



## Review article

## Structural art: Past, present and future

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## ABSTRACT

The idea of structural art has gained an increase in interest due to the pioneering book by David Billington in 1983. With this, a paradigm shift is emerging with the belief that structural engineers can become artists in the design process by cooperatively integrating three tenets: economy, efficiency, and elegance. The objective of this up-to-date review is to present a broad perspective of structural art during the past three decades (1983–2013). Historical engineering projects and the stories of their structural engineers are discussed to identify the key conditions that have contributed to various works of structural art. Further, this review promotes the importance of the structural art concept and equips future engineers by discussing the potential resources and tools that can be utilized to learn more about structural art.

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## Contents

1. Introduction	407
2. Structures as art: from concept to design	408
2.1. Form innovation: the dominant role of the engineer	408
2.2. Necessary conditions	409
2.2.1. Structural principles	409
2.2.2. Material efficiency	410
2.3. Sufficient conditions	411
2.3.1. Aesthetic motivation	411
2.3.2. Competitive environment	411
3. Engineer as artist: from education to practice	411
3.1. The power of education	412
3.1.1. Education prototype	412
3.1.2. Education reform	412
3.2. The value of practice	413
4. Discussion: structural art in the future	413
5. Summary	414
Acknowledgements	414
References	414

## 1. Introduction

Is structural design an art? Are structural engineers artists? Most people will say “no” if you ask them these two questions.

Most of the time, people wonder which *architect* designed remarkable structures, such as the Eiffel Tower and the Brooklyn Bridge, not which *engineer*. It is reasonable that people believe the design of a building or a bridge is under the architect’s control, while the

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structural engineer is charged with finding a way to make it stand up. Architecture and structural engineering are professions that have been historically misunderstood, even though the core of both professions is shaping man-made structures. In fact, up until the end of the 18th Century, the two professions were one. After the Industrial Revolution however, engineering developed as a discipline in its own right with a scientific basis, and increasingly drifted away from the school of architecture. The aesthetic principles of architecture and of structural engineering were separate and different [1]. Along these lines, the profession of structural engineering has been gradually overtaken by the school of science and technology, and the possibility of a structural engineer also being an artist was ignored. As a result, it is a popular opinion among structural engineers that a structural design typically places little emphasis on the aesthetics and creativity while the majority of creativity elements are held within the architectural design.

Compared to the well-documented history of architecture, little investigation has been conducted into the history behind the works of structural art and the history of structural artists. This is because the works of art created by structural engineers are only occasionally documented, and remain anonymous in the public mind. Along these lines, it is ironic that some of the great structural engineering artists have been reported as architects in architecture history. Moreover, while it is often easy for architecture students to produce a list of great architects, this is not necessarily the same as for engineering students. With today's way of teaching, it is not common practice for engineering students to learn about the prominent structural engineers in construction history, let alone the structural artists. And yet, much can be learned and applied for future engineering designs if the history and idea of structural art can be embraced among the engineering profession.

Can structural design be a work of art? Can structural engineers be artists? The pioneers of engineering design have answered these two questions. Civil engineering was once defined by Thomas Tredgold as “the art of directing the great sources of power in nature for the use and convenience of man” [2]. Both Italian engineer, Pier Luigi Nervi, [3] and Spanish engineer, Eduardo Torroja, [4] were also known to challenge conventions of structural forms and redefined the relationships between the aesthetic beauty and the structural function, which remains fresh and daring even today. Other studies [5,6] of structural principles in multiple forms have also shown that structural design can be regarded as a process of developing art.

In 1983, David P. Billington, a civil engineering professor from Princeton University published a book “*The Tower and the Bridge*” [7] and presented a series of well-known works of structural design along with their engineers. Most importantly, he defined the greatest works of structural art and design to be those that integrate three tenets: economy, efficiency, and elegance. Efficiency concerns using the minimum amount of material consistent with adequate performance and safety; economy refers to achieving a competitive construction cost consistent with minimal maintenance requirements; and elegance is defined as emphasizing aesthetics to the greatest degree consistent with efficiency and economy. Consequently, structural art is quite distinct from the visual maxims of architecture because structural artists seek elegance without compromising safety, serviceability, and economy. A short version of the history contained in his book can be found in a paper [8].

Since Billington's pioneering work, most of the literature followed the same approach; critical reviews and case studies which link the works of structural art and the achievements of structural artists. It has been shown that the works of structural art are commonly large-scale structures [9]. Since then, researchers have recognized structural art as a concept, and structural forms are discussed as such in the literature, including: bridge and long-span structures [10–20], thin-shell vaults/roofs [21–23], towers [7,24,25], dams [26–29] and special forms [30]. More recently,

studies have evaluated works of structural art by using finite-element numerical tools such that a historical design work can be evaluated with Billington's three criteria of economy, efficiency, and elegance. However, in spite of the noted interest in this topic, most research work to date has only conducted a single case study on one structural artist and his works. As a result, it creates misconception that a works of structural art can be only created by those great structural engineers. An overview of the earlier works on this topic has not been done, and it would be worthwhile to present such review to identify the conditions behind a work of structural art and how it can guide potential research studies and structural designs.

The main objective of this review is thus to present a broad perspective of the study of structural art over the past three decades (1983–2013). The year of 1983 was chosen as the beginning point for literature because of the amount of impact Billington's book in 1983 brought to the concept of “structural art.” This review is to emphasize the concept of structural art as a neglected piece of modern construction not a departure into the other extreme to ignoring the creativity in architectural design. The literature discussing structural principles from an architectural perspective can be found in [31,32]. Case studies on works of structural art are discussed to identify how those works were born and have left a lasting impact on the structural design profession. Ongoing efforts within this broad topic are also presented to demonstrate how the paradigm has shifted and how the design community has benefited from studying these historical cases. In addition, various topics will be explored such as the great achievements of structural artists, the limitations of the current engineering education system, the potential for these studies to be used as a catalyst for future innovation.

## 2. Structures as art: from concept to design

The evolution of structural forms has been driven by the need to provide more living space, to cross large natural obstacles, or to build lasting monuments. Along these lines, the process of creating a structure is complicated and requires elements of both science and art. Engineering forms are dictated by structural needs, primarily to support multi-load combinations. In modern structural design, we need more “form givers,” not just “form takers.” Engineers may struggle to find an optimal as well as elegant form, such that they have to copy some existing designs. It is easy to copy the design of a masterpiece, but it is hard to gain its success as a work of structural art.

The structural forms in Fig. 1 were selected as recognized works of structural art. The completion of these structures in the past two centuries have proven that structural engineers are capable of designing a work of art in their discipline with scarce support from architects or artists. Most of those designs are in relatively large-scale structures with less architectural usage, such as bridge. The reason why these great works can be regarded as structural art is that a paradigm shift has emerged. Following those design philosophies has had a huge impact on the entire structural design industry. This leads to a logical question: “What are the conditions that lead these designs to be considered a masterpiece of structural art?” The most convincing approach to studying structural art is to evaluate a work of structural design from three perspectives: scientific, social and symbolic [33]. Through these guiding perspectives, the following section will identify key conditions to generate a work of structural art.

### 2.1. Form innovation: the dominant role of the engineer

Man-made structures can be categorized into two types based on the roles of the architect and structural engineer in the design

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