60th Anniversary Symposium of the International Association for Shell and Spatial Structures

IASS Symposium 2019

9th International Conference on Textile Composites and Inflatable Structures

Structural Membranes 2019

FORM and FORCE

7-10 October 2019, Barcelona, Spain

Carlos Lázaro, Kai-Uwe Bletzinger and Eugenio Oñate (Eds.)

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SUMMARY

INVITED SESSIONS

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7 – 10 October 2019, Barcelona, Spain
C. Lázaro, K.-U. Bletzinger, E. Oñate (eds.)

Connecting Engineering Rigor and Visual Creativity

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Abstract

This paper describes a studio-style project-based graduate course that introduces classic and computational approaches to creating design options for long span structures and tall buildings. The course aims to convey how an iterative design process serves to refine solutions that can be conceptually anticipated using methods such as Graphic Statics or the Maxwell Theorem, and validated through numerical analyses. While student teams employ engineering principles to explore relationships between form, geometry, and performance of structural systems, they also reconcile questions about the environmental impact, constructability, and visual strength of the designs. Learning from the best examples of built structures develops sensitivity to proportion and elegant structural solutions that merit architectural expression and convey economy of the design through thoughtful use of materials. In addition to structural engineering, students in the course have had a background in architecture, façade engineering, or mechanical engineering; therefore, designs reflect a variety of interests and require effective communication of ideas across disciplines. During field visits and guest lectures students gain additional insight into the engineering rigor and creativity in the real-world structures. Regular interactions and project reviews with practicing engineers emphasize critical analysis and optimizing load paths, structural systems, and connection details. A common thread in all class activities, inspired by David Billington's scholarship and teaching, is to understand the cultural and economic meaning of efficient forms that can be achieved through creative and disciplined structural design.

Keywords: conceptual design, form finding, optimization, spatial structures, tall buildings

1. Introduction

Among the most creative and challenging aspects of design is achieving technical and visual strength of structures that fulfill the goals of utility and value for users, while conserving public and natural resources consistent with the knowledge and tools that are available to designers. The notion that the highest achievements in design encompass appropriate social (costs and utility), scientific (form and materials), and symbolic (appearance and meaning) responses within the constraints of time and site conditions (among others), thus upholding the tradition of "S*tructural Art*", was defined through critical analysis of exemplary designs across the ages by David Billington (Billington [1]).

Engineers who holistically integrate elegant shaping with efficient material use and economy in construction, by employing inventive forms to span large distances and reach new building heights, have developed their artistry through experiential knowledge, rigorous application of engineering principles, and sensitivity to the human experience of structures – their aesthetics. Learning about the designers of exemplary structures reveals strivers dedicated to purposeful discovery and development of skill through refinements of design until simplified, essential solutions are found, which may be more challenging to achieve than a complex response that also satisfies design requirements.

This paper presents the activities in which students engage in the graduate course "Structural Design Project" to explore design strategies within the context of two projects, namely (1) a long-span roof, and (2) a tall building. The course is offered to seniors and graduate students studying at the intersection of engineering and architecture at MIT, and in particular, to the students in the Master of Engineering program focusing on Structural Mechanics and Design in the Department of Civil and Environmental Engineering. The students bring their interests in structural, mechanical, or geotechnical engineering, architecture, computational design, and experience from internships, research, or design practice to a dialogue that seeks to distill the complex design process into simple, clear concepts relating the form and behavior of a structure. Study of actual buildings that illustrate relationship between form and element forces, intuitive analytical and graphical techniques, and numerical modeling approaches are introduced with an aim to build upon the various students' experiences and create stepping stones toward their practical application in a new design.

A central course objective is to motivate student-driven learning about structural behavior as a result of geometry and materials, and to encourage students to convey their ideas in a concrete and clear manner to their peers and engineering professionals. Classic approaches to analysis, hand calculations and drawings, assigned readings, and advanced computational methods are used to illustrate possible paths from complexity to the simplified and clear solutions that can help students appraise design alternatives before they engage in a detailed design of a structure. Among the questions being asked in the course are: What lessons about creative design solutions can successful engineering works of the past offer? What does it mean to construct an optimal structure? How can complementary disciplines work together to improve the design of structures in the future? What are the engineers' and architects' roles in consideration of resilience, sustainability, and embodied energy of structures? How can we measure success of a design?

2. Overview of the course objectives and activities

The course aims to integrate educational approaches from the engineering and architecture curricula, to combine practical design and research, and to couple the academic learning with insights and expertise shared by highly regarded practicing designers through guest lectures and reviews of students' projects. Another central idea is to empower the students to work both independently and as part of a team on responding to open-ended questions that range from qualitative analyses of the form and load paths in precedent structures to the comparison of stiffness gains resulting from structural system selection in their own designs.

Throughout the two course projects (with each completed in one semester) the students should become:

- Conversant with technical terminology associated with long-span and tall structural systems
- Aware of the design legacy related to historic and modern-day spatial structures and tall buildings, including major engineering works, and analysis and construction methods employed by designers who influenced the profession
- Adept at generating design options and communicating the relationship between their form and structural action
- Proficient in simplified and numerical methods of analysis for systems resisting static and dynamic loads

2.1. Course topics

Class discussions follow the course topics through lectures, student presentations, assignments, engineering seminars, and class project reviews. For the project in which students design a roof structure to enclose an existing courtyard on the MIT campus the topics include: Study of Precedents and Art in Engineering, Introduction to Graphic Statics and Maxwell's Theorem, Form and Behavior of Spatial Structures, Structural Materials and Systems, Numerical Methods of Structural Analysis, Fabrication and Construction, Connections and Cladding, and Environmental Impacts of Design.

Students begin the project work by visiting the prospective building site on the campus to explore the existing structure and surrounding buildings in order to understand the functional requirements of the new space (for example, location for quiet study and reflection or a dynamic environment for collaboration and gathering), the style, materials, and load bearing capacity of the existing buildings that could dictate the form of the new roof and ensuing loads that may (or may not) be supported at particular locations. The students obtain as-built structural and architectural drawings that guide their subsequent site visits and learning about actual conditions (such as laboratory or library space adjacent to and below the courtyard, foundations and soil properties, and access limitations for the construction equipment), which may define design constraints requiring specific solutions. Students also obtain information about the city and campus zoning, regional climate and hazard data to be incorporated in resilient design concepts, and identify the governing building standards.

2.2. Design exploration

Classical methods for finding optimal structural shapes based on specified material strength, element forces, support reactions, or deflections are introduced through class exercises that demonstrate the use of Graphic Statics and the Maxwell Theorem of optimal load paths in realistic examples drawn from built structures (Zalewski and Allen [2], Baker [3]). These are followed by workshops, led by advanced graduate students in architecture, that focus on computational tools for parametric study of design options including Grasshopper (for Rhinoceros by McNeil and Associates), Karamba, and Kangaroo (Grasshopper analysis and form-finding tools).

In a questionnaire at the start of the term students relate their interests and prior areas of study (e.g., structures, architecture, construction, preservation of historic buildings, geotechnical engineering, and building systems) as well as modeling experience (finite element software for classical analysis, form finding, optimization, physical models, and drawing or sculpting). While approximately one half of the students in the class have had some experience with numerical parametric tools, the classic methods are usually new and surprising to most students for their visual and direct feedback loop between a geometric arrangement in a structure and the resulting forces or deformation.

These examples of parametric analyses lead to the study of precedents, for which the students are asked to have an eye on the flow of forces and connection details when assessing how the overall form and structural action relate to the visual appearance of a built structure. The study of precedents aims to connect the theoretical concepts learned through idealized images of structural elements with the composition and behavior of a whole structure in the context of the site, materials, design decisions, and construction. For example, parallels are drawn between the theoretical analyses of an idealized arch and a built vault or a dome, in order to illustrate potential instabilities due to permanent and variable loads, interactions between systems in a structure (e.g., forces exerted by a vault on the supporting structure), and placement of stabilizing elements, such as tension ties or rings to control horizontal thrust at supports.

Student teams develop three options for their concept design, create hand drawn sketches, and include images of selected precedents for each option along with written reflections on these structures. They are asked to describe the characteristics of each concept design: "What will it look like? How would the structure support the loads? Which materials will be used? How will the roof impact the courtyard?"

In parallel with potential concept designs, teams brainstorm how they would construct a physical model using digital fabrication techniques to represent the overall form of the roof structure and convey design intentions including force paths, connection details, stability, and support conditions. Following team discussions, instructor's feedback, and creating physical model schematics, student teams narrow down their selection to one concept design as the basis for their project. Appropriate structural systems are investigated in an iterative process of assessing potential roof support locations, spans, spatial forms, and by anticipating design and construction impacts of selected geometric arrangements.

Initial iterations based on hand sketches and simplified calculations are followed by the form-finding process using Graphic Statics or numerical tools. Design is guided by students' decisions "to make the structure more efficient by minimizing bending", "selecting shapes with double curvature instead of single curvature," and "connection mechanisms that allow prefabrication," as stated in the final project reports. Students develop solutions for connection details in the main elements of the structure and as part of the cladding design. Based on final material weights the embodied carbon of the structure is calculated and compared to similar buildings to evaluate the environmental impact of the design. In a final oral presentation of the project to the Engineering and Architecture faculty, practicing engineers, and peers, students address questions and critique about their designs (Figure 1).

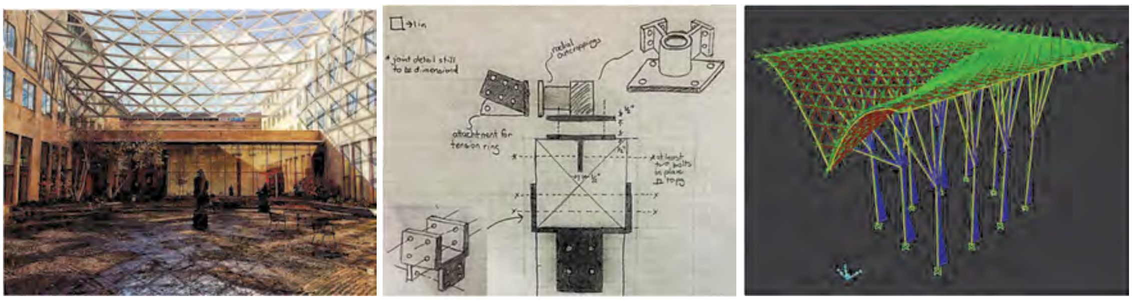

Figure 1: Rendering of a roof design, connection detail drawing, and image from a numerical analysis.

The second project responds to realistic design requirements for a mixed-use tall building situated in New York City. The students are asked to design structural solutions based on considerations of resilience, sustainability, socio-economic and environmental impacts, aesthetics, and cost. Through lectures, assigned readings, presentations and reviews of the project deliverables, individual and team assignments, the student-driven study explores class topics that include: Classifying Tall Building Forms and Structural Systems, Approaches to Conceptual Design, Load Distribution in Precedent Structures, Defining Structural Stiffness, Identifying Optimal Layouts of Lateral Force Resisting Systems, Anatomy of a Tall Building, Connecting Structural Systems, and Structural Performance. Students develop the project from concept to a detailed design, and complete five Design Studies, which are assignments that align with the course topics, and include portions that are submitted individually and by the teams of three or four students. While the team assignments aim to foster collaboration, the individual assignments challenge the students to generate diverse solutions, enrich the discussion, and in some cases, to step out of their comfort areas defined by prior experience.

More than to other aspects of design in the early conceptual stage, attention is given to the shape of a tall building, as one of the key determinants of structural efficiency. Study of historic examples, optimal structural systems for a given range of height, and building typologies driven by socio-economic factors (e.g., flexibility of floor plates to accommodate shorter lease terms in the U.S., versus the required proximity to natural light that motivates designs in Europe) takes place in parallel with generation of initial concept designs. Structural concepts including the framed, braced, and modular tube, outrigger structure, diagrid and exo-skeletal systems are considered in view of the building scale, economy, and appearance. Design begins with sketches and simplified calculations, on paper and chalkboard. Numerical simulations are used to validate static and dynamic structural behavior in the detailed phases of design. Students' proposals are inspired by their research interests, class discussion, and guest lectures. For example, Katia Bertoldi's presentation of the work by Overvelde et al. [4] inspired a student team to explore building forms based on octagonal origami shapes, as seen in Figure 2.

Distinguished engineers often reflect upon the ways in which collaboration and integration of goals across disciplines contribute to the success of projects. Writings on this topic by Ove Arup, Peter Rice, Jörg Schlaich, Leslie Robertson, and Bill Baker are among the class readings that the students explore as they embark upon their own collaborative design effort. An optional peer review questionnaire, outlined early on in the term, was completed by all students in the form of Google sheets upon finalizing the project. Among the merits that the students evaluated were peer reliability (how confidently they could depend on a person to complete his/her task), creativity (how inspiring and original were the solutions offered for the project-related questions), and effort (initiative and interest in research and development of project decisions). Students' comments additionally characterized collaborative qualities:

> *"Creative thinker, problem solver, […] is both an open-minded and pragmatic structural engineer, and her approach is highly suitable to designing innovative systems that are feasible and reasonable."*
>
> *"None of the design decisions were made "because this is the only thing I know how to design", […] was always willing to discuss different options, list pros and cons, always looking for supportive research materials and solutions."*
>
> *"Negotiated with architecture to push and pull between form and function. This requires great problem solving."*
>
> *"Sometimes during group meetings he would solo by himself rather than contributing to the discussion."*

In a studio class that aims to motivate creative thinking rooted in disciplined application of engineering fundamentals, it may be instructive to engage the students in defining the criteria by which collaboration can intrinsically enhance the quality of a design.

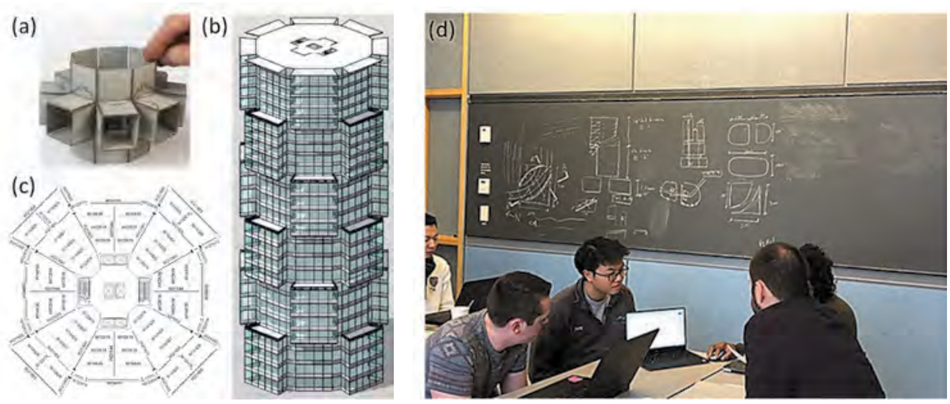

Figure 2: Tall building design: (a) origami inspiration (image reproduced from Overvelde et al. [4]), (b) building shape, (c) building floor plan, (d) project review with Paul Richardson from BuroHappold.

2.3. Design legacy

The course is conceived as a design studio that builds upon the scholarship in the theory of structures with a study of engineering heritage to enable development of practical design strategies that are applicable in the modern day interdisciplinary design environment. To explore the legacy of structural design is to recognize the evolution of form, and also to see how the greatest designers understood *and* conveyed their ideas both conceptually and practically. Using the self-study model, students select an eminent structural engineer whose brief biography they write and present to the class. They document the engineer's formative years in life, education, and career, major accomplishments, and influences by (and on) other engineering works, architecture, art, and people. Biographies also include anecdotes telling of a personal outlook or experience and inspiring quotes such as these:

> *"There is nothing more noble and elegant from an intellectual viewpoint than this – resistance through form."* (Eladio Dieste)

> *"As structural engineers, we have a responsibility to delight clients and the public, not just ensure that structures do not fall down."* (Jane Wernick)
>
> *"It is today necessary to achieve a more efficient collaboration between architectural design, statical study, and the contribution of a knowing competence in construction."* (Pier Luigi Nervi)

Images or hand drawn sketches by the students show designs or innovative concepts that the designers developed (Figure 3). Over the course of a year, students learn from their peers about more than twenty prominent engineers, and co-author a booklet in a series created by the students in the prior years of the program. These biographies affirm the significance of role models and mentors, and uncover various, sometimes winding, paths that have led to exceptional works of engineering. They are the result of talent, enthusiasm, and dedicated development of skill over time through rigorous application of mechanics and loyalty to the aesthetic ideals. They prove the adage that "Rome was not built in a day," and that design education should be grounded in the study of exemplary structures from the past.

Numerical tools for systematic generation of options and analysis of forms based on specified quantitative objectives provide powerful methods for assessing efficiency of a particular distribution of material in a structure. However, they may obscure some of the parallel relationships between performance goals, construction, and the behavior of built systems. To cultivate the "feel" for practical aspects of constructing and controlling load paths through structural elements and connections, students in the most recent class on spatial structures began their study by creating a physical model, as shown in Figure 3. While the architecture students were more comfortable than some engineers with the process of rapidly generating options to fabricate the form, the challenge for all was to authentically model the structural concepts, including joint restraint, membrane action, or system stiffness. Especially relevant for the design of lightweight spatial structures, whose presence in practice has significantly increased in recent decades, modeling (and testing) the complex structural action remains a goal for future classes.

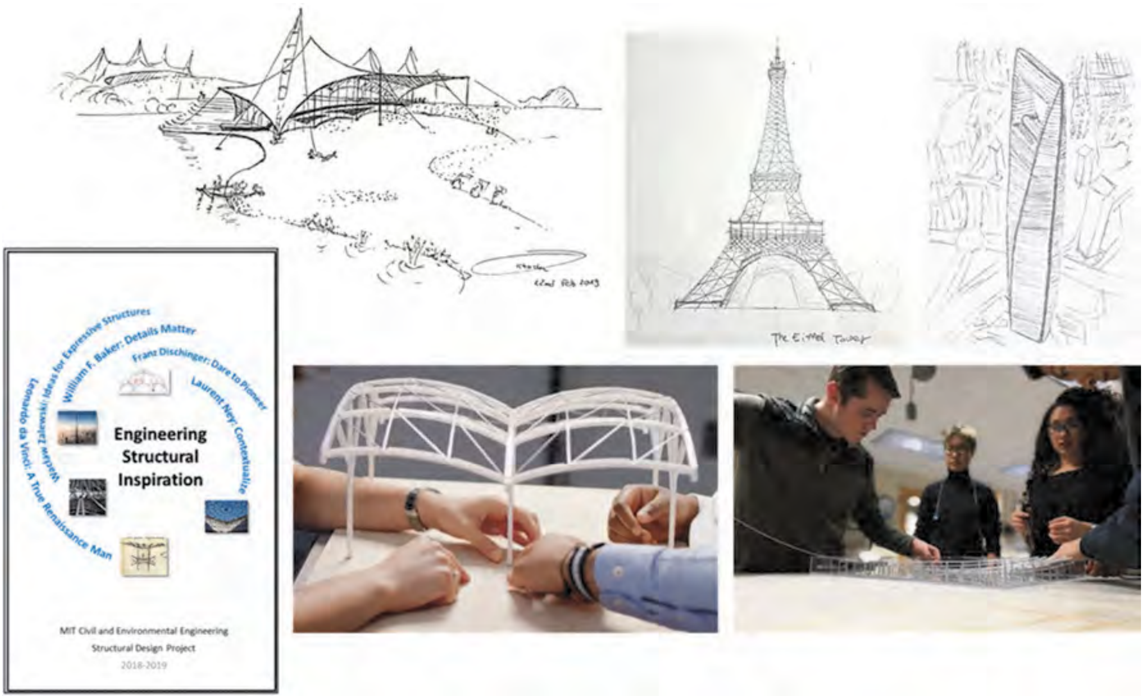

Figure 3: *Top row*: students' drawings of the Olympic Stadium in Munich, The Eiffel Tower, and Shanghai World Trade Center; *Bottom row*: booklet of eminent engineers' biographies (left), and physical model building.

2.4. Conversation with design practitioners

When presenting project ideas to the leading practitioners, students can observe *how* they assess a proposed concept and offer suggestions. Some engineers use simple calculations and hand drawn sketches while engaging in playful conversation through a rapid succession of "why" and "what if" questions. Exceptional skills in generating creative design options seem to surpass the sum of talent, practice, and time – but this sum can certainly engender creativity. Various engineers may offer similar or entirely different critiques of a particular design, and when a challenge resonates with the students' vision, the ensuing exchange of ideas may even spark questions worth exploring further, outside of the scope of a class project.

In addition to interacting with students through project reviews, the invited engineers present lectures that reflect their expertise and the state of the art in built designs that the course addresses. This academic year Laurent Ney delivered the Edward and Mary Allen Lecture in Structural Design entitled *Are Bridges Designed*?, Tim Elliassen from TriPyramid presented *Glass as a Structural Material*, Ramon Gilsanz from GMS explored *Design Options and Decision-Making for Long-Span Roofs*, Yasmin Rehmanjee from BuroHappold introduced *Detroit Hudson's Rising*, Joseph Provenza from WSP discussed *Computational Design for Complex & High-Rise Structures*, Wolf Mangelsdorf from BuroHappold described designing the *Morpheus Hotel*, Angie Neefus from Eckersley O'Callaghan spoke about *Looking Through Glass at the Principles of Structural Engineering,* and Zoe Temco from Arup presented *Data, Datums, and 3D Models*. In recent years, among the invited lecturers were Bill Baker and Georgi Petrov from SOM, Leslie Robertson of LERA, Eli Gottlieb and Hi Sun Choi from Thornton Tomasetti, Paul Richardson from BuroHappold, Powel Draper from Schlaich Bergermann Partner, and Marc Steyer from Tipping Structural Engineers.

2.5. Visiting structures and design offices

In conversations with practicing engineers one learns about examples that underscore the importance of understanding the economy of the construction process and the constraints imposed by the site. The engineers point out personal experiences, including successful partnerships with architects and construction professionals, as well as instances when problematic details required development of alternative solutions during construction, some of which impacted the cost, quality, or schedule of a project.

Visits to structures and design offices are organized during the fall or spring term and the Independent Activities Period in January, when classes are not in session (Figure 4). Conversations during these visits are very informative and timely, as the students learn about remarkable projects from engineers at different stages in their careers. While considering their own post-graduation paths, students also recognize the variety of possibilities for learning and growth within major international firms and smaller specialized design offices.

Figure 4: (left to right) Visit to the Moynihan Station in New York with Alexandra Cheng from Schlaich Bergermann Partner, Manhattan West site in New York with Georgi Petrov from SOM, TriPyramid Structures in Westford, MA, with Tim Eliassen, and Rockefeller University River Campus with Turner Construction.

3. Conclusion

The use of classic engineering and graphical methods that transparently relate geometry, equilibrium of forces, and deformation of a structure engenders an intuitive understanding of form and frees the exploration of possible and rational options in the conceptual design phase. Iterative refinement of form that occurs through a combination of efforts, including critical study of built structures, analyses performed by sketching and simplified calculations, and physical modeling and testing, enables the designer to calibrate numerical simulation of structural behavior and validate the analyses in the detailed phases of design. When the search for new, efficient, and beautiful structural patterns, forms, and systems is energized by insights from actual best works and realistic constraints on resources (both natural and monetary), designs that are respectful of nature and human culture can emerge.

Acknowledgements

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Current Realities and New Opportunities for Efficiency, Economy, and Elegance in Bridge Design

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Abstract

This article examines the relations that link efficiency, economy, and elegance in bridges. The relation between efficiency and economy depends on the ratio of the cost of labour to the cost of materials. When this ratio is low, as it was prior to World War II, efficiency and economy can be embodied in the same structure. When this ratio is high, as it has been since the 1960s, they cannot. In the future, it is likely that the use of robots in bridge construction will lower the ratio of the cost of production to the cost of materials, thus restoring efficiency to its previous role as an enabler of economy. Although it is possible for bridges to be endowed with both economy and elegance in the absence of efficiency, the range of choices available for the design of this type of bridge is tightly constrained. The ability of designers to utilize this limited scope for creative decisions is the primary factor in determining the aesthetic significance of this type of bridge.

Keywords: Bridges, aesthetics, efficiency, economy, elegance

1 Introduction

The central message of David P. Billington's scholarship is that the greatest works of structural engineering are distinguished by three primary qualities: efficiency (minimum materials), economy (minimum cost), and elegance (maximum aesthetic expression) [1]. The standard of excellence Billington thus defined acknowledges the important fact that works of structural engineering have a dual essence. First and foremost, they are works that perform a practical function, and like all practical objects, they are generally expected to perform their function at a reasonable cost. Structures are also visible, and like all visible objects they create an impression in the people who look at them. Because structures are highly prominent and relatively permanent features in the visible environment, the visual impression they create is particularly important. At their best, structures can take on rich aesthetic significance by virtue of their visible characteristics. Billington demonstrated that the practical and the visual natures of structures are intimately related. Through his detailed studies of the bridges of Swiss engineer Robert Maillart, Billington showed conclusively that aesthetic significance is not something that must be added onto a purely functional structure, but rather is a quality that can originate from the visual expression of the way it performs its practical function.

The realities of current bridge design practice, however, have caused engineers to question whether or not the ideals defined by Billington can actually be achieved. This proposition is examined in reference to the bridge shown in Figure 1, a single-span overpass consisting of parallel precast pre-tensioned concrete I-girders and a cast-in-place concrete deck slab.

