

# Integrating Creativity and Discipline into Structural Design Education

*Integrando la creatividad y la disciplina en la educación del diseño estructural*

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## Abstract

In one of the most classic courses at Princeton University, it is argued that the best-designed structures (bridges, buildings and shells) are works of art – structural art. It teaches that design creativity involves both technical skills (discipline and rigor) plus aesthetic sensitivity. This course has been taught to structural engineers, architects and all liberal arts majors for more than forty years. This course on structural art is a gateway course for structural engineering majors that provides context and history and introduces the basic formulas that structural engineers use to create forms and designs. Such an approach needs to be reinforced among upperclassmen once they have a deeper understanding of structural analysis and design. The curriculum of structural engineering students, in other words, should be both rigorous and include the history of the profession. Such integrated teachings illustrate that ‘creative play’ is iterative and ‘disciplined,’ that creativity takes courage and that constraints enable creativity. This article elaborates on these points and shows how such concepts are taught at Princeton starting in the freshman year and continuing on through graduate school.

**Keywords:** pedagogy, historical studies, structural engineering, structural art, creativity.

## Resumen

*En uno de los cursos más clásicos de la Universidad de Princeton se sostiene que las estructuras mejor diseñadas (puentes, edificios y láminas) son obras de arte; más concretamente, arte estructural. Se*

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28

*enseña que la creatividad en el proyecto implica tanto competencia técnica (disciplina y rigor) como sensibilidad estética. Este curso ha formado a ingenieros estructurales, arquitectos y estudiantes de humanidades durante más de 40 años. Para los estudiantes de ingeniería estructural, este curso sobre arte estructural es la puerta de entrada que les proporciona el contexto histórico e introduce las fórmulas básicas que los ingenieros estructurales usan para crear formas y diseños. Entre los estudiantes de cursos superiores este enfoque necesita ser reforzado, una vez que han adquirido un conocimiento más profundo del proyecto y del análisis estructural. En otras palabras, el currículum de los estudiantes de ingeniería estructural debería, simultáneamente, ser riguroso e incluir la historia de la profesión. Las enseñanzas así integradas ilustran que el 'juego de la creación' es iterativo y 'disciplinado', que la creatividad necesita de determinación, y que las limitaciones estimulan la creatividad. Este artículo se elabora sobre estas premisas y muestra cómo estos conceptos se enseñan en Princeton a los estudiantes desde su primer año hasta después de su graduación.*

**Palabras clave:** *pedagogía, estudios históricos, ingeniería estructural, arte estructural, creatividad*

## Introduction

With the Industrial Revolution came new materials, and with new materials – such as industrialized iron, structural steel, reinforced concrete, prestressed concrete, structural fabrics, glass and composites – came new forms of structures. It is in this context that the art of the structural engineer was born: 'structural art,' as defined by David Billington.<sup>1</sup> Structural art encompasses three ideals: *efficiency* is the true ethos of engineering, to conserve natural resources by minimizing materials; *economy* is the ethic of engineering, to reduce costs by intimately connecting design to construction; and *elegance* is the aesthetic of engineering, to create beautiful forms.

Designers who achieve these three ideals in their completed works are defined as 'structural artists' by David Billington. These designers seek to integrate elegance and efficiency rather than superimpose one on the other. They illustrate how the best technical designs leave room for ethical and aesthetic choice. The principles of design creativity that enable great structures are timeless and remain highly relevant today.

The primary author has continued David Billington's Structural Art class (CEE262) for first-year students and, along with other colleagues,

<sup>1</sup> See: David P. Billington, *The Tower and the Bridge: The New Art of Structural Engineering*, (Princeton: Paperback, Princeton University Press, 1985).

has developed derivatives of this course that are designed for more advanced students (CEE463 and CEE540). At their core, these courses show how to integrate creativity with 'discipline' (that is, the fundamental principles of mechanics and other technical skills).

These courses complement the traditional 'design' courses of structural engineering programs, which have been increasingly devoted to the knowledge of regulations and codes, as well as to acquiring the skills needed to use progressively powerful and omnipresent software. However, codes and computers do not enable creative thought and can be a dangerous way to approach 'design.' Students may think that different courses (such as concrete and steel design) are unconnected disciplines, for example. They also are susceptible to the unconscious and erroneous thought that calculations, and not design, are the objective of their work. Furthermore, without mature judgment, computers could be used prematurely when hand calculations would be faster and more reliable. Often, the 'non-technical' aspects of their designs, such as sustainability or visual appearance, tend to be underestimated. Last but not least, students are trained mainly to answer perfectly defined questions, whereas in real life, the question itself is usually unknown and revealing the right question is the first step towards a successful design.

