The Education of a Structural Designer

La educación de un diseñador estructural

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Submission date: August 6, 2018
Approval date: September 12, 2018

DOI: 10.22201/fa.2007252Xp.2018.18.67937

Abstract

A structural designer needs to be able to create something new. What is the source of these new ideas? They can come from an understanding of technology, a knowledge of history, research and educated inspiration.

Not all structural engineers are structural designers, who create work that has structural engineering principles as a central aspect. What does a structural engineer need to learn to be a good structural designer? Structural designers need to understand structural theory, the behavior of materials, mathematics (including a deep understanding of geometry) and the difference between analysis and design. It is important to understand structural failures and learn from what hasn't worked in the past. They need to learn and understand the history of design and designers and have the ability to make freehand sketches. They need to lose their fear of criticism and learn how to free themselves to create. A knowledge of the history of art and architecture will help spark ideas and provide another basis for communication with collaborators. One challenge for structural designers is to go into unknown territory instead of continuing down the same path, but also to not be afraid of utilizing a known solution and adapting it to the situation at hand. A designer needs to learn how to find or create knowledge through research.

The fundamental question is: how can we design the education of engineers to create structural designers?

Keywords: engineering education, structural design, structural theory, structural art

Resumen

Un diseñador estructural debe ser capaz de crear algo nuevo. ¿Cuál es la fuente de estas nuevas ideas? Pueden provenir de un entendimiento de la tecnología, un conocimiento de la historia, la investigación y la inspiración educada.

No todos los ingenieros estructurales son diseñadores estructurales, los cuales crean trabajos que tienen principios de ingeniería estructural como un aspecto central. ¿Qué necesita aprender un ingeniero estructural para ser un buen diseñador estructural? Los diseñadores estructurales necesitan entender la teoría estructural, el comportamiento de los materiales, las matemáticas (incluida una comprensión profunda de la geometría) y la diferencia entre el análisis y el diseño. Es importante comprender las fallas estructurales y aprender de lo que no ha funcionado en el pasado. Necesitan aprender y comprender la historia del diseño y los diseñadores, y tener la capacidad de hacer bocetos a mano alzada. Necesitan perder el miedo a la crítica y aprender a liberarse para crear. El conocimiento de la historia del arte y la arquitectura ayudará a generar ideas y proporcionará una base para la comunicación con los colaboradores. Un desafío para los diseñadores estructurales es adentrarse en territorio desconocido en lugar de continuar por el mismo camino, pero también para no tener miedo de utilizar una solución conocida y adaptarla a la situación en cuestión. Un diseñador necesita aprender cómo encontrar o crear conocimiento a través de la investigación.

La pregunta fundamental es: ¿cómo podemos diseñar la educación de los ingenieros para crear diseñadores estructurales?

Palabras clave: *educación en ingeniería, diseño estructural, teoría estructural, arte estructural*

Introduction

What does it take to make a structural engineer into a structural designer?

A structural designer is a unique kind of designer. Creating willful forms may be a valid approach for a sculptor or a form-driven architect, but the creations of a structural designer should be based on structural engineering principles. This is not to say that a structural engineer cannot create a willful, form-driven object, but that the engineer is, in that instance, not acting as a structural designer. Conversely, architects or artists who choose to base their works on structural principles can act as structural designers. Although anyone using structural engineering principles can be a structural designer, it is logical that a structural designer is most likely to be a structural engineer.

Design is the search for constraints. If you are going to create something, what are the limitations? What are the constraints? For a building, the constraints will include the brief, the environment, the budget, the property line, the zoning restrictions and many other considerations. These constraints inform the design and make the creation richer. For a structural design, some of the primary constraints need to be the principles of structural engineering.

One might think that a structural engineer can naturally became a structural designer. Unfortunately, this is often not true.