Figure 1: Estaire Road over Highway 69, Ontario, Canada

This is not an elegant bridge. Its superstructure is deep and looks heavy. The visible impression it creates is at best mediocre.

Although it is difficult to make a definitive statement regarding the efficiency of this bridge on the basis of a single photograph, there is certainly no visible expression of efficiency. Simply supported spans are intrinsically less efficient than spans that can develop negative moments at their ends, which could have been done had the span been made continous with the abutment walls. The constant cross-section is not consistent with the variable distribution of bending and shear demand along the span, which implies that the bridge contains excess material that could have been eliminated.

This bridge was, however, the least expensive means of performing the required function of this crossing and thus embodies Billington's ideal of economy. By the time this bridge was designed, precast pre-tensioned concrete I-girders with cast-in-place concrete deck slab had already been established as the most cost-effective structural system for this type of crossing. This determination was made by many designers and owners independently, on the basis of actual cost data from a large number of similar bridges built throughout Canada.

The fact that the Estaire Road bridge is economical, of at best dubious efficiency, and not elegant is not particularly significant in itself. There are many bridges with these attributes. Of far greater significance is the fact that for this type of crossing in Canada, it is actually difficult to improve on efficiency and elegance without compromising economy.

This article seeks to determine whether or not this apparent incompatibility of Billington's three ideals in certain common design situations is the result of real impediments that are out of the control of designer and owner. To accomplish this, it will examine the relations that link each pair of these three ideals: efficiency and economy, efficiency and elegance, and economy and elegance.

2 Efficiency and Economy

2.1 Basic Relations

The relation between efficiency (minimum materials) and economy (minimum cost) can be described using a simple mathematical model of construction cost. In this model, total cost C

of a given bridge is expressed as the sum of the cost of materials M and the cost of labour L. The cost of materials is defined as the product of the total quantity of materials Q and the unit cost of materials c_m. (For convenience, it is assumed that the given bridge is built of a single material.) In a similar manner, the cost of labour is defined as the product of the total quantity of labour T and the unit cost of labour c_l. This yields the following equation:

$$C = Qc_m + Tc_l \tag{1}$$

This equation can be used to study the effect of a change in Q on total construction cost for a set of alternative designs, all of which perform an indentical function at the same site, by expressing T as a function of Q. In his analysis of construction costs of concrete bridges built in Switzerland in the 1950s and 1960s, Menn observed that a decrease in T required an increase in Q [2]. This makes sense, since quantities Q and T are related by the geometrical complexity of structural systems and components. An increase in geometrical complexity can produce a reduction in material quantity and will almost always increase the quantity of labour. Conversely, a decrease in geometrical complexity can reduce T but will almost always increase Q.

Gauvreau proposed the following simple formulation of the relation between T and Q for a given set of alternative designs that satisfy the same functional requirements for the same site [3]:

$$T = \frac{1}{\alpha(Q - \beta)} \tag{2}$$

Parameter α is a constant that is related to productivity, i.e., the quantity of labour required to install a given quantity of materials. Parameter β can be regarded as a theoretical lower limit for the quantity of materials. The practical lower limit for the quantity of materials, Q_{Mmin}, corresponds to a design that satisfies all applicable requirements and will be greater than β.

Substituting Equation 2 into Equation 1, taking the first derivative of C with respect to Q, and setting this expression to zero yields an expression for the quantity of materials that minimizes total construction cost, Q_{Cmin}:

$$Q_{Cmin} = \beta + \sqrt{\frac{c_l}{\alpha c_m}} \tag{3}$$

According to this simple model, therefore, the most economical design within the set of alternatives will have quantity of materials Q_{Cmin} as defined in Equation 3. The value of Q_{Cmin} varies with the ratio c_l/c_m.

For a given set of alternative designs, the quantity of materials corresponding to minimum cost, Q_{Cmin}, will always be greater than or equal to the minimum practical quantity of materials Q_{Mmin}. Although this simple model of construction cost does not provide an explicit expression for Q_{Min}, it is evident that it will be a constant for a given set of alternative designs and hence independent of unit costs c_l and c_m. As the ratio c_l/c_m decreases, quantity Q_{Cmin} will move closer to Q_{Mmin}, i.e., the prevailing economic conditions become more conducive to the creation of designs that combine the ideals of efficiency and economy. Under these circumstances, efficiency acts as an enabler of economy. As the ratio c_l/c_m increases, quantity Q_{Cmin} will move away from Q_{Mmin}, which makes it more difficult to create a design that combines that the ideals of efficiency and economy.

2.2 Historical Evolution of the Relation Between Efficiency and Economy

Prior to World War II, the ratio c_l/c_m was generally low and hence so was Q_{Cmin}. As a result, efficiency was a strong enabler of economy. This made it possible for Maillart to design bridges that embodied both efficiency and economy.

After World War II, the ratio c_l/c_m increased rapidly in industrialized countries due to a sharp increase in wages c_l. According to Equation 3, this would be expected to produce an increase in Q_{Cmin}, i.e., a increase in material quantities. This prediction is corroborated by Menn [2], who observed that designers sought to limit the increase in total construction cost C due to the increase in c_l by reducing the total cost of labour $L = Tc_l$. This was accomplished by means of designs that reduced the total quantity of labour T, which mainly involved reducing the use of falsework and re-using formwork through the use of constant cross-sections, constant span lengths, and large precast concrete components. These measures generally required a greater quantity of materials than would otherwise have been necessary, and thus decreased efficiency. Under these economic conditions, it is thus difficult to create designs that embody both efficiency and economy.

Economic conditions have not changed significantly since the 1960s, insofar as the ratio c_l/c_m has remained high. For most short span bridges, the savings in labour arising from the use of large standardized prefabricated components outweigh the additional materials that correspond to the use of constant cross-sections. Efficiency and economy are generally incompatible for most bridges other than very long-span structures.

It is likely that the current economic situation will soon undergo significant change. Robots have already transformed manufacturing by lowering the cost of production compared to the use of human labour. They are poised to bring about a similar transformation in heavy construction.

To study the effect of this transformation on the relation between efficiency and economy, it will be assumed that robots will perform tasks that are essentially identical to those performed in the construction of current structural systems. (Robots that assemble reinforcing steel cages for concrete structural components are one example of this type of system that is currently under development [4].) This will make possible a more direct comparison of the cost structure of bridges built by human labour and those built by robots.

Robots will be used in bridge construction if and only if they lower the cost of production $L = Tc_l$ relative to the use of entirely human labour. The effect of a decrease in L can be estimated using the expressions developed previously. Using the expression for T from Equation 2, total cost of production L is expressed as follows:

$$L = \frac{c_l}{\alpha} \frac{1}{(Q - \beta)} \tag{4}$$

Parameter β is a property of the design requirements of the specific crossing and thus is not affected by the method of construction. For a given quantity of materials Q, therefore, a reduction in the cost of production will occur if and only if there is a reduction in the ratio c_l/α. This requires a reduction in the unit cost of production c_l, an increase in productivity α, or both. It can be seen from Equation 3 that reducing the ratio c_l/α will reduce the quantity of materials Q_{Cmin} that corresponds to the minimum cost design, thus moving it closer to the minimum practical quantity of materials Q_{Mmin}. This implies that use of robots will make it economically worthwhile to design bridges that consume less material, i.e., bridges with efficient structural systems.

Just as designers responded to the challenge of controlling total construction cost in an era of increasing labour rates by producing structural systems that consumed less labour, there is little doubt that they will respond to the opportunity presented by lower overall cost of production made possible with robotic construction by designing structural systems of greater efficiency. By restoring efficiency to its previous role as an enabler of economy, robots will make it possible once again for efficiency and economy to be embodied in the same bridge.

3 Efficiency and Elegance

Minimizing materials requires structural components to be shaped such that capacity is close to demand at as many locations as possible. Since demand generally varies throughout a given structure, an efficient structural geometry will vary correspondingly. The visible form of the structure thus determined by the flow of forces will reflect the underlying state of equilibrium. Efficiency thus makes the flow of forces visible and in so doing can be an important source of aesthetic significance.

Figure 2: Royston Road Underpass, British Columbia, Canada

The effect of efficiency on the visual impression created by a given bridge can be seen by comparing the bridge shown in Figure 2 to the Estaire Road bridge of Figure 1. The two bridges perform essentially the same function, yet they create very different visual impressions. Instead of the deep, heavy looking constant-depth girder of Estaire Road, Royston Road has a variable-depth girder that is remarkably thin at midspan. The girder at Royston Road is not simply supported as at Estaire Road but rather is made continuous with the abutment walls, which enables the girder to develop negative moment at its ends. These measures were designed into Royston Road to minimize materials, i.e., to make it efficient. They also are the primary elements that not only define its visual impression, but also enable this visual impression to be superior to the one conveyed by Estaire Road.

As stated in Section 2, efficiency and economy are compatible only when the cost of labour is low relative to the cost of materials. This was the case when Maillart designed his bridges and his works derive a significant portion of their aesthetic significance from the visual expression of efficiency. This has not been the case, however, since the 1960s in the industrialized world [2]. This implies that economical bridges cannot currently rely on efficiency as a source of aesthetic significance. As long as the cost of production remains high relative to the cost of materials, using efficiency as a source of aesthetic significance will require paying a premium over and above the most economical design.

4 Economy and Elegance

Bridges can embody economy and elegance in the absence of efficiency. The Bridge over the Rhine at Bad Ragaz (Fig. 3), which was designed by Christian Menn and built in 1962, is an example of a strikingly handsome bridge that does not project a strong visual impression of efficiency. The constant depth girder gives no indication of the distribution of forces within the structure. This is an economical bridge that derives its economy to a large extent from its use of constant cross-sections and repetition of other details to minimize labour, rather than a strict minimization of materials. It nonetheless creates a strong and positive visual impression.

Figure 3: Bridge over the Rhine at Bad Ragaz, Switzerland [5]

For bridges that must be economical but, due to a high ratio of the cost of labour to the cost of materials, cannot also be efficient, the possible sources of aesthetic significance are limited. For his design of the Bad Ragaz bridge, Menn drew on two important sources: (1) shaping of structural components and (2) the visual expression of practical innovation.

Shaping of structural components is understood here to mean the visible relations among the most important structural dimensions, which include span length, girder depth, pier width, and pier thickness. The visual impression created by the Bad Ragaz bridge is due in large part to the shaping of these components, which was informed by Menn's impeccable sense of proportion. The bridge looks right in every regard and it is difficult to imagine how it could be improved by changing any dimension. The shape of every structural component is functional and minimalistic; Menn made no attempt to embellish them in any way. He chose the dimensions of these components in the knowledge that for many of them, small changes can have a significant effect on the overall visual impression but will have a negligible effect on cost. This is where Menn excelled, since he embodied the rare combination of a strong aesthetic sensibility, which enabled him to choose dimensions that made the structure look good, and an unparalleled understanding of structural behaviour, which enabled him to be sure that his aesthetic choices could be made without having a negative effect on economy.

The visual expression of practical innovation was identified by Gauvreau [6] as an important source of aesthetic significance. Solving practical problems better than they have previously been solved is the primary motivator of engineering innovation. The new ideas incorporated into the solution of these problems can be associated with new visible forms that could not otherwise have been conceived. At their best, these forms can take on aesthetic significance that is tightly bound to their underlying utility yet also transcends it. For the Bad Ragaz bridge, the problem was to design an economical bridge that was curved in plan (1000 m radius) and which required sharply skewed supports (average skew angle of 40°). Menn's solution was unprecedented at the time of its construction: a continuous single-cell box girder with main span of 82 m and a relatively slender span to depth ratio of 25.2. To demonstrate the validity of his design at a time when digital computers were not used by bridge designers, Menn developed a simple and rational method of calculating the forces present in curved box girders on sharply skewed supports [7], an important innovation in itself and a key component of the design process for this bridge. The visual impression created by the structure that arose from this act of innovation is bold and strong, and the creative spirit that guided its design is still evident in its visible form, even though this bridge was built over fifty years ago.

Unlike efficiency and economy, which can be compatible or incompatible depending on the ratio of the cost of labour to the cost of materials, there do not appear to be any factors outside the control of the designer that prevent economy and elegance from being embodied in the same bridge, even when economy is incompatible with efficiency. In such cases, drawing from the primary sources of aesthetic significance (shaping of structural components and the visual expression of practical innovation) generally requires that designers be highly competent and creative. The challenges of designing bridges that are economical and elegant when they are prevented from being efficient also depend to a large extent on the range of feasible options available to designers. This range is determined by the complexity and the uniqueness of the design situation.

Compared to the Estaire Road Bridge (Fig. 1), the Bridge over the Rhine at Bad Ragaz (Fig. 3) was a complex design situation. Bad Ragaz is a relatively long bridge (total length 198 m) on a horizontal curve that spans a fast-moving river and flood plain, and requires sharply skewed supports. Estaire Road, in contrast, requires a single span of about 45 m and square supports. Greater complexity of the design situation can make the design process more difficult, but it also offers a greater range of feasible solutions and hence greater scope for creative decision making.

The bridge at Bad Ragaz is also a relatively unique design situation. The site-specific requirements and constraints are unlikely to have been duplicated at other bridges. Estaire Road, in contrast, is a very common design situation. There are many overpasses that have practically identical span, width, and geotechnical conditions. This implies that there would have existed an extensive body of knowledge of previously completed similar bridges, from which the best solution could have been readily determined. This would have significantly narrowed the scope of creative work required of the designer. At Bad Ragaz, in contrast, there was no similar "optimal" solution that was known in advance of the design. This required that the designer engage in a more extensive creative process to determine the most suitable solution.

5 Conclusions

Based on this examination of the relations linking efficiency, economy, and elegance in bridge design, it is possible to answer the question of whether or not all three of these ideals can be embodied in common types of bridge such as Estaire Road (Fig. 1).

The question of whether or not efficiency and economy can co-exist in the same structure depends on prevailing economic conditions, i.e., the ratio of the cost of labour to the cost of materials. This is out of the control of designers and owners. Currently, this ratio is high, which means that, except for long-span bridges, the most economical solution will require a quantity of materials that is greater than the most efficient solution.

The current incompatibility of efficiency and economy implies that bridges that must be economical cannot derive their aesthetic significance from the visual expression of efficiency. Although it is possible for a given bridge to embody economy and elegance in the absence of efficiency, the available sources of aesthetic significance are limited and drawing on these sources requires highly competent and creative designers. For design situations that are relatively simple and common, such as Estaire Road, the optimal solutions will have in many cases already been established, which further limits the scope available for shaping of structural components and the visual expression of practical innovation.

It is expected that autonomous robots will eventually replace human labour as the primary means of production in bridge construction. This will reduce the ratio of the cost of production to the cost of materials, and is thus likely to restore efficiency to its role as an enabler of economy. This will enable efficiency and economy to be embodied in the same bridge, and thus will make it possible for common types of bridge such as Estaire Road to derive aesthetic significance from the visual expression of efficiency.

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Exploring the Ideals and Character of Structural Elegance

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Abstract

Strength is common to all structures, but high performance requires that strength be provided efficiently, as demonstrated by minimal material use. Through form optimization, prestressing and other strategies, performance is made efficient, and the structure has the potential for visual elegance. Material economy is also the source of "leanness", an absence of superfluous mass that is key to structural beauty. Visual transparency is corollary to leanness, and structural beauty demands that non-structural elements not obscure the structural form. When a subjectively chosen structural concept is refined through analysis and judgment into an elegant final form, a unique design may appear the predestined solution to its load-bearing problem. The paper explores structures in nature, including the musculoskeletal system of the human body, as models for understanding structural beauty.

Keywords: High performance structures, gothic cathedrals, concrete shells, architecture, lightweight construction, form resistance, adaptive form resistance, internal resistance, liechtbau, human form.

1. Introduction

The Tower and the Bridge [1] and other publications by David Billington have informed and inspired the author and others who share Billington's passionate interest in structural aesthetics. The book describes "structural art" as the product of three ideas: efficiency (minimum materials), economy (construction simplicity, ease of maintenance, and integrated form), and engineering elegance. Efficiency and economy are readily defined - efficiency measurable as the ratio of weight/area, and economy as the ratio of cost/area. In defining elegance, though, Billington faced the imposible task of defining artistic merit itself, and with limited success. He lists contrast and affinity with the structure's context as elements of elegance, but these are only two of many ways we might define elegance (and beauty itself). This author can define elegance no more definitively than Billington. However, routine experience of the structures of nature and of our own bodies have strong parallels to our appreciation of beautiful structures that provides clues to the sources and character of structural elegance.

2. The High Performance Ambition

An expertly performed high jump (Figure 1) is one of sport's most beautiful and iconic movements. In the contemporary technique, brought to prominence by the American Dick Fosbury, the athlete bounds towards the bar and springs from the ground to lift his center of gravity, at the same time rotating his torso until his back faces the bar. He snakes his body over it – head first, then shoulders, hips, and legs, before dropping to his back in the landing pit. Fosbury parlayed the unconventional technique to a gold medal at the 1968 Mexico City Olympics, after which it became known as the Fosbury Flop.

The name belies the beauty of a well-executed flop and its advantage over the previous standard – the straddle. A straddler clears the bar facing down, with his body parallel to the bar, so that head, torso,

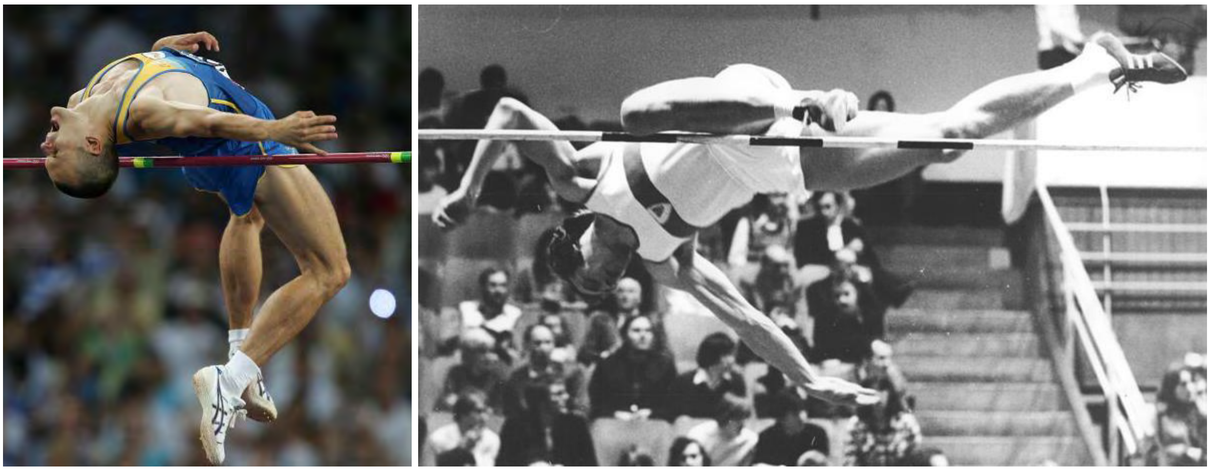

Figure 1. Well-executed flop (left) and straddle (right) high jumps. (Right image Bundesarchiv,Bild 183-S0305-0030/CC-BY-SA 3.0)

and legs pass over it nearly simultaneously. To clear the bar, the straddler must lift his center of gravity about 10-20 cm above the bar. In contrast, the backwards, serpentine movement of the flopper allows him to pass cleanly over the bar while keeping his center of gravity critical centimeters *below* it. If the jumper imparts the same upward thrust as he springs from the ground using either technique, the flop allows him to clear a higher bar. Fosbury's gold medal jump was ungainly next to the well-honed movements of the best straddlers, but jumpers that followed him gradually refined the technique. Their skill, combined with the flop's growing familiarity, make its best practitioners appear natural and graceful as they clear bars placed at heights well above their heads.

The photo captures a well-executed flop as the jumper passes over the bar. The power of the image reflects both the physical beauty of the athlete and the elegance of his technique. He has optimized the form of his body to its task, with the backward flex in his neck and torso and precise positioning relative to the bar conveying the efficiency of his movement. His body is hard-muscled, stripped of excess, and his entire being - from outstretched arm to gaping mouth - conveys singularity of purpose in maximizing his height of clearance. He has relaxed muscular tension that does not aid in clearing the bar, and the legs that have done their work in springing from the ground stream fluidly behind him. Experts might parse his motion into dozens of discrete elements, but it is performed with a fluidity that makes it appear irreducibly simple. The aspiration of the athlete inspires us. The aspiration of structures that span great distances with minimal mass inspires us as well, and is an essential part of their beauty.

3. Leichtbau

All good jumpers are strong, but strength gets them only part way to competitive success. They must also perfect their form and technique, so that this strength is efficiently deployed to clear the bar. Unlike a competitive gymnast, the jumper gains no points for style. He is rewarded only for his performance in achieving a measurable goal, and his technique is directed towards this alone.

High performance structures, similarly, are those whose form and detailing are targeted to supporting their own weight and imposed loads efficiently. Frei Otto is best known for his work on the Munich Olympic Stadium and other tensión structures, but his academic work focused on developing the principles of "leichtbau", or lightweight construction. In Otto's formulation, the work capacity of a structure is defined by its "tra": the load that it carries multiplied by the distance over which that force is transmitted to the support. Otto defined the structure's "effectiveness" as tra/structural mass. His simple formula cannot be used by itself to evaluate the relative merits of two structures, as geometry, materials, and other variables make the demands of each design problem unique. (Supporting a load at the top of a cantilevered 10m tall mast in compression clearly requires a more massive structure than hanging the same load from a 10m long cable in tension, though both structures have the same tra.) However, Otto provides a simple expression for the goal of every high performance structure: to use the least structural mass to support a load over the required height or span.

The engineer Robert Le Ricolais, an important contributor to architect Louis Kahn's best work, aligned himself with the principle of leichtbau in his poetic evocation of the ideal "zero weight, infinite span". Le Ricolais' goal is unattainable, but in their quest to achieve it, designers sometimes create structures that satisfy unprecedented structural demands with the slightest of mass. In doing so, they may create the visceral excitement and particular beauty of high performance structures.

Engineers employ various means to create light and effective structures. The thin shells and arch bridges that are the focus of Billington's aesthetic studies are "form-resistant", or shaped to follow the most efficient load path to the support. The members of form-resistant structures are characteristically sloped, curved, or tapered to carry loads using a minimum of material. Structures as organic and exciting as Nervi's Small Sports Palace (Figure 2) may result.

Figure 2. Nervi's Small Sports Palace displays the leanness and transparency of a high-performance beauty

Variants of form resistant structures are those which change shape under the influence of an applied load in order to carry it with maximum efficiency. This strategy, "adaptive form-resistance", is demonstrated by the trampoline. Wherever the user steps, the trampoline surface deflects downward into the shape of an inverted cone with its ápex at the load point, and the tensioned, sloping surface surrounding the load pulling upward to equilibrate it. The genius of the trampoline, and of adaptive form-resistance, lies in the structure's ability to shape itself to most effectively support the load wherever it is placed on the surface. Employed frequently with flexible structures like the fabric roof used on Bigo (Figure 3) and on cable-supported glass walls, adaptive form resistance provides even greater efficiencies than are possible with its "static" form-resistant cousins built of stone or concrete.

Lightness is also achieved through "internal resistance". Rather than adjusting their shape to achieve efficiency, internally-resistant structures use prestressing to manipulate the stresses in the elements of a structure so that materials are used efficiently. Internal resistance is employed in prestressed concrete, but it is also characteristic of membrane structures and many steel applications.

Contemporary engineers are taking the pursuit of lightness a step further, using a final strategy called "load dissipation", in which the structure dampens or diverts loads, rather than supporting or resisting them. It is seen in bridge decks that are shaped for aerodynamic stability, and in skyscrapers whose stiffness is "tuned" to be out of phase with earthquake ground motions.

Light construction stategies are not unique to modern high-performance structures. Arches and shells are simple expressions of form resistance that are pervasive both in nature and in the stone construction of gothic cathedrals. Leichtbau, though, represents the systematic use of these strategies for structural efficiency, based on the analytical evaluation of internal stresses and the targeted and creative use of one or more high-performance design strategies. It creates a virtuous circle, in which structural efficiencies lead to lighter construction, with the reduced load decreasing the demand on the structure and facilitating further mass reduction. Leichtbau does not by itself assure elegance, but when a light structure is detailed to provide clear expression of the load path, and where non-structural elements do not visually conflict with this expression, the opportunity for beauty arises.

Light structures (and beautiful structures) are not necessarily economical structures, as high strength and durable materials, refinements in the shaping of members, the use of prestressing, and the introduction of curving structural forms bring added expense in fabrication and complications in the erection process. In addition, in the contemporary construction environment of the developed world, labor costs predomínate over material costs, and the material savings associated with leichtbau are often overridden by the added labor required to achieve its refinements. When designers push the techniques of leichtbau to their limits, though, there arises the potential for a special beauty that mirrors the beauty of the strongest and most technically proficient athletes.

4. The Lean & Organic Beauty of High Performance Structures

If we compare two jumpers with identical mechanics and the same ability to generate upward thrust, but with different weight, we expect the lighter jumper to clear a higher bar. A successful jumper must be lean, as well as strong, and the best have a compact but powerful musculature that can generate explosive force, and minimal body fat to hinder their ascent. A high-performance structure must also be lean, and it becomes so through the use of strong materials positioned exactly where required, and the absence of superfluous mass that might increase the tra of the structure. If the engineer employs form resistance or another of the high performance strategies to reduce dead load, the structure can be less strong (and less massive) and still reach the required span or height.