This article elaborates on these points and shows how such concepts are taught at Princeton starting in the freshman year and continuing on through graduate school.

### **Creativity takes courage**

Creativity requires bold and sometimes unconventional choices —it takes courage. It takes courage to have faith in 'disciplined' design decisions that have not been tested before, and it takes courage to face criticism— be it aesthetic or doubts about whether it can be done. Let's examine the example of Eiffel and his world-famous tower. He used a new material (iron) to design to heights never before attempted. He also did this in the face of severe criticism by some of the world's most prestigious artists, who passionately protested the tower while it was being constructed. In their open letter of protest, they referred to the tower as a "truly tragic street lamp," a "belfry skeleton" and a "mast of iron gymnasium apparatus, incomplete, confused and deformed." Eiffel replied to their protest by writing: "For my part, I believe that the Tower will possess its own beauty. Are we to believe that because one is an engineer, one is not preoccupied by beauty in one's constructions, or that one does not seek to create elegance as well as solidity and durability?"<sup>2</sup>

2 "Debate and Controversy Surrounding the Eiffel Tower," accessed July 26, 2017, <http://www.toureffel.paris/en/themonument/history>.

Here, Eiffel solidified his status as a structural artist and touched upon the three qualities of structural art as described by David Billington: efficiency, economy and elegance.

While the example of the Eiffel Tower illustrates courage in the face of aesthetic criticism, the example of the Brooklyn Bridge demonstrates courage in the face of severe public doubt that such a bridge was even possible. These doubts stemmed from its long span, its construction troubles (e.g. fire in the caisson and decompression sickness) and the political corruption surrounding the project. John Roebling, the man with the drive and vision, died before construction began. The project was handed over to his son Washington, who became paralyzed with decompression sickness during construction. His wife Emily played a major role in completing construction in her husband's place. Despite death, sickness, corrupt politicians and a woman playing a major role at a construction site in the 1870's, the bridge was finished years later.

A modern movie captures public sentiment at the time of the construction of the Brooklyn Bridge. The premise of the movie is that a man living in the 870s Brooklyn goes into a time warp to 2001. He comes across the completed bridge and, stunned, remarks to a streetcleaner: "Good lord, it still stands. The world has changed all around it but [the bridge] still stands! That, my friend is a miracle!" —to which the janitor responds with a bored tone: "It's a bridge".<sup>3</sup> Those who know the history of the Brooklyn Bridge understand the 'miracle,' but to most of the world, it's just a bridge.

The world knows of the Eiffel Tower and Brooklyn Bridge —but few know the history of these icons and the stories of the engineers and their courage. It's just a tower or just another bridge to most. Today we can find new examples of courage —engineers using new materials (such as composites, stainless steel, ETFE, etc.) and using modern numerical tools (carefully not allowing these tools to replace human creativity and judgment). These examples of courage need to be told to our students so that they may also be inspired to be courageous; but, of course, they must also be told that courage must be rooted in 'disciplined' knowledge and not whimsical, untethered artistic choices.

### Constraints enable creativity

The primary author has written: "The constraints of efficiency and economy in design do not stymie creativity; in fact, more often than not, they result in iconic structures, innovative forms and novel construction techniques. All [structures] are, in large part, defined by the spatial constraints imposed by



Simone Roda, *Brooklyn Bridge*, flickr.com

3 "Kate and Leopold," *Konrad Pictures and Miramax Films*, 2001.

the site and program. The structural solution is further constrained by budget, time, logistics, availability of equipment, expertise and experience, cost and availability of materials, customs and preferences (to name but a few). The importance of limiting material expenditures is especially paramount in tall and large structures where even a small change in efficiency can translate into large material and economic savings.<sup>4</sup>

Many historical examples exist to illustrate the importance of constraints and how creativity has flourished as a result. For example, Pier Luigi Nervi was a structural designer in Italy during World War II. When Italy shifted to a state of autarchy, or economic self-sufficiency, reinforced concrete structures became an 'anti-autarchic material' since metal reinforcements were primarily imported. Steel reinforcements were partially banned in 1936 and then fully banned in 1939. It was under these constraints that Nervi innovated with his construction methods and developed a 'Nervi System' consisting of (1) a construction practice (structural prefabrication) and (2) a material (ferrocement).<sup>5</sup>

Using these innovations, developed due to constraints, Nervi designed masterpieces such as the Palazzetto dello Sport in Rome and the Agnelli Exhibition Hall B in Turin. His style consisted of ribbed surfaces for thin-shell concrete structures, which are difficult when using traditional construction methods but possible and economical using his Nervi System.