A structural design versus a structural solution

Engineers are trained to be problem solvers, but many times the engineer is someone who solves problems that other people create; that is, making a building that will not fall over. The solution will have a structure, but it is, in a fundamental sense, not a structural design. If it's more of an integrated process and the design is meaningfully informed by structural engineering, then it may be a structural design.

There is an important difference between engineering a solution and creating a structural design. The difference between a 'structural design' and a 'make it work' or 'make it stand up' structural solution is fundamental. Sometimes a complicated problem or form that is not based on structural principles requires a structural solution that is, in a certain sense, quite clever and the engineer uses a sophisticated understanding of engineering principles to create the solution. But that process, "making it work," does not make it a structural design, in the sense used here, because the overall system was not created based on structural engineering principles.

It is important to recognize that analysis is not design. Engineers are educated in such a way that they are given a problem which they then analyze, determining the forces at work and sizing elements. They aren't really designing and aren't involved in the creative part of the design. Often, in school, there is only 'one right answer' for the stated problem. Unfortunately, this 'one right answer' concept becomes engrained in the engineer's thinking and is very limiting.

The essential components of a structural design are often related to geometry. The correct geometry is central to a structural design. Geometry can be thought of in terms of the domain of design, topology, shape and size. A structural designer needs to address all aspects of geometry.

Key design steps include defining the problem, creating the topology and refining shapes and sizing elements and the connections between them. Engineers often spend most of their efforts on sizing an element or connection but little or no time on the topology or shape. Unless the connection or element is particularly inspiring or central to the design idea, this is not structural design in the sense being used here.

Education for the creation of structural designers

We need to design the education of structural designers. We design buildings, bridges and other structures, and we should likewise design the education process.

What are the things that a structural engineer who aspires to be a structural designer needs to know? The list is broad and deep. The engineering topics should include theory, behavior, computational and graphical tools, mathematics and the history of the design of structures.

Theory refers to the physics and mathematics that describe the response of structures. These include the theories of elasticity, plates and shells, vibrations, plasticity, strength of materials and energy methods.

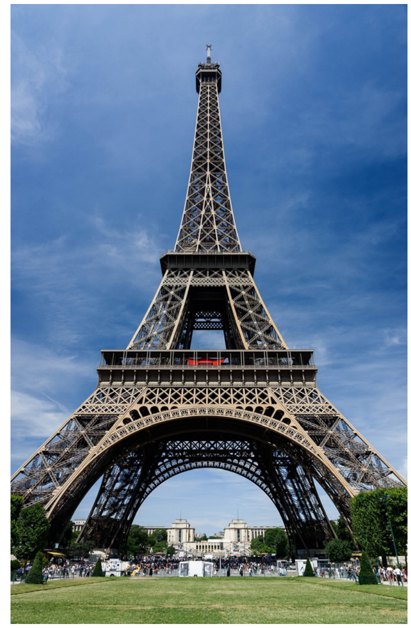
Traditionally, these theoretical classes were taught with an emphasis on the application of theory to analysis because it was only through theory that many things could be calculated. Today, theory should be taught with an emphasis on design, namely, how the knowledge of these fundamental topics can lead to creative solutions.

There also needs to be an emphasis on the theory of structural systems - how the arrangement of structural elements will fundamentally change the structural properties of a system.

Knowledge of the behavior of different materials used in structures is essential to someone who wants to be a structural designer. Structural systems comprise a broad range of materials, including concrete, steel, masonry, timber, glass, aluminum and composites. Knowledge of the behavior of materials needs to go beyond how to size the element or connection; it should include an understanding of how the selection of a material informs the structural design.

The behavior of structures includes knowledge of past structural failures. Knowledge of failures should be at several levels: one level is a catalogue of knowledge of individual failures, another level is an understanding of what processes or situations can lead to failures. Henry Petroski's *Design Paradigms*[1] is an important book which explores how an incorrect, but commonly held, understanding or paradigm of how structures work can lead to failures. These failures then lead to new structural design paradigms that may also have their own problems or limitations. The author of this paper often gives this book to engineers who are just starting out in their professional careers to remind them that we do not know everything that we would like to know. We may not even be aware of our own ignorance. We should realize that we don't know what we don't know.