The forms of high-performance structures often curve to conform to the path that their loads take to the ground, and the cross sections of members sometimes vary along their length to reflect variations in internal forces. The forms of high-performance structures are typically derived from objective efforts to achieve lightness and efficiency, more than they are shaped by the conscious effort to create beauty. Horst Berger's Denver Airport Terminal roof (Figure 3) provides an example. Cables spanning from side to side in the fabric valleys are prestressed, pulling downward on the fabric to pretensión it. Both cables and fabric are shaped to provide equilibrium under the required design prestress. While high performance mandated curvature in cables and fabric, the masts themselves are straight and plumb, to deliver the downward pull of fabric and cables to grade by the most direct path.

Just as leanness alters a building's structural performance, it profoundly changes its visual character. Again, the athlete provides a useful metaphor. The leanness of an athlete's body draws his skin tight to the muscle and bone beneath in a way that exposes the mass and geometry of his own biological structure. Leanness also reveals the athlete's actions, telegraphing the tension or relaxation in each muscle and the articulation of joints in motion. In a lean structure, similarly, the delineation of form gives clues as to the path that forces take through the structure, and the bulk and shape of the beams and columns that compose a structure suggest the forces they resist. The layman may be unable to articulate the way that an athlete or a structure carries and responds to load. Each of us, though, through long familiarity with the action of our own bodies and observation of the trees and shells and other structures that comprise our world, can intuit with pleasure the way that a structure supports a load when leanness allows it to.

Figure 3. The Denver Airport Terminal's roof design pursued lightness and efficiency, with beauty the result.

Leanness can't be appreciated if obscured by non-structural elements like ceilings or partitions, or if structural members compete visually with mechanical ducting or other building services. A comparison of Nervi's two Rome Sports Palaces illustrates the point. The dome form of the Small Palace is clearly articulated on both exterior and interior (Figure 2). From either viewpoint, it is easy to visualize the weight of the roof thrusting downward and outward against the sloping buttresses, which distribute the roof weight to the ground at their feet. The Large Palace roof has similar form, but a tall curving wall encloses support spaces around the building perimeter, and hides the view of the dome on the exterior (Figure 4). We can admire the sculptural geometries of the Large Palace form, but its façade masks expression of the roof's load-bearing behavior. The effect is as if Fosbury had made his gold medal jump while wearing a bathrobe. The mechanics and height of the jump might be the same, but we would not appreciate its lovely efficiency. Arguments may be made for the architectural merit of either Nervi structure, yet it terms of their structural expression, the Small Palace elegantly reveals the behavior of its high performance roof, while the Large Palace does not.

Figure 4. The elegance of Nervi's Large Sports Palace roof is obscured by competing elements on its exterior.

Revealing or obscuring a structure's connections and other details also changes its visual impact. In designing Bigo, a waterfront canopy in Genoa, Italy (Figure 5), engineer Ove Arup (in collaboration with architect Renzo Piano) sought economy and ease of construction. Their design had another ambition, though - the athletic expressiveness derived from clearly articulating the structure's load path. All structural members are exposed on Bigo, and detailed in a manner that makes it easy to follow loads from roof to grade. This begins with the pretensioned fabric roof, whose weight and pretension join with wind and other applied loads to pull downward on the four arches that span over the fabric. The arches are in turn held up by the arrays of suspension cables that attach to them and rise to the tops of the two tall tapered masts. In the close up on the right of the figure, the suspension cables (to the right of the mast) attach to steel gathering plates, which are linked in turn to the mast top. The overturning effect of the suspension cables is equilibrated by the counteracting pull from the stabilizing cables (to the left of the mast.) The tensions in both the suspension and stabilizing cables pull down on the mast, which carries this compressive load to grade.

Figure 5. Bigo's structural elements are all exposed, and clearly display the load path.

Bigo's details reinforce the clear expression of the load path, at the same time embodying all of the leanness of a fine high performance structure. The photos show a subtle increase in the diameter of the masts towards the center of their length, as required to prevent buckling, while at the same time minimizing the bulk at the mast ends. A further refinement is seen in the gathering plates which collect the suspension cables at the mast top, where the large circular cutout in the middle reduces both the the visual and actual mass of the plates.

The forces in the members of a structure vary constantly along their length, and designers of high-performance structures select carefully articulated forms and details that express the load path. They may vary the cross-sections of members along their length, in the way that an animal bone varies in stoutness from one end to the other in response to the varying forces that the leg of the living animal needed to resist along its length. This places these designers at odds with colleagues designing more conventional structures, who employ uniform cross sections and repetitive detailing to reduce the cost of construction labor (and their own design costs.)

Structures of the natural world are nearly infinite in variety, and respond in ingenious ways to the widely varying loads imposed by natural life. The diversity and cleverness of natural structures make them frequent models for engineered structures. Those who design vertical columns that split into sloping branches may describe them as "trees", while the curving roof forms pioneered by Candela and others are called "shells", in recognition of the sea shells and egg shells they suggest. Designers of curving glass walls stabilized by steel cable nets draw inspiration from spider webs.

The familiarity that all of us have with both these natural structures and the musculoskeletal structures of our own bodies provides a means for non-professionals to appreciate the behavior and beauty of high-performance structures. It also provided the means for designers of an earlier era (who lacked contemporary analytical tools) to understand and explain their work. They frequently turned to the human body as a model of how their structures carried load. When completed in 1890, the Firth of Forth railroad bridge (Figure 6) was the first long span bridge built entirely of steel. To demonstrate to the public how the bridge spanned the large chasm, the engineers used three men as props to create the iconic photograph seen on the right. The torsos of the men seated to either side of center represent the cross-braced supporting towers of the bridge displayed on the wall behind them. Each of these "supporting" men extends one arm (braced by a sloping strut) towards the center of the bridge to support the "suspended" man seated between them. In order that the weight of the suspended man not topple the supporting men, the latter extend their outside arms (again braced by sloping struts) to ropes which are lashed to stacks of bricks. The bodies of the supporting men are balanced symmetrically between the suspended man in the center and the bricks to either side, so that they can bear their load comfortably. Their arms are straight, suggesting the tension tugging at their elbows and shoulders, but we can imagine that the muscles in their arms are relaxed. Their spines are straight and relaxed, as well, and their faces bear no strain. The ease with which they support their load provides a vivid representation of the high performance structural behavior of the Firth of Forth bridge itself.

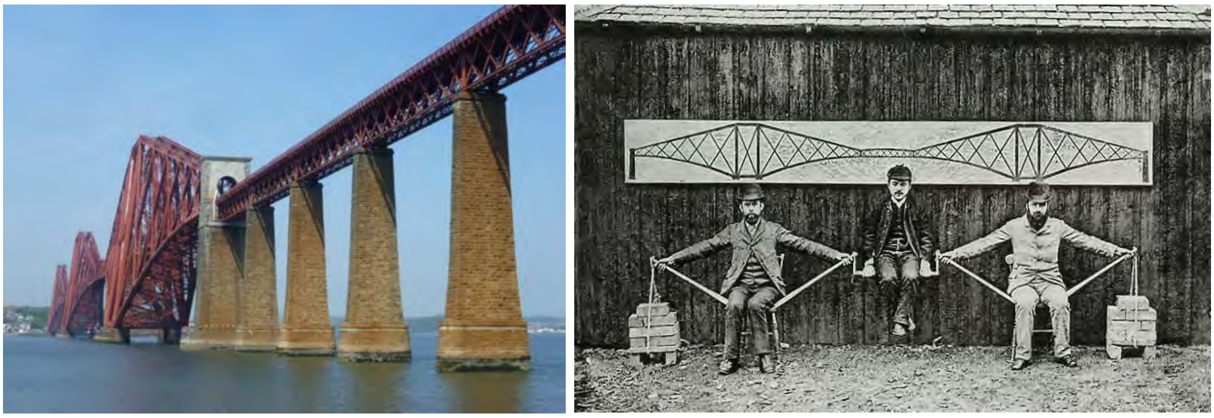

Figure 6. Human "members" were used go model the load-bearing action of the Firth of Forth railroad bridge.

5. The Pursuit of Perfection

In *The Tower and the Bridge*, Billington makes a powerful case for the subjective nature of the design choices of the select group of engineers he crowned "structural artists", and for the elements of personal style with which they worked. Billington is not incorrect, but the principles of high performance design suggest an aesthetic that relies equally on a search for "ideal" form. The architectural critic Ada Louise Huxtable eloquently captured this quality in her 1960 Nervi monograph [3]. "It is possible even for the layman to feel tension and compression, the direction of forces, and the inevitable, *correct* relationship of structure to shape", she wrote. "The fusion of structural function and abstract form creates a kind of building that is so fundamentally *right* that most other architecture seems superficial beside it." Her terms "correct" and "right" (emphasized by the present author) suggest that structures of exceptional beauty are as much the outcome of the designer's search for the ideal solution to a particular problem of loading and span as they are products of personal expression.

Rationalizing the special nature of any mode of beauty is impossible, but Nietzche's yearning "to see as beautiful what is necessary in things" provides a further clue to the aesthetic appeal of beautiful structures. Structure is the most necessary element of architecture, providing support for a building's plumbing and mechanical "organs" at the same time that it gives shape to its roofing and façade "skin".

The forms of both gothic stone cathedrals and concrete shells are founded in the simple goal of efficient load bearing – an objective more fundamental and enduring than the complex artistic and programmatic forces that drive most architectural design. Architectural critics may argue incessantly about the relative merits of particular schools of architectural practice and particular works, but there seems an unalterable quality to the structural forms of the engineering masters. How might the arch of the Salginatobel Bridge (Figure 7) be improved? Most of us prefer unblemished admiration.

Structural designers who have created work of enduring beauty have done so through a commitment to perfecting form similar to that demonstrated by elite athletes. The principal is demonstrated most clearly in the slender forms of gothic cathedrals. Cathedral designers lacked the means to provide tensile reinforcement across the joints between the stones that formed their structural skeleton, so, in order to avoid explosive failure, they were compelled to shape structural members so that the load path always fell within the member cross section.

Figure 7. Robert Maillart's contrasting concrete arches at Salginatobel (left) and Schwandbach (right).

In examining most structures, an observant structural engineer will consider the design possibilities not chosen, perhaps imagining the supporting arches with steeper or shallower slope than its designer selected, or suggesting that the arch itself be replaced by a beam or a truss. To engineers and other critical observers, the examination of most structures is an intellectually and creatively active process. The experience of examining a masterful high performance structure, though, is less one of critical engagement than of serenity in the presence of something much like perfection. An engineer might surmise the presence of a great work by the absence of his usual desire to tinker with or change it. Speaking of his contemporary Robert Maillart, shell architect Felix Candela said, "he did possess that rare quality of being able to challenge the conventional wisdom and come up with the obvious solution, one, nevertheless, which nobody could think of before" [4].

This paradox - challenging conventional wisdom to arrive at a perfect and obvious solution – is amply illustratedby Maillart's Schwandbach Bridge near Hinterfultigen, Switzerland (Figure 7), where the bridge deck, straight in elevation but curved in plan to align with the roadway approaches, is supported by an arch which is straight in plan but curved in elevation. This design, bold and unlikely in conception, appears so perfect in its finished reality that it is difficult to imagine a change to the design, or at least one that would not be a defacement of its well-integrated beauty. The nature of structural elegance, in combination with the genius of Maillart, led to a design that is unique in conception, but executed with such skill and elegance that it appears to be the inevitable solution to the design problem.

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Lateral load resisting facades

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Abstract

Simple modifications to traditional curtain wall slab anchors allow designers to incorporate a structure's building envelope system into its lateral system, leading not only to improved structural performance, but a reduction in the building construction's carbon footprint. This approach of integrating architecture with structural design to optimize building performance and construction embodies the principles of efficiency, economy, and elegance championed by David Billington. In this paper, the potential benefits of utilizing façade members to contribute to the building stiffness is studied by reanalyzing 510 Madison Avenue, a 2012 Class-A steel high rise office building in Manhattan. The building's lateral system is comprised of moment and braced frames. The building's façade is a unitized aluminum curtain wall system that utilizes traditional curtain wall anchors designed to prevent the transfer of loads between the façade and the structure. If the curtain wall slab anchor is redesigned to allow some fixity of the vertical mullions, then the curtain wall can partly carry out-of-plane loads. The results of the study indicate that a unitized hybrid curtain wall system, consisting of a shallow aluminum extrusion with a steel back-up member, can reduce the sway of the building at the upper floors and reduce the overall building CO^2 footprint for some anchor and installation layouts. The shallow aluminum extrusion provides the exterior finish, glazing cavity, thermal break, and air/water tightness system and the steel back-up member provides the structural capacity. For this case study, based on the spacing and depth of the members the curtain wall may reduce the inter story displacement by 2% to 6%.

Keywords: envelope performance, energy analysis, lateral resisting system, parametric performance modeling, carbon footprint.

1. Introduction

Current curtain wall anchors are designed to prevent the transfer of loads between the façade and structure, keeping a structure's building envelope system independent from its lateral system. However, mullions in curtain wall systems have a capacity to carry some out-of-plane loads. By integrating curtain wall design with the structural design, a building can potentially improve a building's behavior while also reducing the environmental impact of its construction. This approach of incorporating architectural elements into a building's structural system to optimize building construction and performance embodies the principles of efficiency, economy, and elegance championed by David Billington.

Exploring solutions to minimizing the "embodied energy" of the building's systems (i.e. energy used prior to a building's operational phase measured in equivalent emission of kg CO^2 per kg of material) has become increasingly important from an environmental standpoint as one considers how the performance of envelope enclosures is increasing (thereby reducing energy consumed during the operational life of a building), and the overall life expectancy of buildings is decreasing [1]. As the red trend line in Figure 1 illustrates, the impact of the energy used prior to a building's operational phase (embodied energy) is increasing.

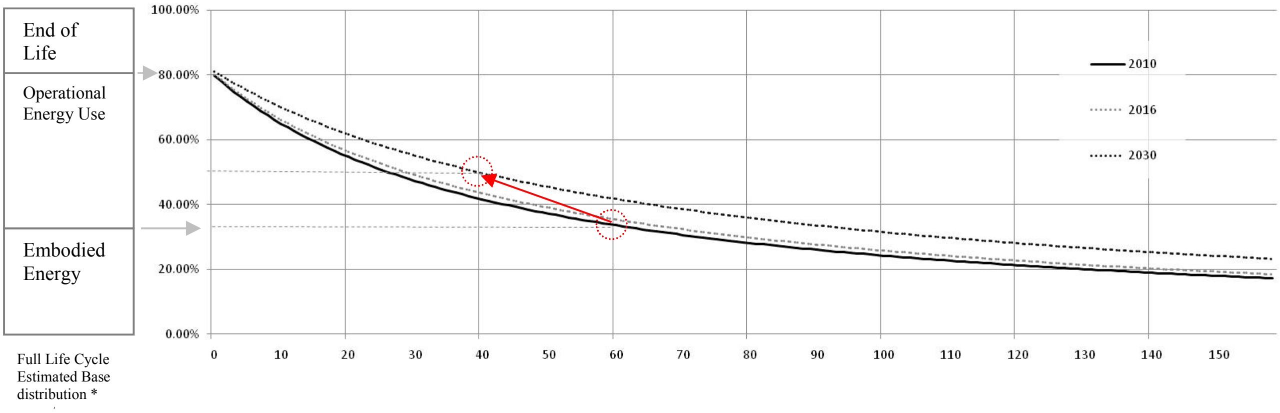


Figure 1: Embodied Energy/ Total Energy * percentage distribution over life of building.
* Total Energy to Date = (Embodied + Operational (t) + End of Life).

2. Building envelope

Current commercial buildings enclosures are dominated by lightweight unitized curtain wall facades [2]. In the last five years, these facades are estimated to make up approximately 70% of the total envelope surface area of new office buildings and they are having an increasing presence in high-end high-rise residential buildings (circa 15% increase). Of the total of curtain wall surface area erected in this period approximately 64% are unitized systems, of which 92% are extruded aluminum systems.

2.1. Current curtain wall design

The curtain wall (CW) is a non-load bearing exterior skin that does not contribute stiffness to the building structure. Current curtain wall construction technologies are optimized to perform two tasks: providing the envelope enclosure and resisting the tributary cladding wind load. Hence, mullion anchors are designed to intentionally allow rotation at the points of support.

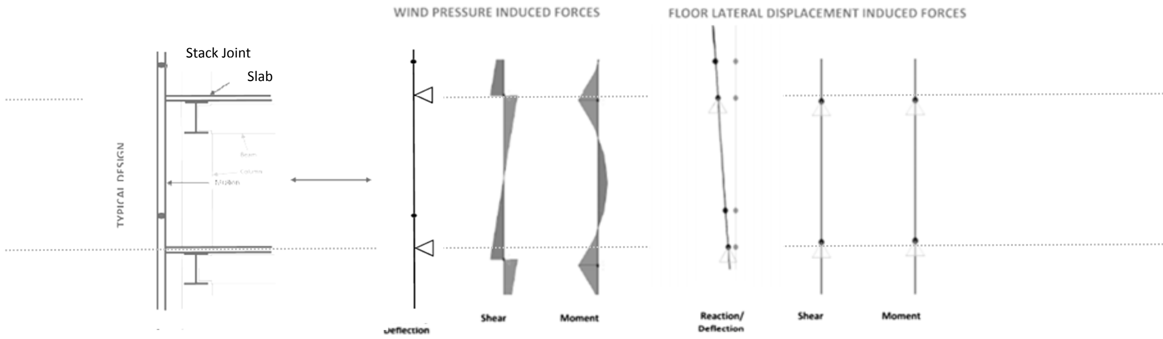


Figure 2: Existing curtain wall design load distribution diagram

Traditionally, typical mullions are made of aluminum. For high cladding wind loads or inter-story heights the mullions are reinforced with steel sections to limit the depth of the mullion and the reduce impact on the floor area ratio.

Newer façade designs are employing heavier materials than glass (e.g. terracotta, stone, or photovoltaic rain screens), hence the curtain wall is evolving from a "barrier" system to a "barrier + carrier" system

[3]. In addition, tighter thermal performance requirements have increased the minimum size of glass panels for glass curtain wall façades. The result is an increasing demand for stiffer curtain wall frames capable of withstanding higher loads.

In a unitized CW the main stresses occur at: the vertical mullions in the out-of-plane direction due to wind suction, and at the vent transom connections due to the torsion produced by the in-plane gravity load of the glass and the wind suction. The capacity of these component limits the spans and dimensions of the CW units [4].

2.2. Mullion material

In order to select the optimal mullion materials, several factors need to be considered including: structural capacity, stiffness, weight, and environmental impact. Figure 3 compares the Young modulus, the "nominal" material density, and the environmental impact or "adjusted material density" (as measured by the weight of CO^2 emissions required to produce and discard 1 m^3) of various typical CW framing member materials. As Figure 3 highlights, while steel weighs more than aluminum, it is both stiffer than aluminum and has a smaller carbon footprint depending on the type of steel and aluminum being considered.

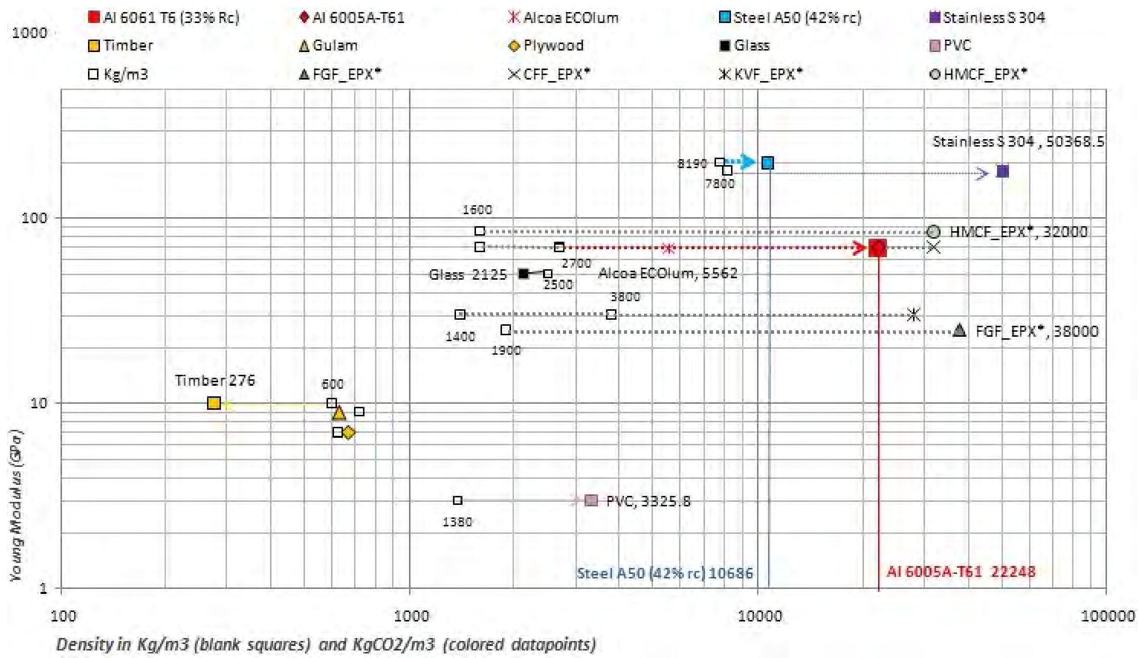


Figure 3: Typical CW framing member material* comparison. Young modulus vs. "nominal" material density (kg/m^3) vs. environmental impact or "adjusted density" (kgCO^2/m^3).
* FGF=fiber glass fabric, CFF=carbon fiber fabric, KVF=Kevlar fabric, HMCF=high modulus carbon fiber fabric. [Fibers @ 45° (UD), 0° (fabric) to loading axis, dry, room temperature, Vf = 60% (UD), 50% (fabric)].

Though some specialty aluminum products (e.g. Alcoa ECOlum 5562 kgCO^2/kg) can potentially have a lower carbon footprint per kg than typical structural steel (10686 kgCO^2/kg), it is unclear if this offset can compensate for their different structural capacities.

It is important to note that the carbon footprint of each material can vary considerably depending on how it is sourced and produced (e.g. raw materials versus recycled materials). For our case study, we used the current industry standards for percentages of recycled content per ingot (33% for aluminum and 42% to 47% for steel).

We can plot the ratio between the densities of a material and its Young modulus to verify if the offset between different materials can, in this application (bending), compensate for the difference in stiffness. As observed in Figure 4, the "nominal density" ratio is approximately constant between aluminum and steel. However, steel appears substantially more efficient if we consider the "adjusted density" of the materials even when compared to 100% recycled aluminum.

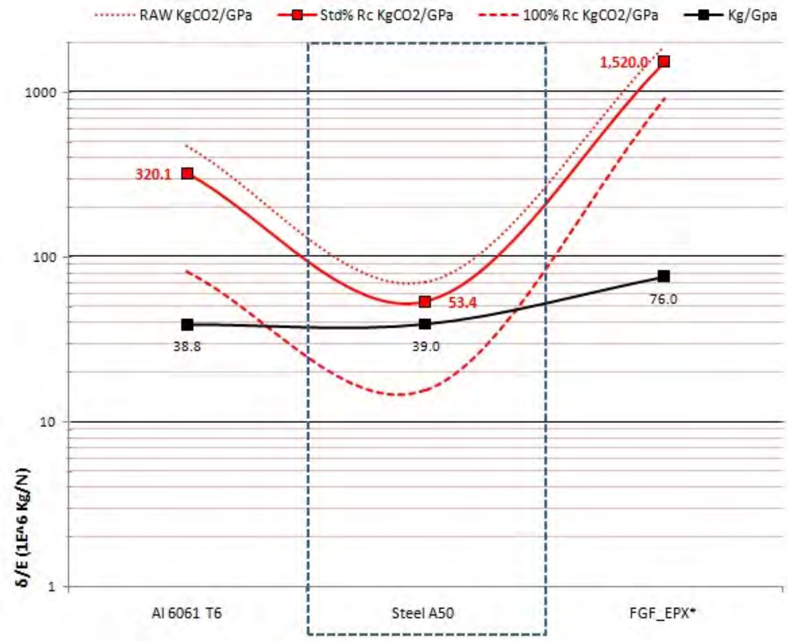


Figure 4: Proposed framing materials "nominal" (black) and "adjusted" (red) density over Young modulus ratio.

3. Proposed mullion design changes

Two proposed mullion design changes can potentially help address the design challenges discussed in this paper. First, increasing the number of CW anchors from one connection at each floor to two connections. Two connections generate fixity against rotation. The mullion then resists its tributary cladding wind load *and* contributes to the stiffness of the building's lateral resisting system.