Overcoming tough challenges due to constraints requires 'design engineering,' meaning problem solving with creative thinking. 'Technician engineering,' meaning doing calculations without innovative thought, is not enough to achieve a solution. Another example of constraints enabling creativity is that of Fazlur Khan, who, along with Graham and Goldsmith at SOM, built milestone high rises. New forms and structural systems for tall buildings were developed under both spatial and economic constraints—and it is arguably because of those restraints that innovation and creativity occurred. Another example of constraints enabling creativity and innovation is the 1964 DeWitt-Chestnut apartment building led by project engineer Fazlur Khan.

Maria E. Moreyra Garlock has written about this apartment building in the next section and these arguments are summarized below. The constraint was to avoid street-level congestion and the solution was to set the building back, resulting in a smaller footprint. To achieve the total square footage of the original design, the total height had to rise from 26 to 43 stories, which increased the forces imposed on the building.



Maliek Lulko, *Palazzetto dello Sport*, flickr.com

4 See: Maria E. Moreyra Garlock and Annette Boegle, "Efficiency and Economy." In *SOM Structural Engineering*, (Munich: Detail, Institut für Internationale Architektur-Dokumentation, 2015), 82-103.

Khan knew that reinforced concrete with shear walls in the service core was the most economical solution; however, the layout of the building's apartments and services would not permit this solution. He innovated with the so-called 'framed tube,' which can be described as a vertical cantilever with a hollow profile cross-section that had perforations for daylight openings. The columns were spaced at 5'-6" and connected by 24" height spandrel beams. The short distance between the columns and the stiffness of the beams is the major reason that this system is stable and functional. This exterior lateral system required only small gravity columns inside the service core, resulting in functional flexibility.

These are just two examples that are taught in detail to students in the introductory course on structural engineering. Historically, such examples abound. If one talks to the best structural designers today (or listen to their presentations at conferences), one will hear them say that it is challenges (e.g. constraints) that enable creative thinking and design innovations. This is a message that needs to be brought to our students, many of whom are so used to having sophisticated tools, all types of materials and instant information at their disposal. Abundant resources may subliminally send the wrong message and may not give students an opportunity to face challenges and solve them creatively –whether in engineering or in life.

### **The significance of integrating rigor with historical studies**

A study of the history of one's profession is expected of architecture students, as is visiting the structures designed by the best architects they study. Historical studies and site visits are not expected of structural engineering students. Why? No room in the curriculum? The most likely reason is that it is not seen as important. However, those that are familiar with the history of structural engineering know that history teaches and inspires. Ignoring history is like showing an aerial view of a tall building, where only the roof can be seen, but not the rest of the building that supports it. Those that have studied history know that it should be an essential part of a structural engineer's education. This goes back to the idea of educating 'designers' versus educating 'technicians.' Advocating for the study of history does not mean letting go of rigor in the engineering curriculum. To be a designer, one needs both: the rigor of a deep understanding of theory (not codes), plus the knowledge and inspiration derived from historical as well as modern design.

The greatest designs are disciplined, respecting the limitations of efficiency (statics, calculations) and economy (construction). Yet the best engineers recognize that, within these limitations, there is room to 'play' and seek elegant forms.

Architects and engineers should both be educated so that they are adept at rapidly finding approximate dimensions using simple formulas;



Maria Garlock, *DeWitt-Chestnut apartment building*

complex analyses come later. In addition to their rigorous technical training, engineers should be educated in important historical works of architecture and should know how to critique them. The study of history and criticism is not common in the engineering curriculum. Our profession often seems to have little interest in the recent history of engineering and therefore tends to see engineering as the work of teams of technologists and committees of experts. In short, the neglect of history has the direct consequence of dehumanizing modern engineering.