1 See: Henry Petroski, *Design Paradigms: Case Histories of Error and Judgment in Engineering* (Cambridge: Cambridge University Press, 1994).



Salginatobel Bridge is a reinforced concrete arch bridge graphically designed by the Swiss civil engineer Robert Maillart.
Image: Naue Anthony V., *Salginatobel Bridge*, flickr.com

The Eiffel Tower was designed by Gustave Eiffel in collaboration with the Franco-Swiss civil engineer Maurice Koechlin, who used graphic statics for the design.
Image: Joe de Sousa, *The Eiffel Tower from the Champs de Mars*, CC0

To be a structural designer, you need to analytically test your ideas and be able to present your ideas to your collaborators. In addition to standard linear and non-linear finite element method tools, it is recommended that structural designers be familiar with various hand calculation methods, such as virtual work. Hand calculations force the structural designer to simplify the problem to its essence. The structural designer should be conversant with graphic design tools such as graphic statics. It is worth noting that some of the most beautiful structures in the world were designed graphically.

For the structural designer, the feedback of the geometry of both the structure and the forces at work is powerful.

Much of the time, standard analysis software is sufficient, but, at times, structural designers create designs that do not work well with existing software. The ability to script and write computer programs can greatly expand the reach of the structural designer. They also need to be able to use the latest graphic software to both develop and present their ideas, as well as to examine and explore the proposals of others.

Design collaboration needs to be fluid and fast-moving. Team members need to present their ideas quickly and react to the proposals of their colleagues during a team meeting. If a would-be collaborator has to return to a computer to draw a proposal or counter-proposal, that person may be left behind. It is recommended that all engineers should be trained to make freehand sketches of their ideas.

Mathematics is already recognized as a core element of an engineer's education. Calculus, differential equations and linear algebra are necessary tools for all types of engineers. Structural designers can benefit from a deeper understanding of geometry, as geometry is a key attribute of structures. Additional studies in geometry, particularly differential geometry (which includes the geometry of surfaces), can extend the reach of a structural designer.

Picasso is quoted as saying, 'bad artists copy, great artists steal.' The author of this paper takes this to mean that repeating the designs of the past is uninspired, but understanding the ideas behind an earlier design can lead to inspiration and new creations. Structural designers should know the history of structures and the designers involved. They should be familiar with Telford, Brunel, Roebling, Maillart, Sukhov, Schlaich and many others.

NOTABLE STRUCTURAL ENGINEERS AND DESIGNERS		
Othmar Ammann	Antonio Gaudi	Isamu Noguchi
Benjamin Baker	Chuck Hoberman	Frei Otto
Isambard Kingdom Brunel	Heinz Isler	Ron Resch
Santiago Calatrava	Theo Jansen	Peter Rice
Félix Candela	Fazlur Khan	John Roebling
Jamie Carpenter	William LeMessurier	Les Robertson
Jorge Conzett	Fritz Leonhardt	Jorge Schlaich
Mike Cook	Robert LeRicolais	Mike Schlaich
Abraham Darby III	Sol Lewitt	Kenneth Snelson
Michael Dickson	Ian Liddell	Werner Sobek
Eladio Dieste	Robert Maillart	Juri Strasky
James Eads	Christian Menn	Vladimir Suchov
Gustave Eiffel	A. G. M. Michell	Anton Tedesko
Aldo Favini	Leon Moissieff	Thomas Telford
Ulrich Finsterwalder	Jean Muller	Eduardo Torroja
Miguel Fisac	Pier Luigi Nervi	Michel Virlogeux
Eugene Freyssinet	Laurent Ney	Chris Wise
Buckminster Fuller		Waclaw Zalewski

It is very unfortunate that most structural engineers are not taught the history of their profession. There are many brilliant ideas out there that can be molded into new designs, but this will only happen if structural engineers are aware of them.