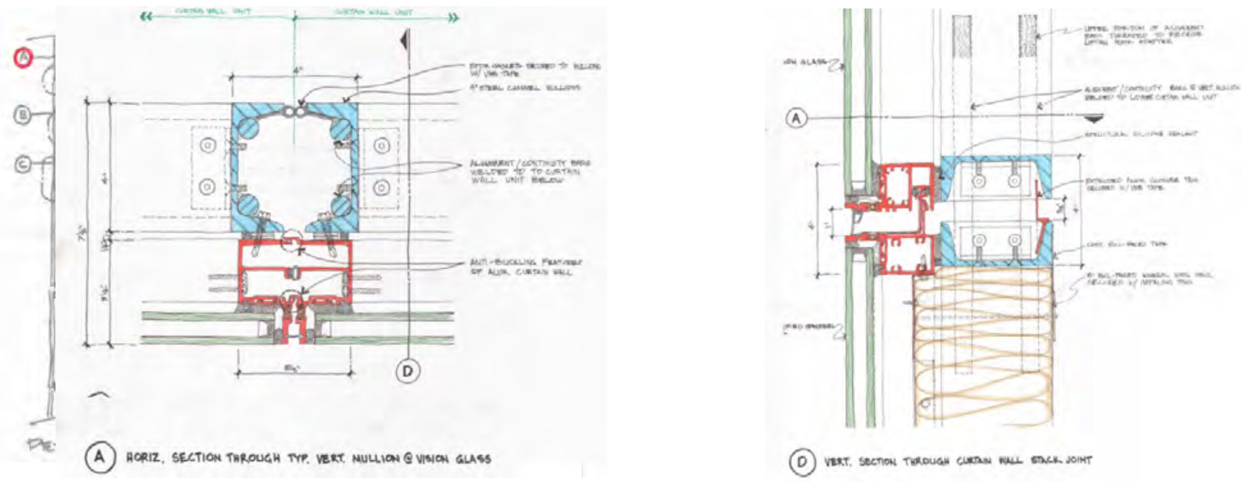


Figure 5: Proposed system typical details A & D. Hybrid (Al+steel) unitized curtain wall (HUCW)

Second, changing the single aluminum mullion to a combined aluminum plus steel mullion. The additional stiffness and strength of steel versus aluminum and the support fixity makes the new system stiffer and stronger than a CW system of the same depth.

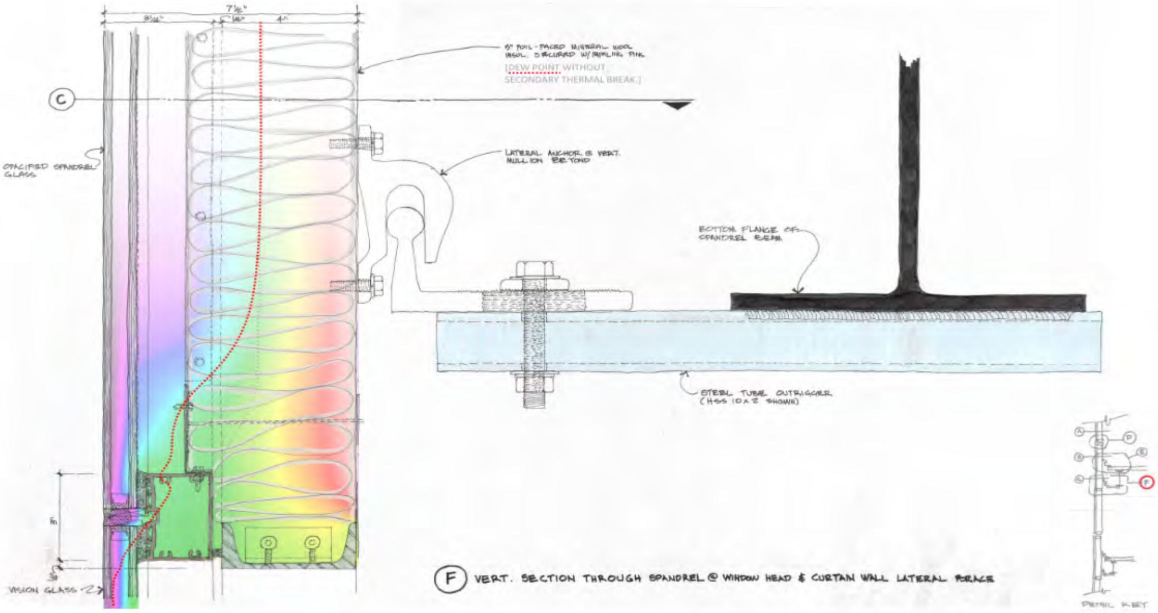


Figure 6: Proposed system typical detail F. Anchor at bottom of spandrel beam.

4. Case study

An existing Class A office building located on Madison Avenue in Manhattan, New York was used as a baseline. The base building, completed in 2012, is 30 stories high and has a gross floor area of approximately 31,500 m^2 with a floor plate form factor of 1.75**.**

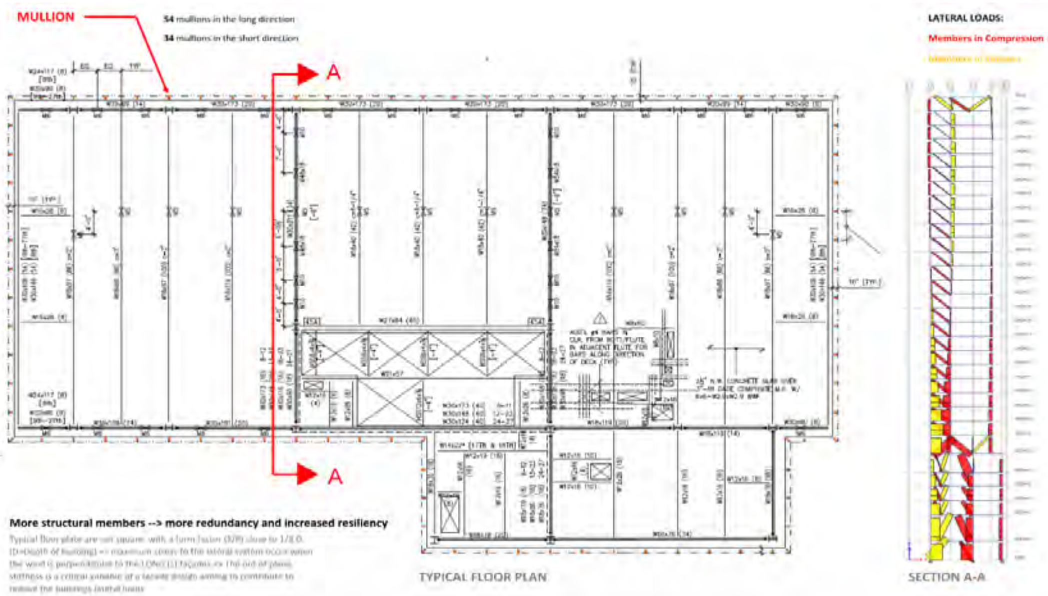


Figure 7: Typical floor framing plan

4.1. Mullion FEM modeling:

The mullion for the hybrid system was modeled with a finite element program. The support restraints were placed according to Figure 8. The stack joint connection is represented by a rotational "end release" that avoids the transmission of the bending moment between the two beams and a translational "end release" that allows the translation along the mullions axis.

The top anchor was modeled as a pin with the rotation released. The bottom anchor of the proposed hybrid system was model as a spring to account for the bracket deformation.

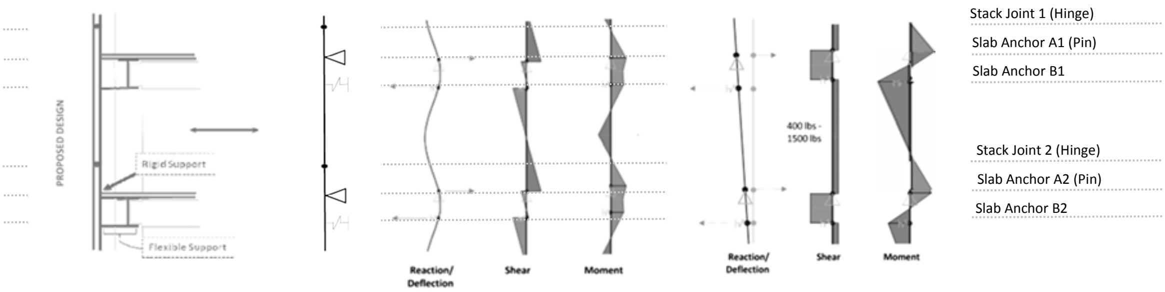


Figure 8: Proposed hybrid system load distribution diagram

4.2. Building

The building and the hybrid façade were modeled by a finite element program (SAP 2000).

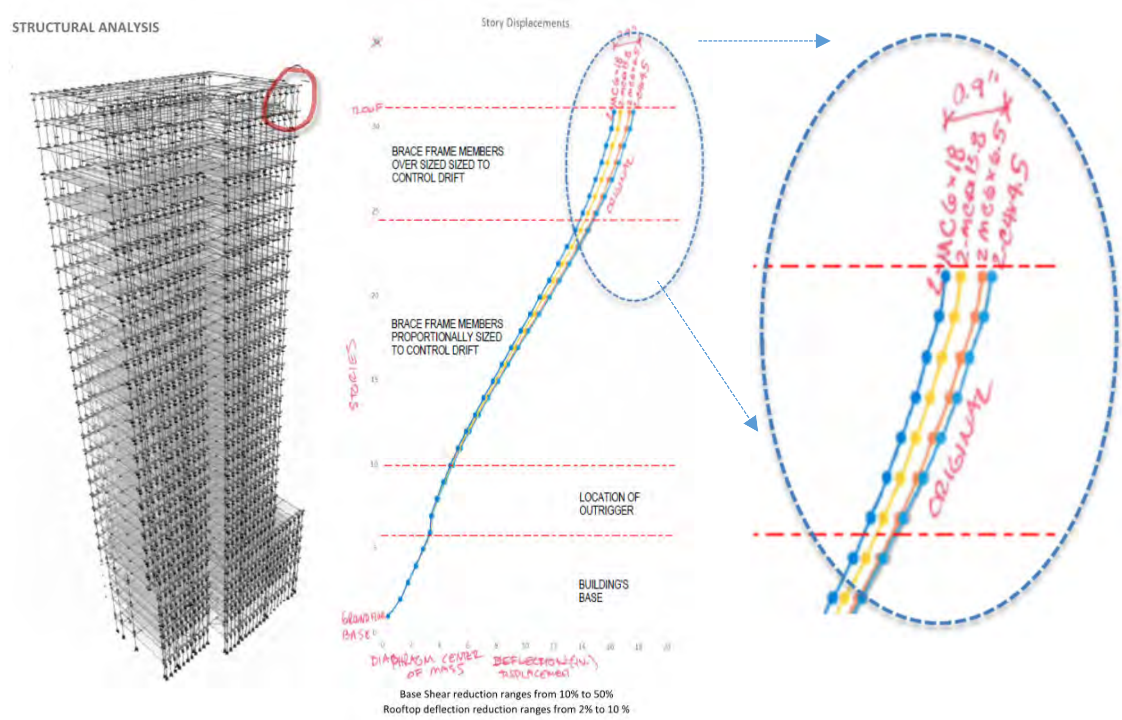


Figure 9: Building FEM 3D model and deflection curves for base and Alts 1 – 3 designs.

For the baseline building, the façade mullions were not modeled and only their tributary loads were included in the wire model as point loads as the façade transfers the wind loads to the floor diaphragm.

For the proposed hybrid system, the mullions were modeled as continuous beams with a rotational and axial release at the stack joint. The beam was connected to the diaphragm at the slab level. An elastic diagonal element connected the mullion at the bottom of the spandrel beam to the diaphragm (see Figures 8 and 9) simulating the bracket connection to the spandrel´s flange and perpendicular beams.

5. Results

A target for this study was to identify the type of trade off relationship that may exist between heavier sections, structural performance, and environmental costs. An analysis of the selected set of steel shapes identified a limited range where there was a potential reduction of the overall carbon footprint of the building's structural and envelope framing components. Figure 10 plots the environmental costs of each component against its contribution to reducing the displacement of the rooftop center of mass (CoM).

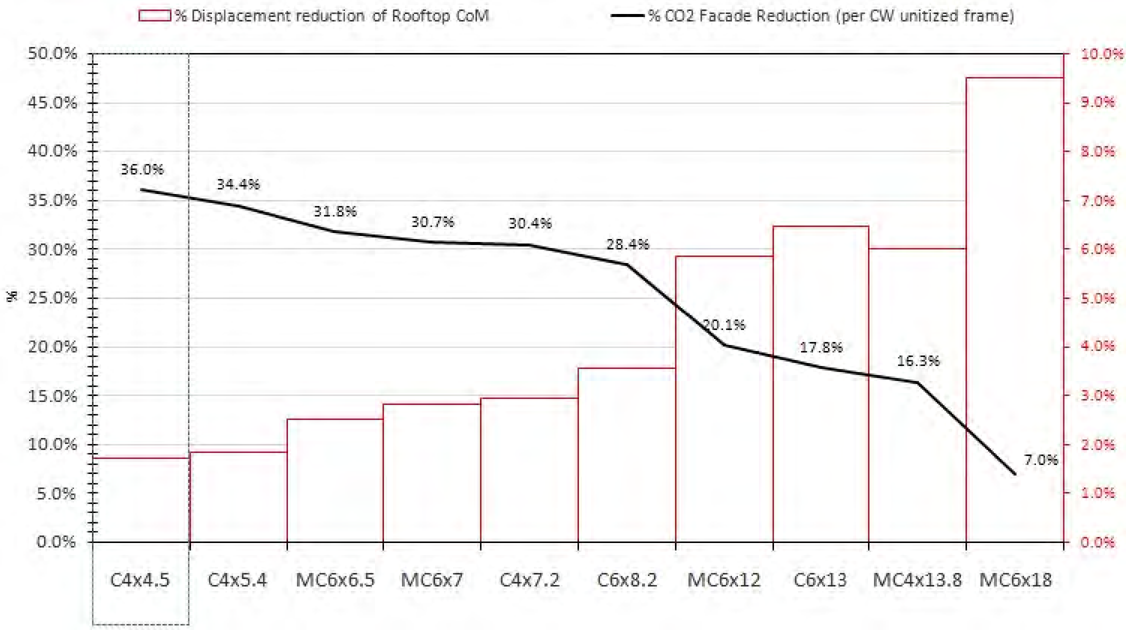
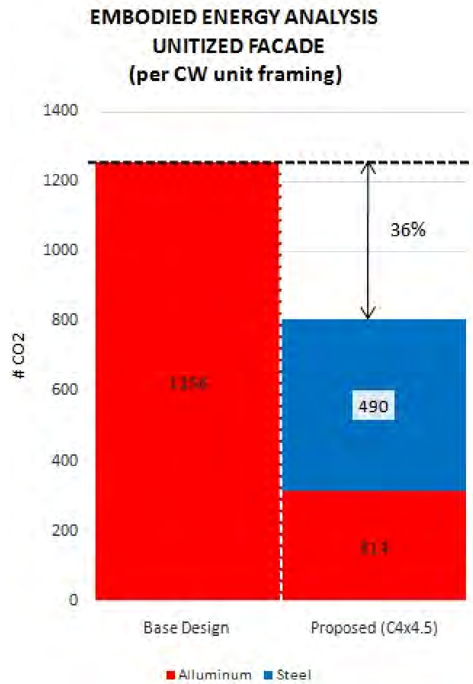


Figure 10: Proposed steel member analysis @ CW framing back-up | Braced with L/400 (wind 60 psf)

5.1. Re. Structural and thermal performance

The added stiffness of the steel backup components reduced the sway or lateral displacement of the building's rooftop center of mass by 2% to 6%. The replacement of the back-up area of the aluminum extrusion by a steel member reduced the embodied carbon tonnage of the façade components (excluding the glass) by a maximum of 36% depending on how the aluminum and the steel were produced. The total maximum reduction in the embodied carbon tonnage of the building façade and structural components is approximately 7%.

The thermal performance of the hybrid system is comparable to the baseline system. The thermal operational energy consumption was assumed as constant for the study.



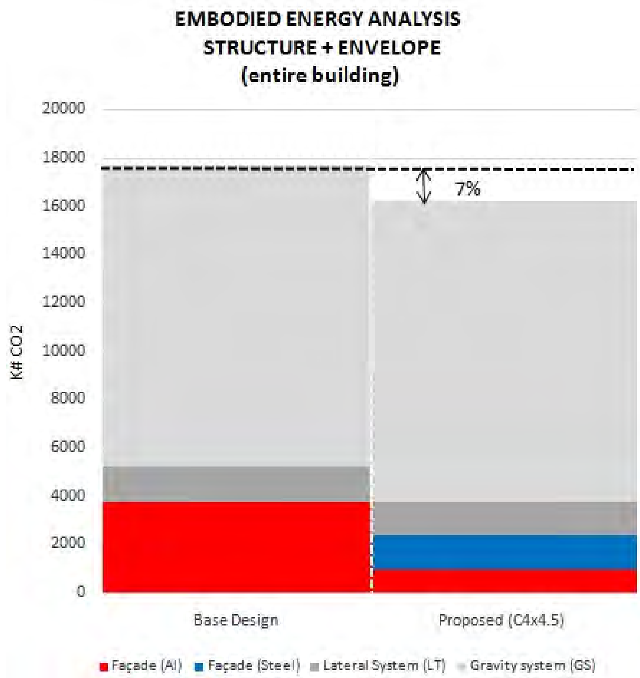


Figure 11 (left): Embodied energy analysis (EEA) per curtain wall unit (framing).

Figure 12 (right): Embodied energy analysis of above grade structural and envelope framing systems

6. Acknowledgements

The insight, editing and support of Connie Yang is greatly appreciated.

7. Conclusion

While the overall weight of the façade increases, the offset between the embodied energy of aluminum and steel, and the potential reduction of the building frame lateral system, provide a net reduction of CO^2 emissions. By replacing the back section of the aluminum extrusion with a steel member, you reduce sway and reduce the carbon footprint of a building based on industry accepted mean coefficients. These conclusions apply to the example modeled and depend on the production costs, availability of resources, and the impact on the erection.

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Making His Story of Structures My Own

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Abstract

The challenge of re-inventing a classic is fraught with many difficulties. A useful analogy is the performance of a cover of a well known song, most often the re-created cover is not as good as the original. Yet once in a while, a cover is remarkable because it clearly is the same as the original, yet it is still unique, it is marked by the personality of the cover artist. The strategy employed by the author in the making of a "cover" of Billington's course was to take the following three steps: (1) Take the best of the original version, namely the premise of scientific, social and symbolic critiques as well as The Pantheon of Heroes; (2) Remove the parts that need adjustment (antipathy towards architects); and (3) Make it my own, with my own style and color.

Keywords: History, Structural Art, General Education

1.Introduction

Each year from 2013 to 2019 the course History of Structures has been offered as a General Education course at California Polytechnic. It is designated as an "Arts and Humanities" course and within that category it fulfills the "Fine and Performing Arts" requirement. The initial offering had quite a humble beginning, with only 20 students. The latest offering hosted 138 students.

The Course Description in the University Catalogue is as follows:

Social, symbolic, and technical importance of landmark structures. Analysis of breakthrough ideas that led to major advances in building design. Contextualization of these advances. Tools by which to assess and critique structural art as a separate and distinct art form. No prerequisites.

The fact that History of Structures fulfills certain University General Education requirements adds one large layer of complexity, namely that this is Writing Course, which means that "a significant portion of the grade arises from written papers". One technique for addressing this complexity has been adopted.

The course philosophy has always been to celebrate and promote the best works of structural engineering completed during the last two hundred and fifty years. Some of the works studied in History of Structures rise to the level of "structural art" and the rich tradition of such masterworks, independent of the tradition of architectural history, is important to all students interested in building design and construction. The critical tools used throughout the course appeal to all students interested in the broader topic of design and art criticism. History of Structures fulfills a need because it addresses the "affective response" that many people have to large scale structures. This affective response is sometimes referred to as the emotive power of structure, and this course provides tools to assess and critique built works that enrich the public life of modern industrial, urbanized society through language that is precise and rigorous, language that is formed through the prism of the engineer's imagination. Such language is best utilized during the contrast of three dimensional works created by the engineer, the architect and the sculptor. Three dimensional forms created by the engineer are governed by more technical and economic concerns than are the forms of the sculptor, who typically does not have to worry about life safety issues. Yet all three forms seek to maximize aesthetic expression and sometimes reach the level of having great symbolic impact.

2. Course format

Nineteen separate lessons are currently presented. Each lesson focuses on either one person (for example Peter Rice) or one idea (for example The Spanish Tradition of Thin Shell Roof Vaults). A personal fun touch is that prior to the start of each class, as the hundred or so students are gathering, a musical video that is somehow paired to the day's lesson is playing on the large screen and filling the auditorium with music. The Gypsy Kings might be playing during the Spanish Tradition lecture, or Kurt Weill during the German Tradition lecture. Other small links to the period being studied are interspersed, these typically are either art or music, as both are considered specialties of the author. The language and critiques of structural form are meant to be consistent within each and every lesson, they begin with rudimentary scientific analyses of the structures being studied, primarily investigating load flow, tension and compression. Then a small social critique is performed such as "how was the structure used?", "how long or expensive was the construction process?". The final and most important critique however is the symbolic analysis. This is what makes the course a general education course that can be enjoyed by first year students or graduating seniors.

Attendance currently constitutes 50% of the grade. This is so because each lesson is packed with 70 or 80 slides containing almost no text. Detailed written-out narratives, mapping each slide to a specific spot in the text have been created by the author for each lesson. Yet the students do not receive this text. Rather, they receive two identical single sided sheets of paper. On these sheets are listed 10 to 12 short questions. Some are merely descriptive (Name the chief designers of the John Hancock Building in Chicago), others are more open ended (could Felix Candela be presented as a role model to high school Latino youth considering a career in engineering). Students answer a few of those questions during class and had in one copy of the sheet as their "attendance ticket". Students retain the other sheet to prepare for exams. The exams are solely made up of these 150 or so questions that have an unambiguous answer. Students know that the open-ended questions will not appear on an exam. Thus, the students have the questions as well as the answers to each and every exam!

Perhaps it is heresy to state that the required textbook for the course is not The Tower and the Bridge [1], but rather Building: 3000 Years of Design, Engineering and Construction, by Bill Addis [2]. The reason is that the Addis text is more breadth-oriented, rather like an encyclopedia, making it suitable for a first course in structural history. Ideas and language from The Tower and the Bridge are used for almost all of the topics, but specific helpful resources were very valuable in creating the story behind other topics. These other resources are cited in the following list of topics.

Topics:

- The Washington Monument and The Eiffel Tower, Symbolic and Social Critique
- Technical Critique of the Eiffel Tower
- Robert Maillart and the Origins of Reinforced Concrete [3]
- Form and Forces, an Overview of Technical and Aesthetic Ideas [4]
- Catalan Vaulting [5]
- The German Tradition of Thin Shell Concrete Roofs [6], [7]

- Max Berg and the Centennial Hall in Poland [8]
- Felix Candela and the Hyperbolic Paraboloid [9], [10], [11]
- The Italian Tradition of Thin Shell Concrete Roofs [12]
- The Spanish Tradition and some Swiss Ideas
- Skyscrapers with a focus on Chicago
- Myron Goldsmith and the Diagonally Braced Tube [13]
- Lakepoint Tower [14] ….. Poly Canyon
- Fazlur Khan and Tall Buildings [15], [16], [17]
- Bill Baker and Tall Buildings [18]
- Tange, Tsuboi and Kawaguchi, The Japanese Engineer-gods [19]
- Frei Otto and Lightweight Structures
- Peter Rice, Le Traice de la Main [20]
- Jorge Schlaich, The Ethics of Engineering Design [21]

Successes:

The course is very popular. Students from every possible major have said that it is one of their favorite courses. A common observation is that students "have never really thought of buildings in that way before", i.e. they never considered the technical and aesthetic challenges surrounding major buildings, nor were they aware of any of the members of the Pantheon of Heroes. For architectural engineering students, this course often inspires them to find a Senior Project to study in depth that was based on something they saw in class (Catalan Vault, thin concrete shell, grid shell, solar chimney). Even first year students have attempted to create structures that are based on what they saw in class (Eiffel Tower, Farnsworth House). There is one Model Making Exercise, done by teams of students as a homework assignment. They create either an Isler-type of hanging cloth structure, or a Gaudi-type of hanging chain structure. They solidify the form, invert it and photograph it with scale factors. How nervous and excited are some of the students during this exercise! For many, it was their first time ever constructing a physical model.

Challenges:

As the course grew in popularity several challenges have developed. One is that personal rapport with the students is very limited. It is simply impossible to interact, by name, with over 100 students. Another is that multiple choice questions must be used for exam. As previously stated, the students know the questions beforehand, and if they attend the lectures they know the answers as well, thus the multiple choice format has not been a source of complaints. A larger challenge is that papers must be graded by teaching assistants. The teaching students are exclusively made up of architectural engineering students who have previously taken the course. This is necessary to address the small, but significant, scientific critiques of buildings done in the papers.

The prompt for the first paper follows: Details about the process of handing in copies for peer review may be helpful to anyone who wants to manage a large number of student papers.

Learning Objectives:

- Appraise and critique key buildings using the language and criteria of the theory of structural art
- Contextualize seminal buildings by linking them to specific people (designers), cultures, and times

Use the given form to provide constructive criticism. Hand back your peer review to the authors on Monday 2/11 but PREFERABLY SOONER VIA EMAIL OR TEXT OR …

Hand in your revised assignment to the instructor on Wednesday 2/13 and hand in your peer review forms at that time also. Do not hand in the original draft.

Details:

This is the first of two larger writing assignments in this course. The purpose of this exercise is to create a "museum exhibition" didactic panel. Choose one structure that is pictured in your textbook. Include one or two images of your chosen structure, either from the textbook itself or from other sources such as the internet or the library. Images are to be printed separately, not in the writing assignment itself.

