry led to innovative structures such as the geodesic dome; *Felix Candela*, creating thin-shell concrete structures which are efficient and beautiful; and others (refer to Fig. 1).

The same issue that exists for architects and structural engineers also exists between architects and other types of engineers. An environmental engineer will consider as part of the *function* of the building its cost and efficiency to operate, the comfort of its occupants, and its sustainability. The collaborative efforts between architects and environmental engineers is similar in nature to that between architects and structural engineers, not to mention possible trade-offs in the design of a project due to perhaps divergent goals of structural and environmental engineers. One recent example of a similar multi-disciplinary design optimization can be seen in the flexible workflow framework for engineering design optimization presented by Crick et al. [4]. This example illustrates how a process with conflicting requirements of the different disciplines attempts to converge upon a description that represents an acceptable compromise in the design space.

On this note, we reflect on the innovative work of a well-known structural engineer, *Fazlur Khan*, who was influenced by the collaboration with the architect, *Bruce Graham*, which changed the idea of modern building architecture. Sabina Khan [5] described that *Bruce Graham* "inspired Khan to strive for structural systems that were not only structurally efficient but also worthy of becoming the core idea on which architectural design could center".

1.1. Motivation for structural topology optimization

As a possible avenue to achieve balance between the form and function, the authors strive to introduce a new, modified topology optimization framework, specifically for the design industry. Topology optimization can be used as a means to minimize the material consumption in a structure, while at the same time providing a tool to generate design alternatives of benefit to both the engineering and architectural communities, where the architecture works closely with the structural engineering in these proposed designs. This tool can be an initial step towards the creation of efficient designs and provides an interactive rational process for a project where architects and engineers can more effectively incorporate each other's ideas, rather than simply "making it work". In such a situation, the architecture might not "sacrifice" design for efficiency. Furthermore, the question of whether function follows form or vice-versa will no longer be of concern because through the use of structural topology optimization, the architecture and engineering are integrated together.

1.2. Paper organization

The remainder of this paper is organized as follows: in the next section, we review existing topology optimization techniques in the literature and corresponding numerical implementations. Then, in Section 3 the topology optimization framework for buildings and other structural applications is discussed. In Section 4, several case studies are presented for a variety of high-rise buildings and other architectural problems to illustrate the aesthetic value of topology optimization in this context. Finally, we conclude with some remarks about the application of these ideas.

2. Existing techniques in literature

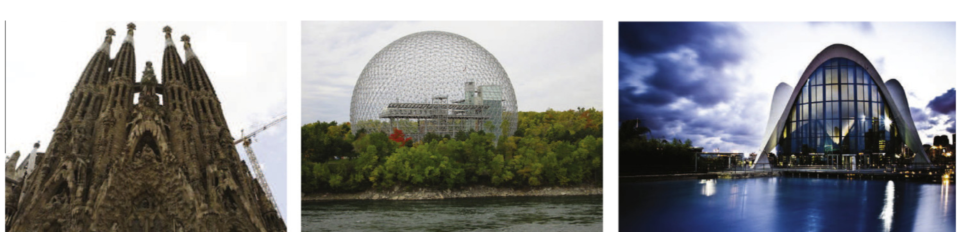
Researchers have previously developed many computational optimization tools, in which the goal is to reduce the cost or material usage in a structure while satisfying specific design criteria. Among these tools, there are the cases of size optimization, shape optimization, genetic algorithms, topology optimization and others. The existing state of the art technologies are discussed next.

2.1. Background information

Size optimization is commonly used for finding the optimal cross-sectional area of beam elements in a frame or calculating the optimal thicknesses of plate elements while satisfying design criteria. In this method, the shape or connectivity of members may not change, but they may be removed during the process ([6]).

An alternative technique, *shape optimization*, looks at the shape of the initial material layout in a design domain and morphs the shape boundaries to obtain an optimal solution. In this case, the optimization can reshape the material inside the domain, but retains its topological properties such as number of holes ([7,8]).

Optimization tools commonly used in the industry are based on genetic algorithms, where principles from nature and natural selection can be used to identify the ideal design for a specific criteria in a certain design domain ([9]). Though this technique works on a wide range of problems (including size and shape optimization) and does not require the use of potentially complicated derivatives, it often requires more function evaluations and is not necessarily convergent, even to local minima ([10]). For a review of these techniques, the reader can refer to the paper by Suzuki and Kikuchi [11].



(a) (b) (c)

Fig. 1. Examples of structures by architects with strong and innovative engineering concepts: (a) Antonio Gaudi ([1]), (b) Buckminster Fuller ([2]), (c) Felix Candela ([3]).