### Examples at Princeton

At Princeton University, the study of the history of structural engineering is offered to all students. The course CEE262: Structures in the Urban Environment was first offered by David Billington in 1974. Structural engineering students are encouraged to take it their first year. Our motivation for making this class accessible to all students (not just engineering students) is that we believe that everyone should be technically literate – and our structures (e.g. bridges, buildings) are part of everyone’s daily lives. CEE262 traces the development of structural engineering through case studies of outstanding structures and designers. The course covers a timeline that begins with early iron structures from the Industrial Revolution and culminates with the supertall buildings, long-span bridges and sustainable designs of the 21st Century.

Recent education research shows that incorporating pedagogical techniques that engage students during lectures improves student attitudes towards engineering and leads to a higher rate of knowledge acquisition. A recent National Science Foundation grant has enabled the dissemination of this course to other universities with effective teaching approaches.<sup>6</sup> A website has been made containing the material needed to teach the course (<http://casce.princeton.edu>).

5 See: Tullia Iori, *Pier Luigi Nervi*, (Milan: Motta, 2009).

6 Maria E. Moreyra Garlock, and others, “Effective Approaches for Teaching STEM-literacy for All Majors: The Example of Resonance,” (Proceedings of the 2017 ASEE Annual Conference, Columbus, OH, June 25-28, 2017); Evelyn H. Laffey and others, “Enhancing Student Cognition and Affect through the Creative Art of Structural and Civil Engineering,” (Proceedings of the 2016 ASEE Annual Conference, New Orleans, LA, June 27-29, 2016); Aatish Bhatia and others, “Engaging Students with the Creative Art of Civil Engineering,” (Proceedings of the 2016 ASEE Annual Conference, New Orleans, LA, June 27-29, 2016) and Maria E. Moreyra Garlock and others, “Introducing Modern Teaching into a Classic Course on Structural Art,” (Proceedings of the IABSE Conference – Structural Engineering: Providing Solutions to Global Challenges, Geneva, Switzerland, September 23-25, 2015).

CEE262 is a gateway course for structural engineering majors – one that provides context and history and introduces the basic formulas that structural engineers use to create forms and designs. Such an approach needs to be reinforced among upperclassmen once they have a deeper understanding of structural analysis. This is the purpose of CEE463 and CEE540.

CEE463: A Social and Multi-Dimensional Exploration of Structures has been taught biannually since 2010, changing themes every year while maintaining the same pedagogical objectives and studio-style format. It is co-taught by two faculty members. In Fall 2017, the theme was “Creativity in Cuban Thin Shell Structures.”<sup>7</sup>

This course includes site visits, studies of historical data, structural analyses, the construction of scaled prototype models and the creation of websites, films, essays and an exhibition. The course has several impacts: (1) it significantly broadens students’ perceptions of the profession of structural engineering, putting it into a global context; (2) it increases their motivation and self-confidence to exercise structural engineering as a profession; and (3) it significantly improves their communication skills. Our pedagogical approach is based on the idea that students learn best by teaching themselves through challenging, open-ended assignments. Some pedagogical objectives include:

1. Developing a sense for implicit understanding by studying precedents;
2. Learning how to communicate complex technical issues with peers and laymen;
3. Developing spoken, written, pictorial, analytical and numerical proficiency;
4. Critically reflecting upon the social, political and historical influences on successful structural designs from the past.

7 More about the course and its previous themes can be found in Branco Glisic and others, “Innovative Education in Engineering: A Social and Multi-Dimensional Exploration of Structures,” (Proceedings of the ASCE Structures Congress, ASCE, Boston, April 2014); Ignacio Paya Zaforteza and others, “The Art of Spanish Bridge Design: A New Course Promoting the Holistic Learning of Structural Engineering,” (Proceedings of the IABSE Conference – Structural Engineering: Providing Solutions to Global Challenges, Geneva, Switzerland. September 23-25, 2015) and Sigrid Adriaenssens and Maria E. Moreyra Garlock, “Teaching Social and Multidimensional Aspects of Structures through Fazlur Khan.” In *Festschrift Billington* Eric M. Hines and others, (International Network for Structural Art, 2012), 122-155; and its website: <https://cubanshells.princeton.edu>



CEE540: Elements of Conceptual Design is a newly-developed course intended to show students how to use and combine the many tools they will learn as structural engineers to create forms and design structures that are efficient, economical and elegant.<sup>8</sup> The objective of this course is to stimulate creative design thinking via a holistic study of basic design principles (which the students would have already studied) and their applications in real design examples. While the course takes some 'deep dives' into theory, it also always 'flies above' the theory to see the big picture of design and how theory, combined with other engineering principles, results in efficient, economical and elegant structural designs. It is this second aspect that the authors believe is missing in the engineering curriculum, but which is valuable for the development of creative designers.