Use the tools that we have been exploring in class to analyze and critique the structure. The first level of the critique will be a technical or scientific one. How does the structure perform? How are the loads flowing? What relevant technical facts can be established about this structure (examples include, dates, location, cost, weight, name of designer, length of construction, you may or may not be able to provide all of these). Since this is your first exploration of such technical matters you will have to rely on the explanations of the book, or use the technical explanations found in other sources. Be sure to cite things properly to avoid plagiarism. Citations means using more than one reference (Wikipedia is ok if you trust it) and linking the citations to specific spots in the text using superscript numbers1, 2, etc. Don't make this technical critique too lengthy.

Next, analyze and critique the social aspect of the structure. How did people use it, how did people perceive it? Did it play a prominent role in the community? This social portion will probably be a brief critique, that is fine. There may be some citations to reference here.

Finally, create a symbolic analysis of the structure. By placing it in a broader historical context, find some larger meaning to this structure. Has it risen to the level of icon? Has it become a source of civic pride? Is it an embarrassment or a folly? Here there will almost certainly be no citations since these should be your wholly original thoughts.

Submit one or more images of your building and then printed separately approximately one and a half pages of text that would act as didactic panels in our exhibit. I will not be counting words, we are interested in content and in style. The audience is the average museum attendee who is very interested in buildings, but is not an architect or structural engineer by trade.

Use the following examples of didactic materials taken from actual museum catalogues as a possible model of writing. Feel free to search for other examples in our library, on the internet or at our local art museum in downtown SLO called SLOMA.

The prompt emphasizes Contextualization as well as Scientific, Social and Symbolic critiques. This is in alignment with the course philosophy.

3. Issues to discuss

Issues which we all should discuss at this Symposium and in the near future:

- Intellectual property, online versions, ownership
- Disseminating each other's course notes in a somewhat public manner

The first question is a bit thorny. Whose course is it? Clearly it is David Billington's creation, but what if we wanted to make it more public today? Could it be presented in an online format? Where would any royalties, if there were some, go to?

The second question is less problematic. The efforts of Princeton University and the Seminars they have conducted are greatly appreciated and are a valuable repository of important archival material. From that core group, a loose affiliation called INSA has been active via email links, but we rarely get into the fine details of how a re-invented version of David's course might work. Do we have any desire to film lessons and share them within a members-only group? Do we have special resources that we would be willing to share within the group? A good example would be the Kawaguchi lecture on the history of trusses. This lesson could be expanded and Kawaguchi has permitted the author to take steps to re-create it. But the effort has stalled. Similarly, the work of lesser known masters (Richard Bradshaw's Shells, Myron Goldsmith's structural studies, Castiglioni's Plates and Arches) could be rapidly documented if we pooled our resources together.

Acknowledgements

David Billington was my hero. He had faith in my research abilities and he nurtured my growth as a professor. I will always be grateful for this.

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Quintessentially Billington: The Evolution of Structural Art Teaching at Princeton

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Abstract

One of the most classic courses at Princeton University (*CEE262, Structures in the Urban Environment*) was founded by Professor David Billington (1927-2018) in 1974. The course, based on his scholarship, argues that the best designed structures (bridges, buildings, and shells) are a work of art – structural art. The course integrates humanities with engineering through studies of cultures, people, and art as reflected in works of engineering. Professor Billington used alliterations to reinforce learning: The measures of structural art are efficiency, economy, and elegance; and the structural artist's designs evolve from imitation, to innovation, to inspiration. The authors are Princeton University faculty in who have continued teaching Billington's classic courses (*imitation*), enhanced it with modern pedagogical approaches (*innovation*), and created new classes and scholarship inspired by it (*inspiration*). This paper, in essence, illustrates the many ways that David Billington's legacy and scholarship continue to thrive in creative approaches that one can say are quintessentially Billington.

Keywords: Structures, Engineer, Art, Princeton University, Billington, Pedagogy

1. Introduction

The Industrial Revolution brought about new materials for construction, which, in turn, brought about new forms for structures such as bridges, buildings, and vaults (long spanning roofs). It is in this context that the art of the structural engineer was born, "structural art", as defined by David Billington [1]. Structural art encompasses three ideals: *efficiency* is the true ethos of engineering, namely, to conserve natural resources by minimizing materials; *economy* is the ethic of engineering, to reduce cost by intimately connecting design to construction; and *elegance* is the aesthetic of engineering, to create beautiful forms through structural honesty of the form. "Structural artists" are designers who seek and achieve these three ideals in their completed works. These designers seek to integrate elegance and efficiency rather than superimpose one on the other. They illustrate how the best technical design leaves room for ethical and aesthetic choice.

The teaching of structural art and structural artists began with Billington's course, (*CEE262, Structures in the Urban Environment*). The course was first taught in 1974, followed by the publication of *The Tower and the Bridge* [1]– a seminal book that defined a new field and inspired generations. This course is still taught today by the first author, with an enrollment of over 200 students. The course is accessible to students of all majors and all years. For the students of engineering, the course provides important historical context of their profession as well as a language and means for making aesthetic judgment on engineered designs – topics rarely taught at other institutions. For the non-engineering students, the course satisfies a general education requirement and educates them about importance of their built environment. The authors created new courses, which were inspired by CEE262 and Billington's passion for integrating engineering, humanities, and art. These courses are discussed next.

2. A Classic Course Reinvented

CEE262 has evolved to include modern design and modern pedagogical methods that are now possible with new technologies. The course has also inspired other courses as will be described in the sections to follow.

2.1. CEE262: Imitation and Innovation

Forty-five years later, many of the lecture themes in CEE262 remain as they were in 1974 – but not all. Over the last 10 years, CEE262 lectures have integrated new scholarship such as that of Felix Candela [2], Laurent Ney [3], and other research developed by the authors. In addition, lectures devoted to wind design, earthquake engineering, and ethics have been added. This has necessitated the difficult challenge of combining or removing some of Professor Billington's original lectures. The 'core' lectures remain however, as does the objective and spirit of the course – the message of engineering as a *creative* discipline. In addition, the lectures include active-learning approaches, as will be explained next.

CEE262 current innovations include modern 'active-learning' activities embedded in the lectures such as internet polling and short physical experiments conducted by the students during lectures. An active learning based approach has been shown to reduce the achievement gap and benefit underrepresented minorities in STEM. Since 2013, the first author has gradually incorporated active-learning pedagogy into the lectures, and currently approximately 100% of CEE262 lectures utilize active-learning pedagogy, including demonstrations, hands-on activities, and discussion questions. Classroom response systems have been shown to be effective in raising the level of student engagement in college courses. In this course, we made use of *Poll Everywhere*, a classroom response system in which students submit answers to questions via text message or internet connected devices. We used this technology to help motivate a topic, to elicit discussion, to assess understanding, and to encourage experiential learning [4, 5, 6, 7]. An example of active learning is given in Figure 1.

The active learning enhancement, as well as dissemination of the course to other institutions, was made possible by a federal grant through the National Science Foundation. A website describing the outcomes of this grant, contains resources to teach the course [8].

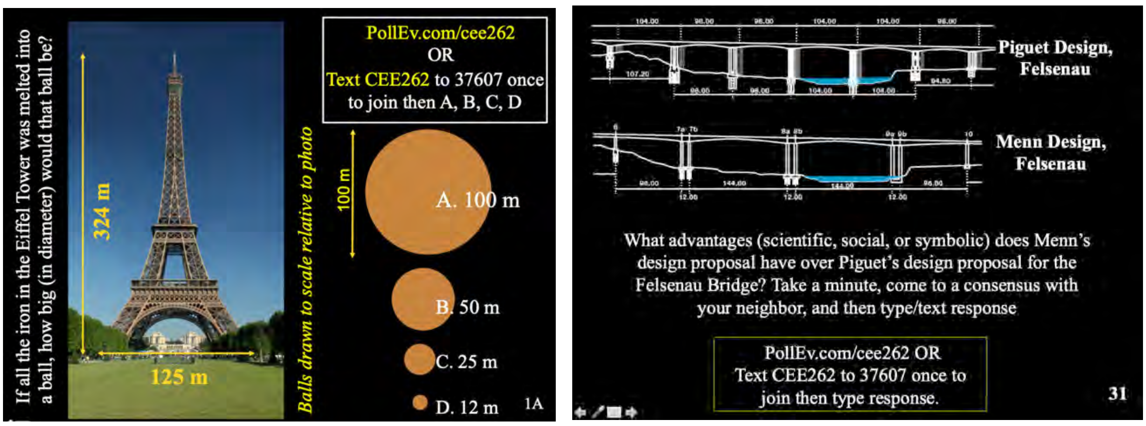

Figure 1. Example of CEE262 active-learning slides: (left) motivating learning of the Eiffel Tower (correct answer = D); (right). eliciting discussion through the works of Christian Menn.

2.2. CEE463: An Inspirational Derivative of CEE262

An inspirational derivative of CEE262 is intended for more advanced students studying structural engineering: *CEE463 (A Social and Multi-dimensional exploration of Structures*). *CEE463* has been taught biannually by the authors since 2010 and it develops the student's skills in drawing, model making, aesthetic considerations, and advanced engineering analysis. It also emphasizes the humanities aspect of our built environment through a study of the social and economic context of the built work. The theme of the course changes every time it is taught, where the themes have been Fazlur Khan: Structural Artist of Urban Building Forms (2010), Evolution of German Shells (2012), The art of Spanish Bridge Design (2014), Creativity in Cuban Thin Shell Structures (2016), and Two Millennia of Structural Architecture in Italy (2019).

The course includes: site visits, a study of historical data (both socio-political and engineering), structural analysis, building of scaled prototype models, and creation of websites, movies, essays, and an exhibition (see Figure 2). The course has several impacts: (1) students' perception of the structural engineering profession is significantly broadened and put into a global context; (2) their motivation and self-confidence to exercise structural engineering as profession is energized, and (3) their communication skills are significantly improved. Our pedagogical approach was based on the idea that the students will learn the best by teaching themselves through solving challenging open-ended assignments. Some pedagogical objectives include:

1. Start to develop a sense for implicit knowing by studying precedents;
2. Learn how to communicate complex technical issues with peers and laymen;
3. Develop spoken, written, pictorial, analytical and numerical proficiency;
4. Reflect critically upon social, political and historic influences of past successful structural designs.

Figure 2 shows students using hand drawn sketches and calculations, computer modeling, and physical models for their study of a horizontal cantilever structure in Havana, Cuba. Outcomes of this course can be observed though the course websites [9] and some more detail is given in [10].

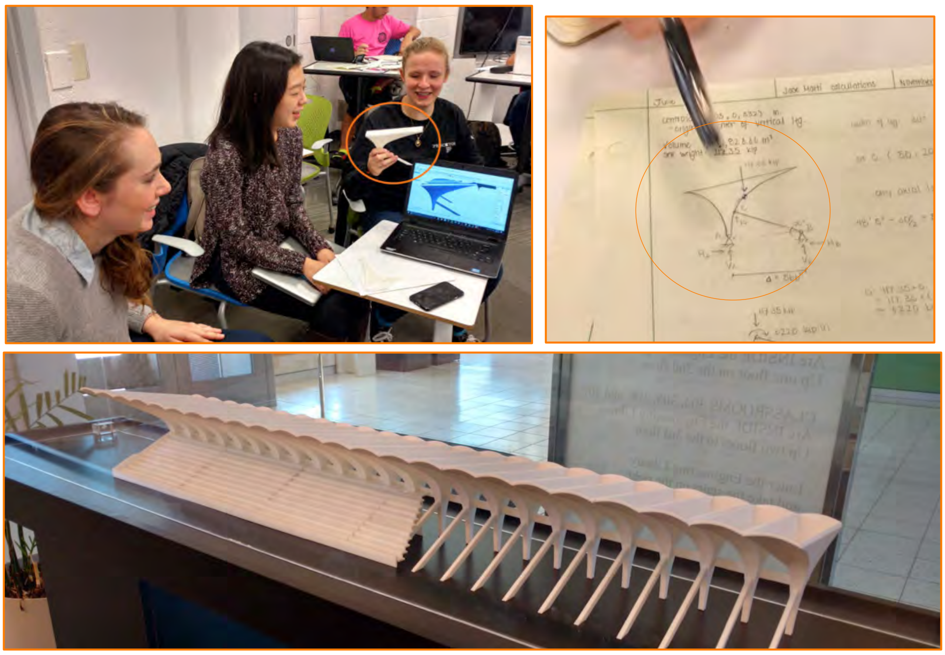

Figure 2. CEE463 students using hand drawn sketches and calculations, computer modeling, and physical models for their study of a horizontal cantilever structure in Havana, Cuba.

3. Inspiring Derivatives in the Humanities

Other inspirational derivatives of Billington's teaching and scholarship are represented in three more courses that are more heavily invested in the humanities as discussed in this section.

3.1. CEE 538 – Holistic Analysis of Heritage Structures

CEE 538 (Holistic Analysis of Heritage Structures) is held bi-annually and connects the Departments of Civil & Environmental Engineering (CEE) and Art & Archaeology (ART). Taught by the third author, the course enrolls students from CEE, ART, and the School of Architecture, and it introduces engineering students to the humanities aspects of structural reconstruction and the analysis of heritage structures, as well as introducing humanities students to the scientific and engineering rules to consider in artistic reconstruction. Graphic statics is used to help students visualize the flow of forces, but also as a simple tool for initial structural analysis. Example of slides from the course that explain flow of forces in lintel arch is given in Figure 3.

Heritage structures – such as residential, public and sacred buildings, bridges, and monuments – constitute invaluable cultural legacy. Still standing, or partially or completely collapsed, heritage structures are witnesses of the cultural, engineering, economic, scientific, and political development of humans, which engraved an everlasting impression on societies. Besides their cultural, aesthetic, and societal impact, still-standing heritage structures demonstrated an extraordinary capacity to face natural and man-made hazards, which greatly contributed to the resilience of societies they have been serving.

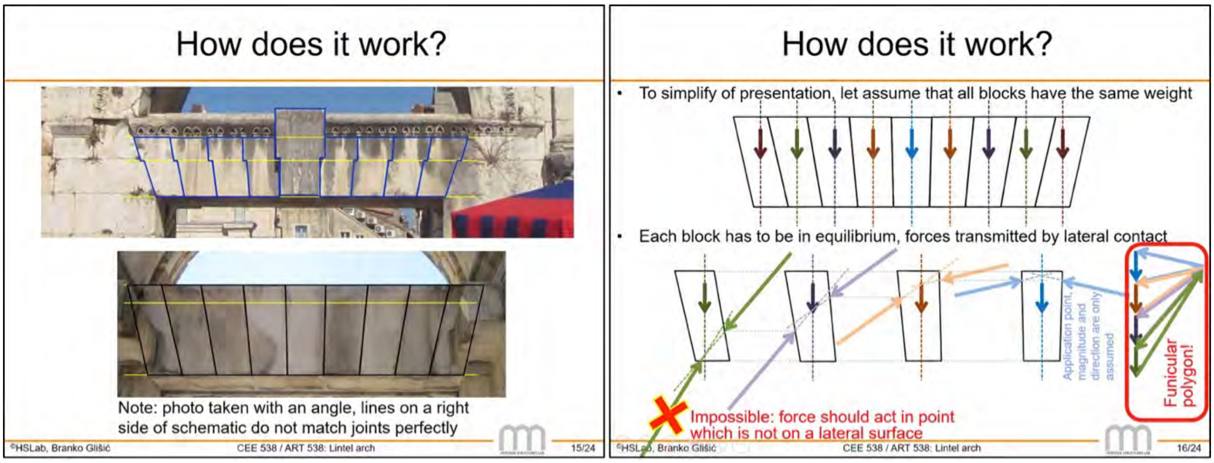

Figure 3. Example of slides from CEE 538 presenting graphic-statics analysis of lintel arch.

3.2. CEE 418 – Extraordinary Processes

Over the past 100 years, artists around the world have become increasingly interested in the aesthetic value of everyday life. Pablo Picasso's *Still Life With Chair Caning*, Virginia Woolf's *Mrs. Dalloway*, Andy Warhol's *Soup Cans*, and El Anatsui's mosaics are all examples of ordinary objects becoming extraordinary works of art. As a hands-on studio class, *CEE418 (Extraordinary Processes)* investigates the creative processes and technical skills that made these transformations possible. The course specifically focuses on the extraordinary (structural and aesthetic) potential of ash wood, currently a beetle-infested waste material in USA. The course is taught by the second author and Visual Arts Faculty [11].

Processes is a material- and studio-driven course taking place in three locations: testing labs in the department of Civil and Environmental Engineering;a sculpture studio in the Lewis Center (Figure 4) ; and field work in the natural habitat.The focus of the course is to: research the circumstances of infested ash trees; develop a thorough understanding of the wood's material properties; and ultimately design, make, and analyze novel experiments made of infested local ash wood. Overall, the course is a hands-on learning environment in which engineering and art can intersect and inform each other in a team-taught studio setting.

The overall educational objectives of the course for both undergraduate students are: to

1. Develop an understanding of the interrelationships between material properties, forms, and forces through lab testing and simple analysis;
2. Conceive and make prototypes for a number of artworks and value added products that exploit the properties of infested ash wood, based on this analysis; 3
3. Test and evaluate these artworks/designs; and (iv) to communicate the social, economic, and aesthetic aspects of these artworks/designs in final presentation and exhibition to a group of laymen.

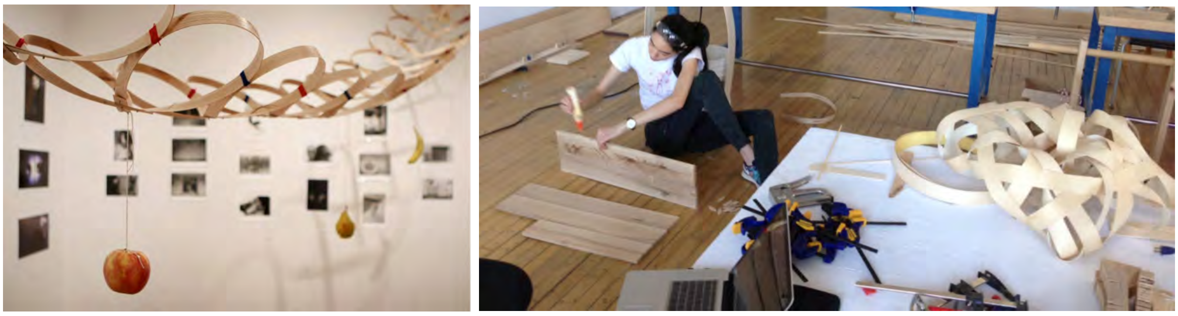

Figure 4. In CEE 418 the students cut thin strips of ash wood, using steam to soften and bend them. As a final project, the students built a wood bridge to span a gallery. The bridge was required to support 16 pounds and also portray motion (deform and spring back) when the weights were added and removed. Photo by Frank Wojciechowski for the Office of Engineering Communications

3.3. CST 209 – Transformations in Engineering and the Arts

Faculty from various engineering and humanities departments have come together to teach *CST 209 (Transformations in Engineering and the Arts)* [12]. First taught in the Spring 2016, this course explores the parallels and intersections of design and composition in engineering and the arts, emphasizing a merging of artistry and systematic thinking. Students use what they learn to create as engineer-artists and artist-engineers. The course is organized around four modules: visuals, sound, structure and movement. It is led by faculty from computer science, music, civil engineering, and mechanical engineering, with faculty from the Lewis Center for the Arts. 'Transformations' unifies the modules by engaging the different disciplines and allowing the course to serve as an introductory experience for students with diverse academic backgrounds. At the end of the four modules, students are placed in teams for a final project design. One group, inspired by the desire to help broaden boundaries for vision-impaired people, created an armband device that allows a wearer without the ability to see to interpret color (Figure 5).

Figure 5. Small group project in STC209 - armband device that allows a wearer without the ability to see to interpret color. Photo by David Kelly Crow for the Office of Engineering Communications

4. Conclusions

David Billington's influence has extended beyond teaching; it has set the foundation for and stimulated an *Engineering and the Arts* initiative on Princeton's campus. This initiative has inspired a Symposium, internal funding from an alumnus, and gathered an enthusiastic group of faculty from various engineering departments and the arts/humanities who are finding innovations and inspirations in their research by collaborating at the intersection of engineering and art.

What began as one course at Princeton in 1974 (CEE262) has inspired many more – only some were discussed here. Other notable courses include *CEE102 – Engineering in the Modern World*, which centers on the transformation of American society by the four traditional branches of engineering – civil, mechanical, electrical, and chemical. Like CEE262, the course is intended for a general audience of all majors and continues to have a large enrollment.

The paper demonstrated how Billington's classic courses (e.g. CEE262) continue to be taught (*imitation*), but they have been enhanced with modern pedagogical approaches (*innovation*). Examples of new classes inspired by Billington's structural art concept and humanities approach to teaching were given (*inspiration*).

It is concluded that Billington's legacy at Princeton is not only alive, it is thriving.

Acknowledgements

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Simplified closed-form expressions for horizontal reactions in linear elastic arches under self-weight

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Abstract

Finite and/or discrete element modeling are typical modern tools for determining reactions and internal forces in arches. However, while these tools are excellent in performing detailed analysis, they might be less suitable for conceptual design and "back-of-the-envelope calculation" due to their complexity of application. Simplified closed-form formulae for reactions and internal forces might be more appropriate as they enable fast solutions and easy development of parametric studies. Hence, the aim of this paper is to present novel simplified closed-form expressions for determination of horizontal reactions in segmental, catenary, and parabolic arches under self-weight. Three typical structural systems for symmetric linear-elastic arches with constant cross-section and various rise-to-span ratios were considered: three-hinged, two-hinged, and hingeless. It was found that the horizontal reactions, to large extent, do not depend on arch shape or number of hinges, but only on linear weight, span, and equivalent angle of embrace. Surprisingly, with few exceptions, single formula presented in this paper provides almost universal solution for all shapes of arches, rise-to-span ratios, and boundary conditions. In addition, linear relationship between horizontal reactions of the three structural systems (hingeless, three-hinged, and two-hinged) was discovered, which is valid for any shape (segmental, parabolic, and catenary) and any rise-to-span ratio.

Keywords: Segmental, parabolic and catenary shape, Symmetric linear-elastic arch, Closed-form equations, Horizontal reaction, Three-hinged, two-hinged and hingeless arch

1. Introduction

Creation of large-scale infrastructure in antiquity started by mastering arch structural system. First experimentation and small-scale arch structures were created by Sumerians; however, Etruscans enabled widespread methodical use of arches in IV century Before Common Era (BCE) [1]. During the next 2500 years the arch has been omnipresent in wide range of structures. In ancient and medieval times, the shape of an arch was mostly semi-circular, although some rare exceptions are identified [2]. Engineering mechanics and resulting analytical techniques that were developed in XVII-XIX century enabled analysis and understating of arch structural system [3]. Consequently, the shape of arch shifted from segmental to other forms such as elliptic, catenary, parabolic, etc., and it was optimized based on project-specific design constraints.

Leonardo da Vinci was among the first engineers who provided hints on structural behavior of arches (1508?): "An arch is nothing other than a strength caused by two weaknesses; for the arch in buildings is made up of two segments of a circle, and each of these segments being in itself very weak desires to fall, and as the one withstands the downfall of the other the two weaknesses are converted into a single strength" [4]. Robert Hooke understood that segmental shape is not ideal for an arch under self-weight and stated in 1676 in an anagram that ideal shape under self-weight is catenary [3,5]. Since then, an enormous body of knowledge regarding arches was developed (e.g., [1], [3-14], etc.).

However, to the best of author's knowledge, current literature does not present simple closed-form equations for reactions and internal forces of arches. The aim of this paper is to address that challenge. Due to restriction in paper length, the scope is limited to presenting simplified closed-form equations for horizontal reactions of segmental, parabolic, and catenary arches under self-weight and to evaluate relationships between horizontal reactions of three different structural systems – three-hinged, two-hinged, and hingeless arch. It was assumed that the arch behavior is linear-elastic. While this assumption restricts to certain extent the applicability of equations, they still have very broad applicability. Due to limited space, the paper focus is on horizontal reactions under self-weight, only; more detailed study, including internal forces, as well as other load cases can be found in [15].

2. Differential equations of segmental arch

Typical symmetric segmental arches are given in Figure 1. Let us denote the radius of arch centerline with R, span with L, rise with D, and angle of embrace with β. To simplify presentation of figures, these parameters are only shown in Figure 1c. To simplify presentation of formulas, β is substituted with 2α, where α is half-angle of embrace ($\beta=2\alpha$ i.e., $\alpha=\beta/2$).

