The Role of the Structural Engineer in the Contemporary Design Process

Amanda Yeager

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The Role of the Structural Engineer in the Contemporary Design Process

A Capstone Project Submitted in Partial Fulfillment of the Requirements of the Renée Crown University Honors Program at Syracuse University

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Honors Program Capstone in Civil Engineering
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Abstract

This capstone is a critical look at the contemporary design process, particularly design competitions, and the role of the structural engineer in that process. Often, the design process for competitions is architect-led with the technical experts entering the process after the major design decisions have been made. As a result, structural requirements and other technical considerations are too often left out of the conceptual design proposals, leading to extensive design changes and costly structural issues to resolve before the structure can be realized. To investigate this issue, a structural analysis of an ambitious winning pedestrian bridge design was conducted. The results demonstrate several problems with the design as proposed in the competition winning entry as well as a disconnect between the architect’s models and the engineer’s analysis. These issues and the implications of this disconnect is further discussed by comparing the design process used in contemporary design competitions to the process employed for the world’s most successful structurally innovative designs. The latter process includes the structural engineer in design decisions from the very beginning, integrating engineering and architecture through early collaboration. In support, a discussion on collaboration from leading professionals and firms in the fields of architecture and engineering was included.

The methodology of this capstone is a demonstration of the issues that arise from the current design process through an analysis and critique of the bridge, comparison of the issues resulting from the design process to contrasting successful holistic design processes, and support for this latter process with examples of successful designs resulting from collaboration and words on collaboration from leading professionals and firms in the fields of architecture and engineering. Overall, this capstone argues for a change in the contemporary design competition process, wherein the role of the structural engineer is at the design table as an equal to the architects, because early collaboration between the two is essential to ensure structural viability, constructability, economy, efficiency, and elegance in the final proposed design.
Executive Summary

This project is an exploration and critique of the contemporary design competition process and the role of the structural engineer in that process. The current design competition process, and indeed much of building design generally, is architect-led, meaning the architects make the major formal design decisions, and the technical experts enter the process (after the major decisions about the schematic and aesthetic aspects of the design have been made) to figure out how to make the design work. The problem with this kind of process is that since the competition entry design does not include these technical, specifically structural considerations in the proposals, the proposed design may have to undergo significant design changes before it can be realized. Thus, the built object may (and often does) look significantly different than the proposed design that the judges based their selections on. Further, a lack of technical validity in proposed structural forms can lead to extensive and costly structural issues to fix as the design process proceeds, the costs of which can fall on the taxpayers as many design competitions are for public works. In order to prevent such issues, this project argues that engineers have to step into the design process earlier as a matter of civic duty.

To investigate the issues that arise from the current design process, a structural analysis of a competition winning and structurally ambitious pedestrian bridge design was conducted. Using the renderings of the bridge available online, models were created using an architectural drawing software and exported for loading and analysis to a structural analysis software. The results of the analysis demonstrate several technical issues with the proposed design and display a disconnect between the architect’s models and the engineer’s work. The results prove that the design process of design competitions is not explicitly foregrounding technical considerations until after the design is selected, leading to the issues as discussed previously. Design
alternatives are proposed here to address the problems with the design, however if structural considerations were included from the beginning of the process, the problems would have been avoided and the competition judges would select winners based on more accurate images.

In order to demonstrate how an integrative design process improves the success of a design, examples of the world’s most innovative and groundbreaking structures and the holistic design process behind them are presented. In these exemplary cases, the structure and architecture cannot be separated as they are one and the same; the success of the design relies on both the engineering and the architecture. Early collaboration between architects and engineers create opportunities for the realization of innovative and ambitious design ideas as the two professions challenge and stimulate each other. Early collaboration also eliminates the issues that arise from a separated design process, as structural considerations are integrated from the very beginning. The benefits of early collaboration are championed by the leading professionals and firms in the fields of architecture and engineering. It is a practice that has long been argued by some of the greatest engineers and architects in the world, however it still is not evident in the design competition process which dominates much of the contemporary design milieu.

The contemporary design process requires a change, but the change has to start not in practice but in the education of architects and engineers. As many prominent engineers have criticized, the current system has separated the goals of the architect and engineer into the creative and the technical respectively. However, these goals are dependent on each other for success; innovation is the result of creativity derived from technical principles and science. Overall, the change in the contemporary design process must include the structural engineer in the design decisions from conception to completion. The role of the structural engineer is at the design table as an equal to the architect, because early collaboration between architecture and
engineering is essential to the structural viability, constructability, economy, efficiency, and
elegance of a design.
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Preface

This project aims to combine my interests in structural engineering design and architecture. The result is an exploration into, and critique of, the contemporary design process of design competitions and the role of the structural engineer in this process.