This class, for example, illustrates how several structural systems (such as prestressing, torsional resistance and curved beam theory) are combined to create forms, such as in Jörg Schlaich's Kelheim Footbridge. Students also learn how to find forms and optimize them using graphic statics and the Maxwell Theorem. They then apply this skill to real designs. Novel and effective pedagogical approaches are taken to teach the class. While lectures and weekly calculation assignments are given, other creative approaches are taken as well. For example, students are required to keep a journal where, once a week, they practice their drawing skills by sketching an assigned structure on the university campus and outlining the flow of forces. They also visit New York City's long-span bridges and tall buildings and make reports and presentations on the structures visited.

Students have said that CEE540 is both instructional and inspirational because it is based upon exemplary designs. This is a course offered to seniors and graduate students. One of the seniors who took the course went on to graduate school at a prestigious university, during which time she wrote that she was enrolled in a class on structural design optimization "where we learned about convex optimization techniques, sensitivity analysis, and optimization with Maxwell's theorem and graphic statics. While this course is extremely technical and informative, I was constantly referring back to your course, CEE 540, which looked at the subject much more creatively and helped me understand the material as it relates to real structures." Such unsolicited feedback reinforces the importance of integrating rigor and case studies, validating one of

8 Juan José Jorquera Lucerga and María E. Moreyra Garlock, "Elements of Conceptual Design: An Innovative Course," (Proceedings of the IASS Annual Symposium 2017, Hamburg, Germany, September 25-28, 2017).



Monika Shröder, *Kelheim Footbridge*, pixabay.com

the course's implicit goals, which is to teach, as Strasky wrote, that "knowledge, and not intuition, is the tool of creativity."<sup>9</sup>

## Conclusion

In 1955, Pier Luigi Nervi wrote, "When the actual behavior of concrete under load and in time is better known, when laboratory practices capable of producing 14,000 psi concrete are commonly applied in the field and when the plastic redistribution of stress in complicated structures is foreseeable, the amazing results achieved so far will be easily surpassed." This is how he ends his book *Structures*.<sup>10</sup> Today, nearly 60 years later, we have achieved the things that Nervi lists, but have we surpassed the results achieved by Nervi? Arguably not; which implies either that Nervi cannot be surpassed and/or that stronger materials and the complex nonlinear analysis of structures are not the recipe for successful design.

Another structural artist, Felix Candela, warned of the dangers of blindly designing extravagant forms, that is, without the discipline of engineering; today, some architects continue to use inappropriate forms to create extravagant structures. The structures of Santiago Calatrava, for example, while striking in appearance, carry an unaffordable price tag that is often a result of improper form. Yet Calatrava is well educated in

9 Jiri Strasky, "New Structural Concepts for Footbridges," (Proceeding of the International Conference on the Design and Dynamic Behavior of Footbridges, Paris, France, November 20-22, 2002).

10 See: Pier Luigi Nervi, *Structures*. (New York: McGraw-Hill, 1955).

engineering, so he knows about 'good' structure. There are some who are so knowledgeable about engineering that they have chosen to put aside its 'discipline' and focus exclusively on the 'play' of finding forms, but there are some who are in need of a better education.

Architects and engineers should both be educated to be adept at rapidly finding approximate dimensions using simple formulas and, as Nervi wrote, the best method to do this is "to trace the development of structural schemes from ancient times up to the present, performing a static critique to show the relationships between materials and construction procedures employed and the results achieved both from the technical and aesthetic point of view".<sup>11</sup>

In sum, it is important for students to understand that engineering design is creative, that it may require courage and that it is an iterative process that involves examining various possible solutions. As Candela has said: "But an efficient and economical structure does not necessarily have to be ugly. Beauty has no price tag and there is never one single solution to an engineering problem. It is therefore always possible to modify the whole or the parts until ugliness disappears."<sup>12</sup>

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11 See: Pier Luigi Nervi, *Aesthetics and Technology in Building*, (New York: Harvard University Press, 1965).

12 See: Felix Candela, "New Architecture." In *The Maillart Papers*, edited by David P. Billington, Robert Mark and John F. Abel, (Princeton: Princeton University Press, 1972), 119–26.

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