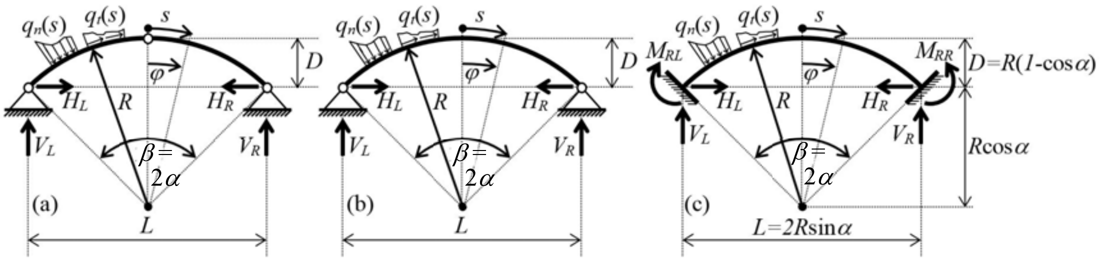

Figure 1: Typical segmental arches: a) three-hinged, b) two-hinged, and c) hingeless arch [15]

The origin of natural (curvilinear) coordinate system is set at the apex of the arch, and the natural coordinate s is positive in clockwise direction. The ratio s/R represents the angle φ (in radian) between the vertical line passing through the origin and the line connecting the center of circle defining the arch and point with coordinate s. Component of load perpendicular to the arch centerline is denoted with $q_n(s)$, while the tangential component of load is denoted with $q_t(s)$. If positive sign of load is as shown in Figure 1, differential equations of segmental arch have the appearance as given in Equations 1a-c [13].

$$\frac{\mathrm{d}N(s)}{\mathrm{d}s}-\frac{S(s)}{R}+q_t(s)=0 \tag{1a}$$

$$\frac{\mathrm{d}S(s)}{\mathrm{d}s}+\frac{N(s)}{R}+q_n(s)=0 \tag{1b}$$

$$\frac{\mathrm{d}M(s)}{\mathrm{d}s}-S(s)=0 \tag{1c}$$

where: $N(s)$, $S(s)$, and $M(s)$ are the normal force, shear force, and bending moment, respectively.

For an arch with constant cross-section loaded only by self-weight $g(s)$=g=constant, g has only vertical component and thus, the normal and tangential components of load (see Figure 1) are determined using Equations 2.

$$q_n(s) = g\cos\frac{s}{R} \tag{2a}$$

$$q_t(s) = g\sin\frac{s}{R} \tag{2b}$$

Equations 1a, 1b, 2a and 2b can be combined into a single differential equation of the second order on S(s) (by deriving Equation 1b and substituting derivative of $N(s)$ from Equation 1a, and normal and tangential components of loads from Equations 2a and 2b). This differential equation can be solved over $S(s)$, but final solution require determination of two constants of integration from boundary conditions. Once $S(s)$ is determined, Equation 1c can used to determine $M(s)$, which also require determination of one more (third) constant of integration from boundary conditions. In parallel, $N(s)$ can be determined using Equation 1b.

However, the solution proposed in previous paragraph is not easy to derive for two-hinged and hingeless arch, as their boundary conditions do not contain three known internal forces; in addition, the solution for three-hinged arch using this approach would be tiresome. Hence, alternative approaches are taken: three-hinged arch is solved from equations of equilibrium, while two-hinged and hingeless arch are solved using force method. For two latter structural systems the Equations 1 and 2 are used in the process on calculating internal forces and reactions on primary structures, see details in [15].

3. Horizontal reactions in segmental arches

To emphasize that equations presented in this text are related to load due to self-weight, superscript g is used in all equations that are presented subsequently. Given that both, the load g and the shape of the arch, are symmetric with respect to vertical axis at the arch apex, the reactions are also symmetric with respect to the same axis regardless of structural system of the arch (three-hinged, two-hinged or hingeless) i.e., $V_L^g = V_R^g = V^g$, $H_L^g = H_R^g = H^g$, and $M_{RL}^g = M_{RR}^g = M_R^g$ (see Figure 1). Hence, for simplification of presentation, index denoting left and right side reaction is omitted, i.e., only the terms V^g, H^g, and M_R^g will be used. In addition, for all three typical structural systems vertical reactions are equal half-weight of the arch, i.e.:

$$V^g = gR\alpha \tag{3}$$

3.1. Horizontal reactions in three-hinged segmental arch

In further text subscript "$3h$" is used to denote forces in three-hinged structure. Since the three-hinged arch is statically determinate structure, its reactions can be calculated from equations of equilibrium. Due to symmetry and given that the vertical reactions are known (Equation 3), the horizontal reactions H_{3h}^g are determined from the sum of moments about apex hinge G acting on one side of the hinge, and presented in Equation 4 [15]. All active and reactive forces, as well as resultant of self-weight load acting on one side of the structure are presented in Figure 2.

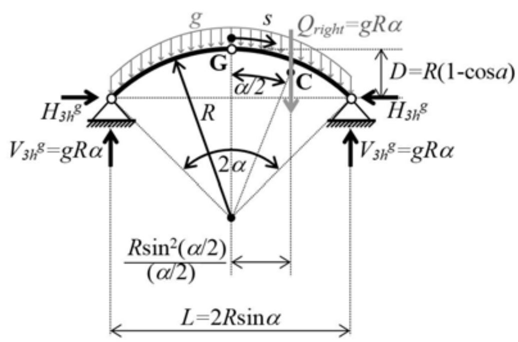

Figure 2: Active and reactive forces, and geometrical properties of three-hinged arch loaded by self-weight [15]

$$H_{3h}^{g} = gR\left(\alpha\cot\frac{\alpha}{2}-1\right) = \frac{1}{4}gL\csc\frac{\alpha}{2}\left(\alpha\csc\frac{\alpha}{2}-\sec\frac{\alpha}{2}\right) \tag{4}$$

3.2. Horizontal reactions in two-hinged segmental arch

In further text subscript "*2h*" is used to denote forces in two-hinged structure. Being indeterminate to degree one, two-hinged arch was analyzed using force method. Figure 3 shows the primary structure and all external and internal forces acting on it. Note that unknown force X_1 acting on primary structure is equal to horizontal reaction $H_{2h}{}^{g}$ in the original structure. Coefficients of flexibility are calculated using Equations 5 and horizontal force is determined in Equation 6. Influence of normal and shear forces on deformation was neglected when calculating flexibility coefficients. Note that the vertical reaction is determined from symmetry in Equation 3.

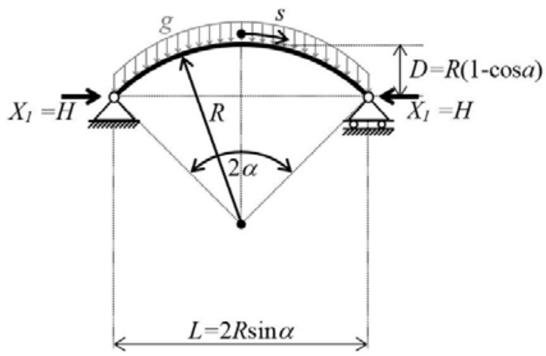

Figure 3: Primary structure of two-hinged arch [15]

$$EI\delta_{11} = \int_{-R\alpha}^{R\alpha} M_1^2(s)\mathrm{d}s = R^3\left(\alpha - 3\sin\alpha\cos\alpha + 2\alpha\cos^2\alpha\right) \tag{5a}$$

$$EI\delta_{10}^{g} = \int_{-R\alpha}^{R\alpha} M_1(s)M_0(s)\mathrm{d}s = -gR^4\left(\frac{1}{2}\alpha + \frac{9}{2}\sin\alpha\cos\alpha - 5\alpha\cos^2\alpha - 2\alpha^2\sin\alpha\cos\alpha\right) \tag{5b}$$

$$H_{2h}^{g} = -\frac{\delta_{10}^{Mg}}{\delta_{11}} = \frac{1}{2}gR\frac{\alpha + 9\sin\alpha\cos\alpha - 10\alpha\cos^2\alpha - 4\alpha^2\sin\alpha\cos\alpha}{\alpha - 3\sin\alpha\cos\alpha + 2\alpha\cos^2\alpha} \tag{6}$$

where $M_1(s)$ denotes bending moment distribution along the primary structure due to X_1=1, $M_0(s)$ denotes bending moment distribution along the primary structure due to load q, δ_{11} and δ_{10} are flexibility coefficients and EI is bending stiffness of the arch (modulus of elasticity E multiplied with moment of inertia I).

3.3. Horizontal reactions in hingeless segmental arch

In further text subscript "*0h*" is used to denote forces in hingeless structure. Hingeless structure is indeterminate to the degree three, and thus, similar to the approach used in two-hinged structure, force method is used to determine the reactions. To simplify the analysis by eliminating "mixed" (non-diagonal) flexibility coefficients (i.e., if i≠j then δ_{ij}=0), the method of elastic center was used [13]. This reduces a system of three equations with three unknowns to three simple linear equations with one unknown. The primary structure, geometry and unknown forces X_1(=$V_{0h}{}^{g}$), X_2(=$H_{0h}{}^{g}$), and X_3 (no particular meaning) are shown in Figure 4. Flexibility coefficients are calculated using Equations 7 and reactions using Equation 8 [15]. Note that flexibility coefficients δ_{10} and δ_{11} are not needed as the vertical reaction is determined from symmetry in Equation 3.

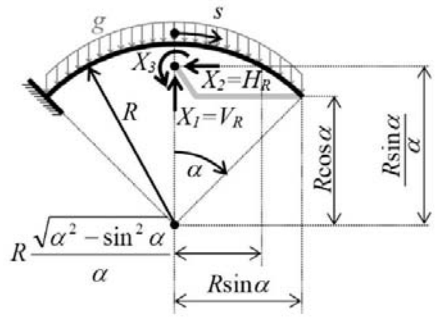

Figure 4: Primary structure of hingeless arch [15]

$$EI\delta_{22} = \int_{-R\alpha}^{R\alpha} M_2^2(s)ds = \int_{-R\alpha}^{R\alpha} R^2\left(\cos\frac{s}{R}-\frac{\sin\alpha}{\alpha}\right)^2 ds = R^3\left(\alpha+\sin\alpha\cos\alpha-2\frac{\sin^2\alpha}{\alpha}\right) \tag{7a}$$

$$EI\delta_{33} = \int_{-R\alpha}^{R\alpha} M_3^2(s)ds = \int_{-R\alpha}^{R\alpha} 1^2 ds = 2R\alpha \tag{7b}$$

$$EI\delta_{20}^g = gR^4\left(\frac{\alpha}{2}+\frac{1}{2}\sin\alpha\cos\alpha-\frac{\sin^2\alpha}{\alpha}+3\sin\alpha\cos\alpha+\alpha\sin^2\alpha-3\frac{\sin^2\alpha}{\alpha}\right) \tag{7c}$$

$$EI\delta_{30}^g = 4gR^3\left(\alpha\cos\alpha-\sin\alpha\right) \tag{7d}$$

$$H_{0h}^g = -\frac{\delta_{20}^{Mg}}{\delta_{22}} = -gR\left(\frac{1}{2}+\frac{\alpha\sin^2\alpha+3\sin\alpha\cos\alpha-3\frac{\sin^2\alpha}{\alpha}}{\alpha+\sin\alpha\cos\alpha-2\frac{\sin^2\alpha}{\alpha}}\right) \tag{8a}$$

$$M_{R,0h}^g = -gR^2\left(\left(\frac{3}{2}-\frac{\alpha\sin^2\alpha+3\sin\alpha\cos\alpha-3\frac{\sin^2\alpha}{\alpha}}{\alpha+\sin\alpha\cos\alpha-2\frac{\sin^2\alpha}{\alpha}}\right)\left(\cos\alpha-\frac{\sin\alpha}{\alpha}\right)+\alpha\sin\alpha\right) \tag{8b}$$

Reactive moment $M^g_{R,0h}$ is calculated by moving generalized forces $X_1(=V_{0h}^g)$, $X_2(=H_{0h}^g)$, and X_3 to the free end of primary structure ($s=R\alpha$; forces $X_1(=V_{0h}^g)$ and $X_2(=H_{0h}^g)$ are resolved into force-couples and the resulting couples are combined with $X_3=-\delta_{30}/\delta_{33}$).

3.4. Simplified equation for horizontal reaction in hingeless segmental arch

Equation 4, expressing horizontal reaction in three-hinged arch, is relatively simple, and to some extent intuitive. However, Equations 6 and 8a, expressing horizontal reactions in two-hinged and hingeless arch are less simple and intuitive, and their simplification would be helpful for parametric studies and back-of-the-envelope calculations. Figure 5 shows relationship between the half-angle of embrace and normalized horizontal reaction of hingeless arch. The horizontal reaction is normalized with product gL. In addition, approximation of this relationship based on the power function is also presented. The figure establishes the following simplified relationship between the horizontal reaction and angle of embrace:

$$H_{0h}^g \approx \frac{gR\sin\alpha}{\alpha} = \frac{gL}{2\alpha} = \frac{gL}{\beta} \tag{9}$$

Direct comparison demonstrates that Equation 9 underestimates Equation 8a for a fraction smaller than

than 2%. Equation 9 can be interpreted as follows: horizontal reaction of hingeless arch is proportional to product of arch span and its linear self-weight (which is not total weight of the arch), and inversely proportional to the angle of embrace. This equation has very simple form, it is easy to memorize and apply, and provides results with relative error smaller than -2%.

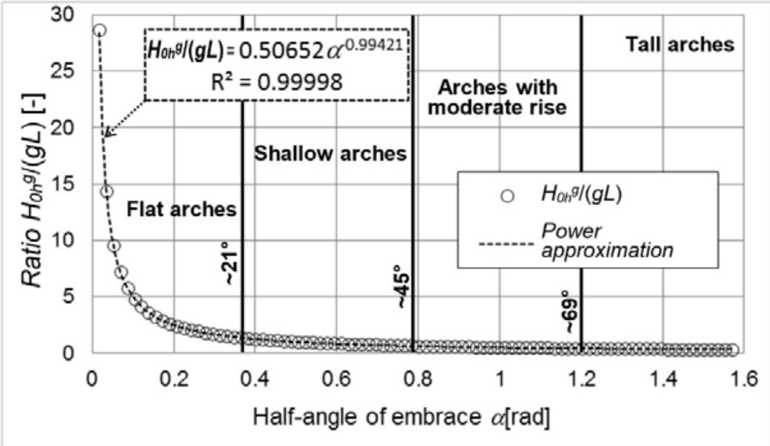

Figure 5: Relationship between normalized horizontal reaction of hingeless arch and half-angle of embrace [15]

Based on Equation 9, the following unformal classification of arches is made in Figure 5: flat arches (0° < $\alpha \leq$ 21°), shallow arches (21° < $\alpha \leq$ 45°), arches with moderate rise (moderate arches, 45° < $\alpha \leq$ 69°), and tall arches (69° < $\alpha \leq$ 90°). Limit for flat arches of 21° (0.37 rad) is chosen because for larger half-angles of embrace the change in normalized horizontal force is only 5%. Upper limit for shallow arches is set to 45° (0.79 rad) as the normalized horizontal force for that angle ($H_{0h}{}^{g}$=0.644) is approximately two times smaller than the one for 21° ($H_{0h}{}^{g}$=1.368) and two times bigger than the normalized horizontal force for 90° ($H_{0h}{}^{g}$=0.320). Finally, upper limit of 69° (1.20 rad) is set for moderate arches as for that angle the difference between exact and approximate equations, 8a and 9 respectively, is maximal (value of normalized horizontal reaction is $H_{0h}{}^{g}$=0.423).

3.5. Relationship between horizontal reactions in typical segmental arches

The relationship between the horizontal reactions of the three-hinged, two-hinged and hingeless arch is explored in Figure 6, which presents the ratio between horizontal reactions of former two with respect to latter.

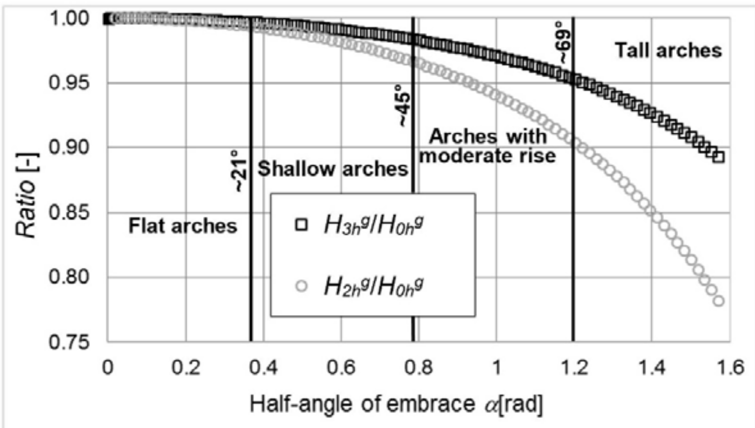

Figure 6: Ratios between horizontal reactions of the three- and two-hinged arch over hingeless arch [15]

Figure 6 shows that Equation 9 can be extended with high degree of accuracy to flat and shallow there- and two-hinged arches, with acceptable degree of accuracy to arches with moderate rise, and with simple modification (correction) even to tall arches. In addition, Figure 6 reveals an interesting relationship between horizontal reactions of the three structural systems, as shown in Equation 10.

$$H_{3h}^{g} \approx \frac{1}{2}\left(H_{0h}^{g} + H_{2h}^{g}\right) \tag{10}$$

Equation 10 states that the horizontal reaction in three-hinged arch is approximately equal to average value between horizontal reactions of two-hinged and hingeless arch.

3.6. Extension to parabolic and catenary arches

As opposed to antique arches, which mostly have had segmental shape, modern arches are frequently made in form of parabola. In addition, it is well known that the perfect (moment free) shape of the arch under self-weight is catenary. Hence, the validity of Equations 9 and 10 was examined for these two shapes of the arch. Given that both shapes are non-circular, an equivalent angle of embrace for these shapes is calculated as the angle of embrace of segmental arch that has the same rise D as observed (parabolic or catenary) arch. This equivalent angle of embrace is given in Equation 11.

$$\beta_{equivalent} = 2\alpha_{equivalent} = 4\arctan\left(2\frac{D}{L}\right) \tag{11}$$

For hingeless catenary arch, relative difference between horizontal reaction determined using Equation 9 and the exact solution is 0.01%, 0.20%, 1.04% and 2.89% for equivalent half-angles of embrace of 21°, 45°, 69°, and 90°, respectively, which confirms high accuracy of approximation. In addition, given that catenary arch is moment free regardless boundary conditions, Equation 9 extends to three- and two hinged catenary arches with the same level of accuracy. For the same reason (moment free), Equation 10 also applies for catenary arches (actually, symbol "≈" transforms into "=" in the equation).

Similar analysis shows that Equation 9 is also applicable to parabolic arches of all three types. For hingeless arches the relative difference from exact solution is 0.15%, 0.70%, 1.55% and 2.43% for equivalent half-angles of embrace of 21°, 45°, 69°, and 90°, respectively; for three hinged arches it is 0.005%, 0.09%, 0.41% and 0.96%, and for two hinged arches it is -0.16%, -0.66%, -1.42%, and -2.31%. Consequently, Equation 10 also applies.

4. Conclusion

This paper presents simplified closed-form equations for horizontal reactions of linear-elastic segmental, catenary, and parabolic arches under self-weight.

Simplified equation for determination of the horizontal reactions (thrust) of the hingeless segmental arch (Equation 9), states that the reaction is approximately equal to the product of arch span and linear weight, divided with the angle of embrace (expressed in radians). This formula is simple to memorize and apply, it is valid for full range of angles of embrace (from 0° to 180°), and it underestimates the true analytical value for less than 2%. In addition, it was found that the same formula can be applied with high accuracy to flat and shallow segmental three- and two-hinged arches, with acceptable degree of accuracy to moderate arches, and with some corrections to tall segmental three- and two-hinged arches, too. Finally, the simplified equation is applicable with high degree of accuracy to parabolic and catenary arches, regardless the arch rise or boundary conditions. For parabolic and catenary arches an equivalent angle of embrace is used in the equation.

Another important equation that was derived in this paper (Equation 10) shows the relationship between horizontal reactions in three-hinged, two-hinged and hingeless arch, i.e., states that the former is approximately equal to average value of the latter two.

In overall, the paper presents two new equations that are versatile yet simple, and that enable back-of-the-envelope determination of horizontal reactions in typical (three-hinged, two-hinge and hingeless) segmental, catenary and parabolic arched under self-weight.

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Structual Art and Conceptual Design in Engineering Education: a Perfect Marriage

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Abstract

Despite being a very important discipline, Structural Art is rarely taught as a full course at the schools of civil engineering. Therefore, strategies to introduce the main ideas of Structural Art in general courses on structural design, bridge engineering or building structures are needed. Within this context, this contribution will detail how the main ideas of Structural Art are introduced on a general course on conceptual design that is compulsory for all the students (around 70 per year) doing the Master in Civil Engineering at the School of Civil Engineering of Valencia (Spain). The contribution presents: (1) the contents of the course with a special focus on the Structural Art component, (2) the practical activities developed (e.g. structured debates to foster critical thinking and activities where the students create their "Decalogue of the outstanding structure"), (3) the methodologies followed to measure the students' performance and (4) measures of the success of the approach.

Keywords: conceptual design, engineering education, Structural Art, David P. Billington.

1. Introduction

The Spanish engineer Eduardo Torroja defined in the middle of the 20th century the main idea behind the words "conceptual design" when, in the first page of his book "Philosophy of Structures" [1], he wrote: *"(...) Before and above all structural analysis there is the idea. This idea shapes the material in a resisting form that enables it to fulfil its mission (...)"*. After Torroja, other authors have also pointed out the importance of simplified analysis methods and conceptual design in engineering education and practice. For example, the shell designer Félix Candela wrote *"(...) all calculations, no matter how sophisticated and complex, cannot be more than rough approximations of the natural phenomenon they try to represent (...)"* [2]. On the other hand, Princeton University professor, David P. Billington published in 1983 the book "The Tower and the Bridge: the New Art of Structural Engineering" [3] where he analyzed the best examples (to his opinion) of structural engineering built from the late 18th century until the late 20th century and coined the term "Structural Art". This term referred to works that excelled for their economy, efficiency and elegance. The work by Billington was very inspiring for engineers and non-engineers world-wide and provided a framework to develop structural critique and to connect structures to architecture and society.

The "idea" Torroja was referring to was very important in the 1950s when the book [1] was written, but it is even more important today when computers make the detailed structural analysis of almost any building form possible. However, modern engineering curricula tend to focus more on the details of the analysis than on the "idea" behind it. The philosophy of Structural Art is also very important today, since current engineering curricula do not usually explore the connection of engineering works with society, architecture, history and art. As a result, the future engineer can be deprived of the creative facet and risks to become a "mere calculator" and one can see public money wasted, especially in times of economic boom (see e.g. reference [4] for some examples related to Spain). Many authors have explored the paths opened by Torroja and Billington. For example, Mike Schlaich [5] has explained in detail the role of conceptual and structural design in the education of the engineer and other authors have explained how creativity can be a part of the engineers' education (Bögle [6], Garlock and Jorquera-Lucerga [7]) or how case studies can be used to develop structural criticism and structural intuition (Payá-Zaforteza [8]).

Within this context, this paper explains how the ideas of Structural Art are included in a course on the conceptual design of singular structures offered at the Universitat Politècnica de València (UPV henceforth), in Valencia, Spain.

2. Overview of the course "Conceptual Design of Singular Structures"

The course "Conceptual Design of Singular Structures" is taught at the second year of the studies the Master in Civil Engineering offered by the UPV. The course is compulsory for all the students and the course enrollment is close to 70 students per year. The number of teaching hours is 45 (25 of theory, 12 of practical classroom activities and 8 of activities at the computer lab). Given the location of the course in the engineering curricula, the students enrolled have an important structural background.

The main goal of the course is to introduce the students to the main principles that guide the design of singular structures, where the term "singular" refers to uncommon materials, structural systems, construction procedures and/or general dimensions (i.e., span lengths, dimensions of surfaces covered or building heights). This general goal can be split up in the following specific objectives:

- To develop historical perspective.
- To understand the relationship between form and forces in a structure.
- To learn how to perform simple calculations of apparently complex structures.
- To study the links among structural engineering, architecture and society.
- To introduce the students to bibliographic search tools.
- To develop critical thinking and communication skills.
- To practice the use of scientific English.
- To show the students how structural engineering can be a very appealing topic.

To reach these goals, the course covers the topics shown in Table 1.

Table 1: Contents of the course "Conceptual Design of Singular Structures"

Teaching unit	Main contents
Previous concepts about linear structural elements	Review of the main structural systems based on linear elements: the arch, the cable and the beam.
Vaults, domes and shell structures	Typology, structural behavior and design of: classical and modern vaults and domes; continuous shells (folded plates, cylindrical shells, revolution shells, hyperbolic paraboloids, other geometries); and grid shells.
Light structures for roofs with singular typologies	Typology, structural behavior and design of light structures for roofs: cable networks; prestressed membranes; pneumatic structures; tensegrities; tensegrities; branching structures; deployable structures; and bending-active structures.
Structural design of tall buildings	Structural types used to resist horizontal loads. State-of-the-art in the construction of tall buildings. Horizontal actions: wind and earthquakes.
Practical application of the ideas of Structural Art	Engineers and architects. Origins and ideals of Structural Art. The three dimensions of the structure. Critical analysis of structures. Importance of Structural Art today.

A detailed description of the course objectives, contents and teaching methodologies can be found in Paya-Zaforteza et al. [9] and therefore is not given here. In addition, the course aims also to make the students develop two transversal competences: (1) Innovation, creativity and entrepreneurship and (2) Design.

3. Introducing "Structural Art" in the course "Conceptual Design of Singular Structures"

3.1 Detailed description of the approach

The Structural Art component is taught at the end of the course during four sessions with the content and activities described next.

3.1.1 Session 1 (2 hours). Defining the Decalogue of the Outstanding Structure.

In a traditional approach, the students would be passive actors of the teaching-learning process who would get the main ideas of Structural Art directly from the professor. Here, a different approach is taken. Following Confucius quote ("Tell me and I will forget, show me and I may remember, involve me and I will understand"), the students are pushed to reflect on the attributes of outstanding structures by creating a "Decalogue of the Outstanding Structure". This activity serves as an introduction to the topic of Structural Art.