Often a young designer feels that a design needs to be completely unique. While unique ideas can be exciting, the ability to take an established solution, such as an arch, and make it fresh is also important.

This is not copying in the sense meant by Picasso if the new creation is idea-based.

Engineers should be trained to approach a given problem as a challenge and to redefine the desired goal. In professional practice, structural engineers tend to accept an architectural sketch and to immediately start engineering a solution. A structural designer will take the architectural sketch as a possible suggestion or as the statement of a problem. A structural designer will explore the issues to be addressed and propose solutions that may have little resemblance to the original sketch but do address the fundamental issues it raises.

An unintended and unfortunate consequence of an education in engineering is the perception that there is one right answer to a problem. In structural design, there are many valid but different solutions to a problem. A related issue is that structural engineers need to lose the fear of being wrong that often leads to a fear of creating. Top engineering students are used to getting 'the right answer.' This leads to a fear of being wrong. Structural engineers are afraid to create because they are afraid of suggesting a solution that may not be the best or that may not be 'perfect.' An engineering education needs to stop implying that there is one right answer when, in general, there is not. In structural design, many of the initial ideas will not survive because they fail to address some aspect of the problem, but these 'failures' often lead to a better understanding of the problem and contribute to the final design. This fear of being wrong often gets in the way of a structural engineer's ability to create.

Structural engineers need to be able to accept critique and criticism; there is nothing wrong with proposing an idea that turns out to be a 'bad' idea. Engineers need to be able to loosen up, take feedback and not be defensive.

It is informative for students to be asked to solve a problem that they have not been taught how to solve. It forces the students to do research. Structural designers need to be constantly exploring new ideas. They need to be able to do research and keep learning.

The education of all engineers should include an exposure to the arts. For structural engineers and structural designers, this exposure needs to include the visual arts, particularly the history of art and architecture. Besides providing sources for ideas, this knowledge will help them communicate with their collaborators. Quite often, a design discussion will include references to works of art or architecture and it is very helpful if the engineer is familiar with these works.

Closely associated with a knowledge of art and architecture is travel. Seeing important works firsthand is invaluable. Even better than seeing them and photographing them is drawing them by hand.

Drawing an important bridge or building by hand makes one look much closer at how it comes together while developing an appreciation for systems and details.

Structural engineers need to realize that design is a team sport where you are collaborating with many, many people. It is very common that the final design reflects the contributions of several people; the final proposal can be different from any one person's initial ideas. Too often, a structural engineer or a structural designer worries too much about getting credit for an idea. This will limit their collaboration with others, which is so important to the design. If you are too worried about getting the credit, you are not a good collaborator. The structural engineer or structural designer should understand that, over time, credit will come. A strong ego is the enemy of design. If recognition and receiving credit is the most important thing to you, your career will be greatly limited.

Summary

Creating a structural designer is a step beyond creating a structural engineer. Educators need to recognize the difference between 'sizing' something and creating a structural design. It starts with recognizing that analysis and design are fundamentally different and, to paraphrase Hardy Cross,[2] analysis and sizing are essential but otherwise unimportant. Because structural designers will be creating new designs and new ideas, they need to be well educated in the fundamentals of engineering theory, behavior, mathematics, computational and graphic tools and the history of structures. Because structural designers will be creating 'the new,' they need to know how to do research and solve previously unaddressed problems.

Students also need to be taught how to explore, understand and possibly change the problem given to them. They need to abandon the idea that there is 'one right answer' to a structural design problem. They also should be encouraged to collaborate and avoid unnecessary impediments, such as egos and being overly concerned about receiving credit.

Designing the education of structural designers can make the path shorter for those with a natural inclination to be structural designers and can facilitate the participation of other structural engineers in structural design.

2 Hardy Cross, "Standardization and its Abuse," in *Engineers and Ivory Towers* (New York: McGraw-Hill, 1952), 141.

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