The Decalogue is defined by the class as a whole using a variant of the 635 brainstorming technique [10] according to the following process:

1. The students are grouped in teams of four. Each student is given a template (see Fig. 1) to write three attributes of an outstanding structure. After 5 minutes, the templates are exchanged within the group and each student should write three new attributes, a process that is repeated three times in total. Therefore, each student has to write 4 x 3 = 12 different attributes and the total number of attributes proposed by the group should be 12 x 4 = 48 (see Figs. 2a and 2b).
2. Each group selects their top ten attributes among the 48 attributes generated.
3. The top ten attributes of each group are shared with the class, grouped –since many of them might be very similar – and written in the blackboard.
4. Each student votes for the five attributes he/she considers to be the most important qualities in an outstanding structure. The 10 most voted qualities define the "Decalogue of the outstanding structure". To vote, each student is given five stickers to place close to his/her favorite idea in the blackboard (see Figs. 2c and 2d).

Name of the student	Idea 1	Idea 2	Idea 3

Figure 1: Template used as a basis for the development of the activity "The Decalogue of the Outstanding Structure"

Figure 2: Development of the activity "The Decalogue of the Outstanding Structure"

The top ten attributes of the outstanding structure in the academic year 2018-19 were:

1. Safety and functionality
2. Durability.
3. Economy.
4. Stability.
5. Efficiency.
6. The structure must be necessary.
7. Aesthetics.
8. The structure must be "comfortable" (absence of vibrations…).
9. Integration in the environment.
10. Sustainability.

This activity is also used to partly evaluate the transversal competence "Innovation, creativity and entrepreneurship". The grade of each student depends on the number of attributes proposed.

3.1.2. Session 2 (2 hours). Learning the basics of Structural Art.

Once the students have thought about the qualities a structure should have, they are ready to start developing structural critique based on the ideas of Structural Art. This is done in a lecture where first some examples of structures are shown and the students are questioned about their quality. At the end of this first part the students are asked if structures can be works of art and the main objectives of the Structural Art teaching unit are presented. This also serves to make a short debate about the type of constructions where the contributions of the structural engineer are more relevant.

Then different models of relationships between engineers and architects are presented. The evolution of this relationship through time is shown through many examples and the current situation, where almost everything is possible, is also explained.

After this introduction, the students learn the three ideals of Structural Art (Economy, Efficiency and Elegance) and the three dimensions of the structure (scientific, social and symbolic) by examining many examples from the past and from the present. A special focus is given to the symbolic dimension to show how structures are more than utilitarian elements and can become symbols of power, of a specific area, of a country, of a continent and even of humankind. The social dimension also receives special attention to make the students become aware than most of our constructions are paid with the taxpayers money and therefore should be designed and built with especial attention to their cost.

3.1.3. Session 3 (1 hour). Debate.

After learning the basics of Structural Art, the students are ready to practice their skills in a debate-style activity. The debate is a role-playing game where the students become members of the jury of a design competition that must take a decision about who is going to design a hypothetical new singular structure in Valencia (Spain), one of the competitors being the Valencian architect Santiago Calatrava.

To do this activity, the class is divided into smaller groups of maximum 12 students. The students of each group are divided into three teams. A first team must support the choice of Calatrava as the designer of the new structure, a second group must defend another choice, and the third group acts as judges and as such conduct the discussion and take a motivated final decision (see Fig. 3). Every student must submit a report showing his/her main points for the discussion before attending the debate. Extra points in the evaluation are given to the students that show proofs of having visited the location of the analysed structure.

Figure 3: Debate about a singular structure.

The debate is organised according to some established guidelines that are given to students prior to the debate and is based on aesthetic, social and technical arguments. Details on this activity can be found in Huyhn and Payá-Zaforteza [11] and are not repeated here. In the past the debate has been related to the construction of a new bridge over the Turia river bed in Valencia and to the construction of a new high rise building hosting a hotel in a protected environment near Valencia beach (see Fig. 4).

Figure 4: Debate activity. (a) Hotel as proposed in the urban planning, source: www.lasprovincias.es (b) Turning Torso by S. Calatrava, (c) Hangzhou Wangchao Center by SOM, source: SOM. The object of the debate was to decide if the design of the new hotel had to be awarded to S. Calatrava or to SOM based on their previous works and their design philosophies.

3.1.4. Session 4 (2 hours). Structural Art today.

In the third part, the students learn how the ideas of Structural Art can be used to understand the value a specific work (Eduardo Torroja's San Nicolas Church in Gandia, Valencia [12]), to make comparative and critical analyses and to study the interaction between politics, engineering and art in a period of the history of a country (Spain). Due to the lack of time, the latter topic is only mentioned and the students are told that, if they are interested, they should watch the chapter "The Politics and Art of Spanish Bridge Design" prepared by Prof. M. Garlock and the author of this paper as part of the MOOC "The Art of Structural Engineering: Bridges".

Finally the students learn why the ideas of Structural Art are important today, even for small scale projects, and as a conclusion of the course, they discover: (1) the common attributes to some of the best structural engineers of the world, (2) how these attributes are common to the best professionals in any profession and, therefore, (3) how the great engineers and their work can be a source of inspiration for them.

It must be noted that all the lectures are very visual and interactive. The students are constantly requested to give their opinions about the displayed structures and some interviews of engineers from the Princeton course "The Art of Spanish Bridge Design" [13, 14] are shown to illustrate many of the points discussed during the lectures. The students are also told that Structural Art is a framework that they can use, not a dogma, and that they should feel free to question this framework and use a different one: the important point is to promote informed and motivated discussions and a critical citizenship, not the framework.

Finally, different non-compulsory activities to complement the course contents are offered to the students every year. For example, in the academic year 2016-17 the students could attend inspiring lectures given at the UPV in the context of the "Workshop on Bridge Design" organized by the Spanish Group of the International Association for Bridge and Structural Engineering and in the academic year 2018-19 the students could participate in a field trip to Barcelona and its surroundings that included a guided tour to the *Sagrada Familia* and meetings with eminent engineers from the firms Pedelta, Enginyeria Reventós and members of the engineering design magazine Dobooku.

3.2 Evaluation of the students

The knowledge gained by the students on the topic of Structural Art is assessed based on:

(1) The reports submitted by the students prior to the debate-style activity and their attitude and

contributions during the debate.

(2) A specific question on Structural Art asked in the course exam. In this question the students should show the knowledge they have gained by giving their opinion about the quality of a specific structure or by carrying out a comparative and critical analysis of two structures.

3.3 Success of the approach

The approach is being very successful as shown by the participation and involvement of the students in the different activities, by the high percentage of the students that pass the course and by the feedback given by the students through the course evaluation polls.

This success is due to the fact that through the lectures and activities the students wrap up all the previous knowledge they had about structures while at the same time they get a new holistic view where structures have technical, social and aesthetic values. This approach is not very common among civil engineering courses and the author thinks it should be much more spread out. The author's experience is that it is not easy to introduce changes in the existing curricula so the changes are more likely to be successful if they are introduced little by little. In fact, the author started by introducing a two hours session describing the main ideas of Structural Art and non-compulsory Structural Art tours in a general course on building structural analysis in 2008 and the success of the approach made it possible years later the birth of new courses on "Structural Systems" (Paya-Zaforteza and Lazaro [15]), "Conceptual design" [9] and "History and aesthetics of structural concrete".

4. Conclusions

Conceptual design and Structural Art are important topics that should be part of the core education of the civil/structural engineer. This paper shows the methodology developed at the School of Civil Engineering of the Universitat Politècnica de València (Spain) to integrate the main ideas of Structural Art in the syllabus of a course on the conceptual design of singular structures. The methodology has been very successful from the students' and professor's point of view and integrates activities to develop creativity and critical thinking, debates and participative lectures.

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Structural Art, the 4th Dimension, and Metaphors for Teaching Design

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Abstract

The potential for a work of structural engineering to extend beyond the literal and inspire our aesthetic sensibility – to be structural art – is to see in a physical work signs of the creative human spirit that are fundamental to design. We understand that structural art is possible from the great achievements of the past, upon which we build both technically and artistically, to design for the present and the future. This indeed was part of the spirit of David Billington's teaching at Princeton University – to abstract principles from the great works and artists of the past to fuel our design creativity. This paper elaborates upon this dual perspective as fundamental to teaching design. Also presented as laudable figures in the lineage of design education, Eugene Emanuel Viollet-le-Duc and Hardy Cross have offered an enriched perspective on time and change in structural engineering.

Keywords: conceptual design, historic structures, pedagogy, load path, relative stiffness, Robert Maillart

1. Introduction

The potential for a work of structural engineering to extend beyond utility and inspire our aesthetic sensibility – to be structural art – is to see in a physical work signs of the creative human spirit that are fundamental to design. In observing the work of art, we may imagine the artist and find inspiration in his or her achievement. We understand that structural art is possible from the great achievements of the past, upon which we build both technically and artistically, to design for the present and the future. Teachers, in various forms, document and disseminate a breadth of such valuable information and help distill its meanings and merits. This indeed was part of the spirit of David Billington's teaching at Princeton University – to abstract principles from the great works and artists of the past to fuel our design creativity. And like the works and artists themselves, the best teachers can inspire us to see more deeply. David Billington was indeed an inspiration for both students and colleagues, as he launched many of us into the world of design, with a versatility of perspective from past to future, and a sense of wonder for the potential of structural art.

As part of a collection of writings in honor of Billington's life work and profound influence, this paper elaborates upon this dual perspective in time, or the 4th Dimension, as fundamental to design and the teaching of design. It also celebrates the role of inspiration and metaphor, that may be found in works of the past and, very often, within the fabric and mechanisms of the natural world that surrounds us. As a personal note, I first became familiar with David Billington through his book, *The Tower and Bridge* [1], as an undergraduate studying Civil Engineering and Art & Architectural History at Tufts University. I also had the privilege of working with him as a Masters Student under his mentorship at Princeton University. Between those degrees I spent a year in Switzerland at the Ecole Polytechnique Federale de Lausanne studying reinforced concrete and bridge design, with regularly scheduled trips to visit the bridges of Robert Maillart. I took the photos included in this article during the academic year from 1989-1990, which are lasting images of the life-changing inspiration a scholar and teacher such as David Billington can have.

2. Learning from the Past

We live in the built environment and envision its growth or change for the future. Part of our mission as designers and teachers is to preserve the values and lessons of the past, most poignantly demonstrated in the works themselves. In many ways, the education of structural engineers lost sight of this during its progression in the 20th century, with the earlier emphasis on precedent and "rules of thumb" being replaced by scientifically derived theory expressed mathematically (Matteo, pp. 96-97, [4]). However, a change in sensibility begain to re-emerge where the value of history was seen as a key component to good design. This transition can be observed in the second edition of David Billington's first book, *Thin Shell Concrete Structures*, which was originally published in 1965. By the time the second edition was published in 1982, he rewrote the first chapter to include a historical perspective and to focus on more qualitative physical behavior, which would in later chapters be developed more comprehensively mathematically. Undoubtedly influenced by his research and 1979 publication of *Robert Maillart's Bridges: the Art of Engineering*, Billington articulates this broadened perspective on page one:

> The two types of knowledge that inform all of the best structural designs are scientific and historical. ... Scientific knowledge as defined in this text means knowing how to define structural behavior, expressed in displacements and forces, to the end of discovering how a given form carries loads safely with a minimum of materials, i.e., discovering how to design an efficient structure…But science, by which we mean primarily classical physics, seeks only to understand how given forms behave, whereas engineering design must first choose a form and it is for that activity that historical knowledge is required. Billington, p.1 [2].

Billington also alludes to his research on aesthetics, which he refrained from elaborating upon in this second edition, but which would very soon be introduced in the landmark publication of *The Tower and the Bridge*, one year later in 1983. Limited scholarship and publication on the history and aesthetic potential of structural engineering preceded this work. One example was certainly Sigfried Giedion's notable *Space, Time and Architecture*, which was first published in 1941. Giedion's work included a developed section on the work of Robert Maillart and it precipitated the 1947 exhibition of Maillart's work at the Museum of Modern Art. However, this was all primarily from an architectural history and aesthetic viewpoint that was not able to integrate the technical perspective of the structural engineer. *The Tower and the Bridge* not only infused a more technical perspective to the appreciation of Maillart and many other structural engineers of the late 19th and early-to-mid 20th centuries, but defined the aesthetic parameters of a new art form – structural art.

In articulating the values of structural art, Billington also offered a roadmap to diverse achievements, technically and aesthetically, in structural design, and began to coalesce a canon of great works that would serve as models for future engineers.

Figure 1: The Salginatobel Bridge, near Schiers, Switzerland, built in 1930

The Salginatobel Bridge, depicted in Figure 1, became somewhat of a pilgrimage site for a growing group of structural engineers and design-minded individuals who were being newly educated about the history of the profession. This paradigmatic work of structural engineering, and numerous others, could now be appreciated within the framework of Billington's engineering aesthetic. Billington's work told engineers that there was great value in looking to the past for a broad range of creative solutions to new technical challenges.

And yet this perspective that embraced the history of structural design, perhaps akin to what architectural history is to architecture, in some significant ways remains distinct from understanding the nature of structural behavior and material condition over a continuum of time – to understand the structural history in the "life" of a structure.

Standing before a work of structural art, what we witness in our time and place is inevitably somewhat different from what was conceived during its design and seen immediately following its construction. We witness the effects of time, which may be seen in the gradual signs of environmental exposure, or from responses to loads imposed by nature, or from changes imposed by human use or intervention, all through the lens of current thinking. If we value the work, we then may ask how to best perpetuate its physical longevity and/or lessons for the future. This is what I will refer to as a conservatorial perspective.

Figure 2: The Schwandbach Bridge, near Hinterfultigen, Switzerland, built in 1933

During my year in Switzerland I traveled by train from Lausanne to Bern, then a small bus to a small town, and then a nice long hike down country roads to reach what is perhaps my favorite work of Robert Maillart, the Schwandbach Bridge (Figure 2). Frost covered every surface of the natural and man-made landscape. The thinness of the arch, despite reading about it in Billington's books, was surprising and beautiful. The bridge form artfully engages the landscape, with uniformly curving deck over an arch width that encapsulates the full plan profile, mediated by trapezoidal cross walls that are both simple and striking (Figure 3).

Figure 3: The Schwandbach Bridge, trapezoidal vertical cross walls

I spent several hours on and around the Schwandbach Bridge. Clambering underneath (perhaps somewhat ill-advised), I was rewarded with a more visceral understanding of the construction (Figure 4). Here, the imprint of the form boards in the cast concrete remained sharp and intelligible. Also apparent was one sign of an ongoing deterioration mechanism – an area of reduced concrete cover that resulted in some localized rusting of reinforcement and spalling of concrete. Though appearing in remarkably good condition, the nearly 60-year old bridge, at the time, showed some signs of its age and of its physical material history.

Figure 4: The Schwandbach Bridge, beneath the deck

A conservatorial perspective of the effects of time on the built environment, with the versatility to apply these ideas to new work, will help cultivate creative and enduring structures. Eugene-Emanuel Viollet-le-Duc was a 19th-century French architect and theorist who, perhaps more than any other, espoused a conservatorial perspective in understanding the mechanisms of environmental exposure on a structure over time. In his fictional, yet pedagogical, work *How to Build a House*, Viollet-le-Duc expresses the value of not only seeing the paradigms and precedents of architecture in the world around him, but also of understanding the mechanisms of time and Nature to which all structures are subjected.

> Seeing that all this would not put me in a speedy way to master my profession, and being so fortunate as to have a few hundred pounds left me, I resolved to travel—to study architecture in actual buildings, and no longer in those shown me on paper. I set myself to observe, to compare, to see practical men at work, to examine buildings that were crumbling to pieces, that I might discover *in anima vili* the causes of their ruin.
>
> Viollet-le-Duc pp. 82-83 [3]

3. Communicating in the Present

We design and communicate about the built, or envisioned to be built, environment within the framework of three main languages – Speech, Graphics and Mathematics (Matteo [4]). This idea helps students develop the breadth of communication skills needed in the profession, but also acknowledge that each language offers strengths and weaknesses in representing the physical world. Figure 5 provides a visual representation of the central role of these three languages in communicating about structures, whether looking back to analyze what exists or envisioning a new design for the future. The sketch to the right uses the analogy of driving while keeping an eye on the rear-view mirror; we inevitably design for the future but remain mindful of the lessons from the past.

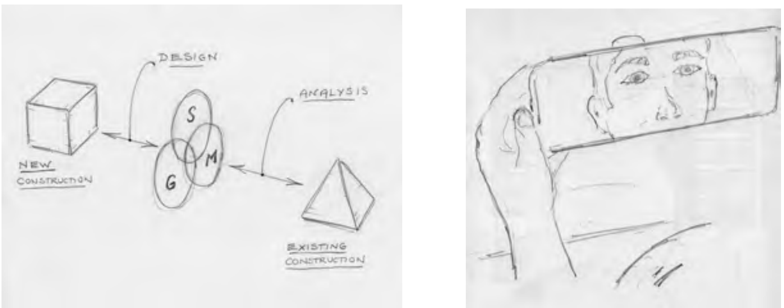

Figure 5: Analysis and Design – Past, Present and Future
(these sketches by Matteo first appeared in reference [4])

The figure may also remind us that there is a discernible space between the objects of our communication and the nature of the communication itself. The languages we use to describe a structure, however poignant, precise, or poetic, are always approximations of the physical reality.

Hardy Cross, professor of Civil Engineering perhaps known best to structural engineers for the moment distribution method which converges toward equilibrium through a series of successive approximations, possessed a healthy relationship to the limits of theory and language in the face of actual physical behavior. In subsequent published questions and responses to his first article on moment distribution, he notes the following:

> The quest of the absolute is a beautiful thing; but he who seeks in engineering analysis a precision that cannot be ultimately translated into such units as pounds of steel and yards of concrete is misled. Structures are analyzed so that they may be designed; not for the pleasure or practice of analyzing them. As Professor Findley well states, "between the analysis of a given structure, which is essentially mathematics, and the design of a required structure, which is essentially art, lie many difficulties." Cross p. 28 [5]

4. Inspiring Design for the Future

Metaphor in language is akin to design thinking itself. From the literal or prosaic, we extend our thinking beyond what is, and envision what could be. Viollet-le-Duc climbed and surveyed Mont Blanc and witnessed nature's effects on the earth's surface as analogous to the effects of time and environment on architecture. Hardy Cross, though primarily focused upon education for structural analysis and structural design, also applied his methods to the flow of water in a network of conduits or conductors (Cross [6]).

For a system of pipes, the total flow at a given junction is distributed to the pipes connecting at the junction in inverse proportion to their resistances (Cross, p. 253 [6]):

$$R = n\,r\,Q^{(n-1)} \qquad (1)$$

This is exactly the opposite of the flow of force in an indeterminate structure. In Cross's moment distribution method, forces at a given structural joint are distributed in proportion with the relative stiffness of the members connecting into that joint. Though opposite in nature, the nature of their respective flows can be determined using this very same methodology.

As one might visualize the flow of water following a path of least resistance down a mountain, the flow of force in a complex structure will follow the path of greatest resistance. And these paths, subject to the forces of environment and human interventions over time, may indeed change over time.

Figure 6 depicts a photo from 1990 of Maillart's Weissensteinstrasse Bridge and a drawing from the associated calculations created by his design office in 1938. The artful curves connecting beam and column seem expressive of this very process of fluid sharing and distribution of forces.

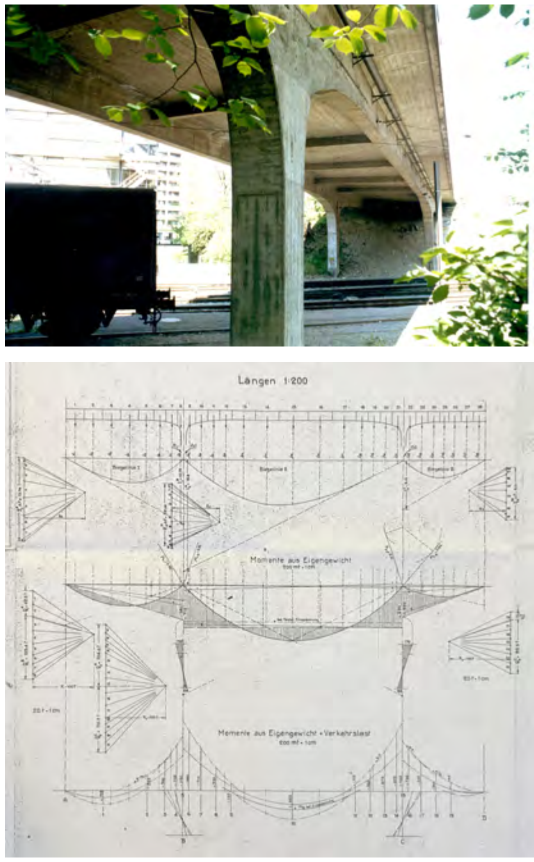

Figure 6: Weissensteinstrasse Bridge and design calculation from 1938 [7]

Rather than a moment distribution approach, the graphical statics of Maillart's calculations represents another means of correlating relative weight and stiffness to the distribution of force in the structure.

The flow of water, cascading down a mountain along the path of least resistance, serves as a compelling metaphor for design or analysis. Viollet-le-Duc also came upon this analogy as a by-product of his project to develop a topographical survey of Mont Blanc. The mountain is like a building, each must sustain and adapt to the forces of nature. Each will change over time and it is up to the observant student to read these signs to best recreate the structural history, or envision a future history of behavior. In many ways, this is the challenge of the engineer seeking to understand a structure – to understand the load path which may be singular or shared, intended by design or incidental by nature. Viollet-le-Duc describes it like this:

> Our globe is, in fact, only a great edifice, all whose parts are capable of rational explanation; its surface assumes forms dictated by imperious laws, following a logical order. To analyze carefully a group of mountains, the manner in which they were formed, and the causes of their ruin; to discover the order in which the phenomena of upheaval occurred, the conditions in virtue of which they have resisted or endured the action of atmospheric agents, to note the chronology of their history, is to devote oneself to a work of methodical analysis which is, on a grander scale, analogous to that which the practical architect and the archaeologist applies himself when drawing conclusions from the study of buildings. […]
>
> I write, however, for the general public, and this I have always kept in view; nor do I aim at anything higher, in publishing this resume of my observations, than imbuing the many with an ardent desire to study Nature, our common mother, whose teachings are always the healthiest and most profitable for the mind. Viollet-le-Duc pp. 12-13 [8]

Figure 7: *Mont Blanc: A Treatise on its Geodesical and Geological Constitution; its Transformations; and the Ancient and Recent State of its Glaciers*,

Viollet-le-Duc, 1877

The forces of nature provide the "imperious laws" that ultimately guide our analysis of existing structures or our designs for the future – a common ground for structures old and new. The flow of force from structure to ground needs only one successful path, even if there are multiple paths to choose from. For an existing structure that has stood the test of time, it is common to find multiple possible load paths that may currently, or during its lifetime, offer a route to stability. Finding a successful path inevitably will induce some movement (discernable or not) or may cause a crack in part of the structure or connecting finishes. These are the signs that may inform the analyst or designer about a structure's history. Many existing structures employ materials or structural systems that predate much of the theoretical development in engineering of the 19th and 20th centuries, or predate many of the ever-changing code procedures and standards. This presents a challenge perhaps similar to the designer seeking to innovate, and is a good reminder for all students who may rely too heavily on the many tools and procedural standards we have today. Inevitably we will be faced with a challenge that pushes us off the paths most traveled, but the way to good structural design must always be rooted in the first principles of mechanics, in obeiance of the laws of nature.

5. Conclusion:

Viollet-le-Duc and Hardy Cross, both theorists and educators of the built environment, found ways to distill widely applicable principles of structural behavior from a broadened perspective in nature. Similarly, David Billington saw art in the best examples of structural engineering and articulated the parameters of a complex, layered meaning that translate to cultural value (Figure 8). To conclude this paper, the beauty and fundamental social value of structural art, and the joy experienced by engineer-artist and observer alike, are perhaps best summarized by Billington himself at the conclusion of *The Tower and the Bridge,* as he describes the role of play in design:

> But to serve the public best, these structural artists had to be playful – not denying discipline but expressing surprise and joy. … They studied long and hard to learn the rules (of nature); they tried continually to play fair (with society); and in creating order they surprised others with the beauty of their works. At the heart of technology, they found their own individuality; they created personal styles without denying any of the rigor of engineering. Billington pp. 273-274 [1].

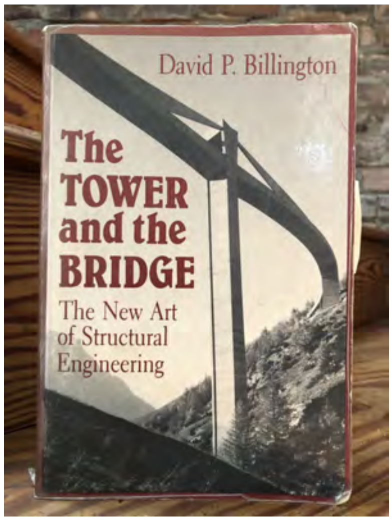

Figure 8: *The Tower and the Bridge: The New Art of Structural Engineering*

Acknowledgements

This paper is written in honor of the Professor David P. Billington who, as a scholar, teacher and mentor, has profoundly and positively influenced me, and so many others.

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The art of collaborative structural design: Structural art in the age of cross-disciplinary collaboration

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Abstract

While laying the foundations for an understanding of structural design as a potentially higher form of achievement, this paper argues that Billington's conception of structural art also established it as the work of a heroic creative genius driven solely by engineering values. By clearly distinguishing structural art from the domain of architectural achievement, the concept contributes to a separation of the two disciplines, and offers little support to those seeking to establish cross-disciplinary collaborative approaches to structural designing. With the criteria defining works of structural art primarily employed to describe completed works of art retrospectively, new questions to be considered may be what kind of design processes will lead to structural art? Do desirable types of design processes necessarily exclude other disciplines? This paper argues that responding to these contemporary challenges may bring about new interpretations of structural art and draw more attention to efforts directed at bridging diverging values already early on in discipline specific education.

Keywords: structural art, David Billington, collaborative design, cross-disciplinary design, design process, design values.

1. Introduction

Billington's concept of *structural art* [1] established structural engineering as a discipline with the potential for higher forms of achievement, transcending the mere accomplishment of compliance with requirements. To distinguish engineering art from other works of engineering, Billington [1] defined three primary criteria: efficiency, economy and elegance. Simultaneously, however, he also explicitly discarded collaborative design between structural engineers and architects as potentially resulting in structural artworks: "Almost without exception it seems that the best works of structural art would have been compromised had there been architectural collaboration in the design of the forms" [1, p. xvi]. Yet, many structural artists have extended histories of collaborating with architects, as outlined by Rappaport [2]. Structural art has also been identified in works of architecture, where engineering ingenuity in response to and in conjunction with architectural design intentions created works of exceptional coherence and innovation [3].

This paper questions the narrow understanding of the concept of structural art as restricted to works accomplished solely by structural engineers in the age of increasingly collaborative design processes and argues that it can also be employed to describe and guide works of collaborative structural design. The paper makes this point based on several cases well documented in existing literature and traces in what ways works of collaborative structural art can extend and enrich an engineering-centric definition of structural art. From this analysis, architectural aspects of structural art are identified and described in more detail, such as the skillful definition of boundary conditions and a refined understanding of the aspect of engineering art described as aesthetics or elegance. By mapping several differences in understanding seemingly shared vocabulary, differences in disciplinary values are identified as key drivers or obstacles for cross-disciplinary structural artworks.

The paper aims to extend the discourse started by Billington's work, continuing and developing it for the changing contexts, design processes, toolsets and workflows the profession(s) face in the 21st century. Drawing on existing literature, the paper finally emphasises the relevance of education in establishing design values allowing exchanges across disciplinary boundaries and discusses experiences made over several years of promoting shared values in cross-disciplinary structural design education.

2. Defining and identifying structural art

Throughout his extensive body of work, Billington established the concept of structural art through careful tracing and analysis of historic precedents. These examples and associated stories continue to provide an inspiring context to illustrate structural artworks and learn about structural artists and their accomplishments. In their comprehensive overview paper on the discourse relating to structural art, Hu et al [4] have however pointed out that most research work related to structural art has focused on either a single case study or a particular structural artist and his works: "as a result, it creates the misconception that a work of structural art can be only created by those great structural engineers." [p. 408] This is somewhat compounded by Billington's insistence that structural art is typically the work of one strong engineering personality rather than teams [1, p. 91].

The criteria for defining and identifying structural art seem deceptively simple: efficiency, economy and elegance. With efficiency and economy well known and quantifiable aspects of engineering design, elegance emerges as a central criterion of structural art, setting it apart from conventional engineering solutions. In addition, the three criteria are used loosely in descriptions of structural artworks. In particular in the case of elegance, the term remains surprisingly vague and is typically described in specific examples rather than defined explicitly. Yet, its abstract nature also lends itself to rich associations, which has generated a wide variety of interpretations.

Elegance as a key criterion of structural art seems to be understood as relating to modernist aesthetics of geometric simplicity and a preference for functional forms illustrating their purpose and structural behaviour. Discussions of elegance in structural art also tend to extend to other terms, in particular to aesthetics, which is also understood in similarly vague yet inspiring and evocative terms. Discussions of aesthetics in structural art mostly skirt around clear definitions and instead describe aesthetics contextually and related to specific cases – avoiding the historical, cultural and subjective nature of the classical discourse. Ironically, architectural discourse has abandoned discussions of aesthetics in terms of beauty for decades and instead tends to focus on compositional and contextual aspects such as conceptual clarity or coherence. An equivalent to this side-stepping of classical notions of aesthetics and a re-direction towards the engineering perspective can be found in Hines' [5, p. 124] emphasis of *conceptual transparency*. Similarly, Saliklis et al. [6] propose an engineering-centred view on aesthetics in structural design based on the analysis of Khan's seminal work in terms of the key characteristics of *simplicity*, *scale* and *surprise*. In particular the third aspect is of interest as it relates to the involvement of the viewer and her spontaneous intuitive judgement in recognising structural art. While subjective effects on users are often the focus of architectural design, there seems to be comparatively little recognition of the experiencing human being in structural engineering. In this aspect, a cross-disciplinary exchange could perhaps offer valuable insights into notions of aesthetics compared to a strict separation of structural art and its related discourse from architectural involvement?

While Hu et al. [4] provide a comprehensive overview of structural art related discourse, they are also careful to exclude the work of the current generation of structural artists: "one must be very careful in using the word ''structural artists'' in the modern multidisciplinary climate and increased complexity of new infrastructure. Only time will tell whether their work will be recognized or not." [p. 413]. With the discourse evolving, confirming contemporary structural artworks, or even predicting structural art seems a risky move when workflows and tools are changing quickly. Can structural artworks be created in this new climate of complex design processes involving multiple disciplines? Maintaining a mostly historical approach to attributing structural art may become a strong limitation for a field that explicitly seeks to share the valuing of structural art to inspire future structural artists.

3. Cross-disciplinary collaborative structural artwork

Despite Billington's [1] warning that the involvement of architects tends to make structural artworks impossible, many structural artists have long histories of collaborating with architects. Rapaport [2] describes these collaborations as long-term dialogues between strong individual designers who are experts in their respective fields, yet share a respectful mutual understanding of each other's design intentions. It may be argued that any structure that involves direct contact with experiencing human users will benefit from an architectural collaborator in its design process, including not only buildings across all scales, but also bridges of small to medium scale. The discarding of potential architectural contributions to structural art seems to be grounded in a particular perspective on the architectural discipline, distorting its key focus on human spatial experience and reinterpreting it as a preoccupation with the visual. This is made explicit in Hu et al.'s [4] summary statement: "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." [4, p. 408] Can structural art really be reduced to a cheap and efficient structure that is relatively elegant? Are structural artworks necessarily more economical than other options? Is it indeed possible to satisfy all criteria without compromising, for all cases of structural art? Could this feat even be ascertained beyond doubt?

Saliklis et al. [6] describe Fazluhr Khan's contributions to high rise building development as structural artworks, even though buildings are often excluded from the category of structural art due to architectural form potentially involving decorative or sculptural aspects: "Structural form is neither decorative nor sculptural because it arises from a melding of creativity coupled with mathematical rigor and economic restraints." [6, p. 25] Yet, Khan's high rise building structures, worked out in close collaboration with architect Bruce Graham, are excluded from this general dismissal. Perhaps the notion of *collaborative structural art* would be more fitting in such cases? Recent research has also identified structural art in a church designed collaboratively between Edoardo Torroja, the architect Echegaray-Comba and a further engineer, Nadal [3]. Hines [5] points out that Joerg Schlaich's works have consistently "demonstrated that it is possible to create structural art as an engineering consultant in collaboration with architects. For this reason, Schlaich's work offers insight into process that is consistent with contemporary culture." [p. 125] From the other side of the disciplinary divide, architects have long endeavoured to productively integrate structure into architectural design, as Andrew Charleson's book "Structure as architecture" [7] and many similar others illustrate. These structurally-oriented approaches to architectural design are driven by the ambition to create built space with a quality that transcends diverging disciplinary viewpoints and values. Those collaborating across disciplines are usually well aware that there may not be an optimised solution to multiple, interlinked and often contradictory design challenges, and design proposals may be difficult to evaluate on simple scales – gains in economy may lead to losses in efficiency or elegance, and vice versa. Yet, outcomes of collaborative design processes can demonstrate innovative ways of employing available resources, conceptual clarity and surprising ingenuity. It may be argued that both collaboratively designed works of structural art as well as classic works of structural art necessarily involve project-specific assessment as well as considerable degrees of subjective judgement.

This paper proposes that collaborative structural art is not only possible, but a desirable and contemporary development of structural art already implicit in much recent structural art discourse. Collaborative structural art results from the balancing of engineering values with architectural values in a manner that benefits both disciplines. Beyond the classic engineering-focused criteria for structural art described by Billington, a human- and context- focused architectural perspective offers increased relevance of structural design proposals. On the other hand, the values inherent in structural art as an aspiration can provide improved conceptual coherence, feasibility and sustainability for architectural design proposals. A fruitful exchange between the values and perspectives of both disciplines can for example be observed in recent pedestrian bridge design competitions – where collaborative and human–focused design approaches are increasingly successful. Other examples of collaborative structural artworks may include works such as Balmond and Koolhaas' collaboration on the Villa Bordeaux [8], or Sasaki and Ito's collaboration on the Sendai Mediatheque [9].

4. Creating (collaborative) structural artworks

Even though the concept of structural art was conceived based mainly on analytical reflections of past works, its proponents have consistently argued that structural art can also be an aspiration for current and future applied design work. For this reason, structural art should probably be separated more clearly from the individual personalities of structural artists – to avoid the perception that only recognised past masters could achieve such design quality. How, then, can structural art be created? What kind of design process leads to structural art, and how is it different from design processes leading to collaborative structural art? While innovation and creativity are impossible to predict, it is possible to create conditions for them to thrive.

A key aspect to increase the likeliness of structural artworks is a general sensitivity for and appreciation of structural art in those who practice structural as well as architectural design: without an analytical and critical approach to assessing one's environment, the refinement required for structural artworks is unlikely to appear. Billington's descriptive criteria of efficiency, economy and elegance are outcomes of his detailed knowledge and critical analysis of engineering history, which allowed him to develop the concept of structural art and to make it explicit. While awareness of historic works of both architectural and engineering disciplines is common in architects, engineers tend to be less familiar with the history of their own discipline. Moreover, structural art combines quantitative and qualitative assessment, which positions it at the fringe of the conventional engineering canon and attracts little attention from those aiming for efficiency and economy only. The perception and appreciation of the qualities of structural art typically require prior study: Complex notions such as Hine's [5] conceptual transparency are not readily understood without a broad background context, let alone integrated into applied design work. There are parallels to a similar architectural discourse on the relationship of built form, material, structure and architectural expression revolving around the notion of *tectonics* – a discipline specific term that requires prior study and awareness of an ongoing debate in order to be properly employed in applied designing. Awareness of and critical reflection on works created by others, including historical and contemporary case studies, is identified as a key aspect for educating future engineers by Boegle [10], Gauvreau [11] as well as Hu et al. [4], who all argue that learning about case studies is essential for being able to judge quality in design.

A discussion of the criteria defining structural artworks typically leads to a discussion of creativity and innovation in the design process. Hines [5, p. 123] describes creativity as a necessity for high quality engineering design and characterises it as a process cycling through the stages of *imagination*, *expression* and *judgement*. Typically referring to the creation of the new and the surprising [5, 6], creativity is not easily defined or operationalised, as current discourse in various design-related disciplines demonstrates. There is however a broad agreement that creativity can be supported by various techniques and skills, which are at least partly teachable [12]. In the context of structural art, the question arises how design processes can aim for structural art in general, and for its criteria more specifically? According to more recent design theory, designing is not a linear process leading to a predefined outcome – this is only possible for routine design that is based on the adaptation of known structural and architectural types to new sites. Much engineering creativity revolves around routine design, as the invention of genuinely new structural types is rare. The works of sbp (schlaich bergermann partner) illustrate this process, with many of their structural proposals reusing and adapting well known structural typologies for new contexts and site conditions. Design processes can be approached in a way that encourages creativity, by allowing them to unfold in a dialogical and recursive manner. Characteristic for more artistic disciplines, this type of design process is open to risk and uncertainties and different from the more prescriptive linear and directed design process models typically employed in engineering contexts. The latter may suffice if the aim is the adaptation of known structural types to new contexts. If the aspiration of structural art however requires transcending of existing structural types and theory in favour of creating new types and theory to fit them, then the former type of process is more appropriate. There seems to be little room for routine design in the works of a structural artist however: "Creating unique solutions to recurring structural dilemmas is a hallmark of a structural artist." [6, p. 26]

Despite a general agreement that creativity is important for both education and practice leading to structural artworks, descriptions of creativity relating to the concept of structural art are mostly based on personal experience. To date, there seems to be no shared theory of creativity or the process of creative designing in the structural art discourse. In this context, a design cybernetic [13] perspective on design may be useful, as it emphasises a trans-disciplinary vocabulary and offers strategies to navigate the creative process. Such a perspective may help to establish shared vocabulary for key terms often used in cross-disciplinary exchange, such as design, design concept and design process.

4. Education for appreciation of values across disciplinary divides

Given students' early adoption of disciplinary values in their formative years of their undergraduate studies, education emerges as a key aspect of cultivating the basis of structural art. One of the main interests of proponents of structural art has been to continue Billington's method of teaching through detailed discussion of historical case studies of both structural artists and structural artworks, with the work of Garlock and Adriaenssens providing very visible and accessible examples. From the perspective of architecture, new additions to the engineering curriculum in this context, such as case study analysis, model making and site visits, seem very familiar and resemble aspects of architectural studio education. Studio education thus offers not only an educational context to teach applied designing, but also a platform for encouraging collaborative design work between architects and engineers [14, 15].

Beyond offering increased opportunities to practice applied designing and to learn about the respective other discipline, the design studio provides a complex learning environment in which students are given opportunities to engage in design processes that involve unknown territory, risk and often uncertain criteria for success. Gauvreau [12, p. 120] posits that in order to serve society by creating value, future engineers "must be given the knowledge, skills, and values they need to rise to this challenge. For this to happen, universities need to shift their focus from the creation of innovations to the education of innovators." [p. 120] This recommendation implies a shift from learning about structural art to learning to practice, working towards structural art – a shift towards applied design in engineering. In the context of collaborative structural art, shared design studios are not the only possible approach: I have found that engineering students – particularly in their undergraduate studies – often have difficulties to adjust to the ambiguous and dynamic nature of creative design processes. For this reason, joint projects with architecture students tend to require significant preparation and more structuring of design tasks on the part of the engineering students [16].

The most substantial part of this preparation for cross-disciplinary collaborative designing in my own teaching practice is directed towards the teaching of a shared vocabulary – and an appreciation of the respective other side's interpretations of this vocabulary. Important shared language relates to the nature of the design process, conceptual design, making explicit disciplinary values and identifying areas for potential agreement or compromise, and thinking in terms of and generating options based on evaluation [14]. Only when such language is shared or mutually understood can values of the other discipline be recognised as such and integrated into the design process. This exchange is made easier if shared overarching goals can be agreed and defined, such as a shared understanding of what constitutes quality in the built environment, a particular interest to develop a specific structural type or a vision of a sustainable future. In cross-disciplinary collaborative design practice as well as education, early discussion on the particular conceptual design approach chosen for a project often determines the quality of the design process to follow. The more experienced designers are, the better they can set boundaries that serve as constraints rather than as fixed limitations, leaving sufficient space yet also offering sufficient interesting challenges for the design collaborator to address and "own". Different personalities may be expressed in this process – some preferring to drive or help realise the other's ideas and some preferring to treat the design process as a creative conversation on eye level. In both cases, it is important to note that all these scenarios may lead to collaborative structural artworks as described above.

5. Conclusion: Towards a Collaborative Approach to Structural Art

While the concept of structural art in its original form focuses on the creativity and competence of the structural engineer working in isolation, more recent discourse has acknowledged the role of cross-disciplinary collaborations in creating works of structural art. New workflows and closer cross-disciplinary exchanges supported by new digital tools are changing the context for structural art, raising the question of how Billington's celebration of higher achievements of individual engineers can be translated into contemporary professional contexts [17]. Based on an examination of the structural art concept, this paper proposes an extension and opening of structural art to include the work of cross-disciplinary teams involving architects and structural engineers. Arguing that structural art, distinguished from conventional engineering as a domain of creative designing, has much in common with architectural designing, this paper identifies several precedents for collaborative structural art already acknowledged in previous structural art discourse. Calling for an extension of structural art discourse and education beyond references to historical precedents, the paper discusses the question of how structural art may be generated, and how disciplinary education for future engineers and architects may support future structural artists. In the words of Hu and Dai [18], "no matter how much differences between architectural art and structural art still exist, at least one thing is certain - that the ultimate goal for man-made structures is the manifestation of human spirit." Finding a shared spirit through shared aims as well as shared values across the disciplines of engineering and architecture emerges as a key concern for collaborative structural art.

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Travel and the Structural Engineer

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Abstract

Travel facilitates the exchange of ideas and can lead to creative new designs for the built environment. By traveling, structural engineers can visit notable structures, designers, studios, laboratories, and cultures, as well as engage in dialogues. These opportunities, while celebrated in other creative disciplines such as architecture, have perhaps not been as appreciated in structural engineering. The goal of this paper is to demonstrate the influence that travel has had on specific structural engineers and the practice of structural engineering more generally. Documented examples of prominent engineers traveling and having it affect their work include Othmar Ammann, Peter Rice, Jörg Schlaich, and David Billington. This study ultimately seeks to understand the range of ways that travel impacts the profession.

Keywords: travel, structural design, creativity, historic analysis

1. Introduction

Travel provides opportunities to learn about the built environment firsthand. Architects have frequently traveled as a way to expand their perspective on design and building. Le Corbusier [1] is perhaps one of the best known of many prominent architects that have documented their own trips and its impact on their work. But architectural travel is not limited to just a few individuals. Schools of architecture frequently include travel or study abroad programs in their curriculum. Trips consist of not only observation, but also documentation in a range of forms: drawings, paintings, photographs, videos, etc. The observation and documentation skills that they develop in their formal education can then be utilized during future travel. Post-graduation there are a number of architecture travel fellowships available from professional organizations such as the American Institute for Architects [2, 3] and the Royal Institute of British Architects [4]. There are also many other fellowships including the Wheelwright Prize [5], the H. Allen Brooks Travelling Fellowship [6], and a series of awards provided by the SOM Foundation [7]. Recently, scholarly research has examined the impact of travel on the practice of architecture [8, 9, 10].

In contrast, the effect of travel on structural engineers has not been explored as deeply. The authors have previously begun investigating how opportunities for travel (academic travel, volunteer projects, and travel fellowships) can affect structural engineering education [11]. The goal of this study is to demonstrate how travel has impacted the structural engineering profession by examining the influence of travel on the four prominent engineers: Othmar Ammann, Peter Rice, Jörg Schlaich, and David Billington.

2. Travel by prominent engineers

In structural engineering, like architecture, prominent individuals have traveled to inform their thoughts on the built environment (although it perhaps has not been as celebrated or as encouraged). This paper focuses on the travel of four individual engineers.

2.1. Othmar Ammann

Othmar Ammann, educated in the deep tradition of Swiss structural design, decided as a young individual to travel to the United States to study American bridge building and to establish himself there to find opportunities. He was no doubt influenced by his professors at the Swiss Federal Institute of Technology (locally known as the Eidgenössische Technische Hochschule, or ETH), particularly Wilhelm Ritter, who spent time studying bridges in America, lectured on them back at the ETH, and published his findings as *Der Brückenbau in den Vereinigten Staaten Amerikas*, and Karl Emil Hilgard, who had worked for a while as a bridge engineer in America [12]. Ammann not only traveled to the U.S., but moved there and established himself in bridge design positions of increasing responsibility, until ultimately, he became the great bridge designer we know today. Ammann's travel to the U.S. and immersion in the engineering and political culture there ultimately enabled him to design transformative bridges at a range of scales [13]. These include the colossal and celebrated George Washington Bridge (Figure 1) to the subtle and less well known Wards Island Bridge (Figure 2)

Figure 1: The George Washington Bridge (New York, USA)

Figure 2: The Wards Island Bridge (New York, USA) [credit: Jag9889, licensed under CC BY-SA 4.0, https://creativecommons.org/licenses/by-sa/4.0/deed.en]

2.2. Peter Rice

Peter Rice was, like Ammann, an engineer who created innovative and important works of structural engineering primarily outside of his home country (in Rice's case, Ireland). These works include the Sydney Opera House (Figure 3) with Jørn Utzon and Arup and the Pompidou Centre (Figure 4) with Renzo Piano and Richard Rogers. Rice travelled extensively for these and other projects. His travels often influenced his work, in ways both subtle and overt. An example was his travelling to Japan while he was working on the Pompidou Centre:

> Shortly after we had won the competition I made a trip to Japan to deliver a paper at a conference on tension structures. As part of that conference, trips were organized to Osaka to see the surviving structures of the 1970 World Fair. One of these structures was a giant space frame designed by Kenzo Tange and Professor Tsuboi, the eminent Japanese engineer. There I saw large cast-steel nodes… An idea was born. [14]

Thus Rice's travel to Japan, documenting the cast steel nodes there led to his celebrated "Gerberettes" in the Pompidou Centre. This open-minded approach to design, especially by traveling to and working in other countries and cultures, seems to have informed Rice's career.

Figure 3: The Sydney Opera House (Sydney, Australia) [credit: Enoch Lau, licensed under CC BY-SA 3.0, https://creativecommons.org/licenses/by-sa/3.0/deed.en]

Figure 4: The Pompidou Centre (Paris, France)

2.3. Jörg Schlaich

Jörg Schlaich, the eminent German engineer, has designed structures all over the world. In his Gold Medal address to the Institution of Structural Engineers, Schlaich told the story of his travels and the influence it had on the work of him, his family, and his colleagues:

> In 1976 the whole of my family followed the 'British Trail' in a VW van: Europe, Turkey, Persia, Afghanistan, Pakistan and all the way through India, to Calcutta, because we were doing in the true sense a 'Design for the developing world', the Second Hooghly Bridge, at that time the largest cable-stayed bridge in the world with a main span of 457m and 35m wide. It was designed towards a completely indigenous manufacture and erection. [15]

Schlaich goes on to explain how that trip to India and his and his colleagues' immersion in the local culture there influenced the design and construction of the bridge (Figure 5). This influence included the material the bridge was to be made of, since steel was produced locally, as well as the connections and means of construction (the bridge was to be riveted to take advantage of local labor traditions).

Schlaich expands this to also advocate for engineers to become more connected with the world and its needs. Travel is one way for engineers to do so.

Figure 5: The Second Hooghly Bridge (Kolkata, India) [credit: Abhijit Kar Gupta, licensed under CC BY 2.0, https://creativecommons.org/licenses/by/2.0/]

2.4. David Billington

David Billington was one of the foremost chroniclers of individual structural engineers. Beginning with his study of Robert Maillart, which Billington famously became aware of from his students of architecture, Professor Billington wrote the pioneering *The Tower and the Bridge*, which included the stories of a number of great structural engineers and their structures [16]. Billington thought of his work not as a static history, but as a living philosophy, the idea of "structural art," that should be expanded to continue learning about innovative, creative approaches to structural design. To do so, one should travel to see great structures and to document them. Billington's lectures were filled with photographs of him and his family, in front of beautiful structures. Unlike many professors of architecture, who prefer photographs of buildings devoid of any human occupation, Billington wanted his images of structures to include "scale factors," which also served to give a human face to the serious study of these works.

There are precedents for Billington's use of travel as a scholarly tool that he documented in the *Art of Structural Design: A Swiss Legacy* [17]. Billington described how Carl Culmann, prior to taking an appointment at the Federal Institute of Technology in Zürich (ETH Zürich) traveled for two years through Britain and the United States to study bridge and railway construction and published a report on his findings. Billington provided a more in-depth examination of Wilhem Ritter and his travel to the United States to see the Chicago's World's Fair and American bridges. While traveling, Ritter documented his work through writing and drawing. In addition to publishing a report on his trip Ritter also incorporated his experiences into his lectures.

In a similar manner, Professor Billington encouraged and sponsored many of his students (including the authors) to travel and document their travel [18, 19] as part of their development as structural engineers.

3. Conclusions

This paper describes how travel has influenced four prominent engineers, Othmar Ammann, Peter Rice, Jörg Schlaich, and David Billington. Ammann, influenced no doubt by some of his professors, traveled (moved, really) to the U.S. to study the bridges there and find opportunities to design them. Rice traveled extensively to other countries to learn from the works there and potentially influence his work in other countries. Schlaich traveled to create structures that responded to local cultures and their particular needs and wants. Billington utilized travel as a scholarly tool to understand the designs of others and to inspire others to do the same. All of them saw the benefits of travel for structural engineers, albeit in differing ways.

The four examples presented here show that travel can be a positive influence on the practice of structural engineering. All four of these great structural engineers believed in travel as a tool to better their practice, and that seems to be demonstrated by their work. We think the practice of structural engineering, would likewise benefit by structural engineers visiting structures in other places, considering them, documenting them, and sharing and discussing. This study is only a preliminary investigation, though. We believe that further study could show many more historic examples of travel influencing the work of structural engineers, and this might make the story fuller and more representative of the diversity within structural engineers and their work. We also hope that this study might encourage more practicing engineers and academics to share their own stories of travel and how it has influenced their work, as well.

Acknowledgements

This paper is dedicated to the memory of Professor David Billington and seeks to celebrate one of the pioneering aspects of his life and work, among many.

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