More often than not, the design process for a building project is architect led while engineers and other technical experts enter the process after the major design decisions have been made. However, in most projects, the technical considerations actually have a significant (if unacknowledged) role in the design process. The lack of acknowledgement of the technical, specifically the structural, in the design process is never more evident than in the architectural rendering or drawing published at the end of a design competition process. Many prominent public works of architecture (e.g. museums, pedestrian bridges, theaters, significant civic buildings) are initiated by a design competition. Teams of architects submit proposals for buildings that are then juried by prominent individuals in the field. However, it is relatively rare for technical considerations to be included in a stringent way at this stage. This often leads to a disconnect between the images evaluated at the design competition phase and used in promotion of the project, and the actual constructed project. Further, where innovative structural forms are proposed but not validated at the design competition phase, the final result can also be considerably more expensive and take much longer to build than initially planned. Perhaps the most famous example of this phenomenon is the Sydney Opera House, where the final built project is significantly taller and formally different than the winning design competition drawing (see Figure 1 below). The technical complexity inherent in structural resolution of the form also caused a delay of 10 years in the final design and construction of the building, and an increase in $95 million of the final cost (relative to an original budget)\(^1\). This is less of an issue in private projects, but is often a concern in the political sphere when public works are determined by a

![Original design](image1.png) ![Final design](image2.png)

*Figure 1: Sydney Opera House, designed by architect Jorn Utzon, engineered by Ove Arup and Partners. The picture on the right is the original design while the left is the present structure. Notice how the shells are sloped significantly higher, are of shorter length, and create trapezoidal sections at the shell-podium interface rather than arched sections. Also note that the podium is taller and longer than in the original design.*

design competition, and the costs of construction fall on the taxpayers. This is why I would argue that engineers have a duty to step into the design process earlier and why architects should allow them too; it is a matter of civic duty.

To investigate this issue of the lack of early engineering input and collaboration in the design process, I will critically evaluate and analyze a competition winning design that is structurally ambitious. Aiming to select a project that incorporates innovative structural form, emerging construction practices, and/or emerging materials led me to the winning pedestrian bridge design for the international Salford Meadows Bridge design competition.

This capstone is a culmination of structural analysis and explanation of the proposed Salford Meadows Bridge, my own alternative design options for the Bridge, and a discussion of current design processes and collaboration between architects and engineers.
Acknowledgments

I’d like to sincerely thank Professor Sinéad Mac Namara, my advisor, for helping me turn my interests into a project idea, and for guiding and working with me along the way in its culmination. It has been an exciting journey. I would also like thank Tonkin Liu Architects and Arup Engineering Consultants for taking the time to correspond with, aid, and provide information to me about the Salford Meadows Bridge. Their help has significantly increased the accuracy of my analysis and assured me that I was on the correct path with the work I had completed. I am deeply appreciative of the effort and time they put into helping a student overseas with her Honors Program Capstone Project.

I’d like to thank the Renée Crown University Honors Program for both requiring and facilitating this wonderful educational experience. My journey towards completion of this capstone has been transformative. Without being a part of honors, I would not have had the incentive to complete such a project, and I am thankful to have been pushed to explore a topic of my interests and produce something that I am proud of. In particular, I would like to thank Steve Kuusisto, Honors Program Director, for the opportunities I have had being an Honors student from the wide array of interesting and excellent honors courses, the funding for field trips, events, and capstones, and the various events and seminars throughout the year. I would also like to thank Kate Hanson, my Honors advisor, for aiding me throughout my four years here with class planning and scholarships, and keeping me on track with my Honors requirements and my capstone. And of course, thanks to Karen Hall and Hanna Richardson for being amazing Honors advisors and great human beings in general.

A big thank you to Jessica Borri, a 5th year architecture student at Syracuse University for teaching me Rhino and SAP200 and helping me draft my models. Without her help, I would have no analysis and thus no capstone. I am greatly appreciative of the time she spent with me, sometimes hours at a time, trying to figure out how to model the bridge correctly. The work paid off!

Another thank you to Professor Joan Dannenhoffer, my academic advisor who agreed to be my Capstone Reader. Having a second person to provide feedback and guidance on my work is a reassurance that the final product is of its highest quality.
Advice to Future Honors Students

I’d like to say that the long journey towards completing your capstone will feel hopeless and seemingly endless at times, but do not give up. I’m writing this section as I have finished the rest of my capstone and the sense of pride and satisfaction I feel in myself for producing this work was worth the two-year journey. Completion of a capstone can only benefit you in the long run, testing your dedication and providing you with new skills, knowledge, and substantial experience to discuss with employers, graduate school admissions, and other professionals. I found that the topic of my capstone is highly relatable to professionals in the field, giving me opportunities to network with people by discussing the research I have done. It was difficult figuring out what to do my project on, especially as a civil engineer, because it isn’t quite technical as lab research but not as creative as video or film. I ended up changing my project in the Spring semester of my junior year, not really getting the project underway till Fall semester of my senior year which was already busy with classes and graduate school applications. My advice is to start thinking about your capstone before you enter your junior year. Look into the research and interests of professors in your department and talk to them about project ideas. They are more than willing to help. Most importantly, do not procrastinate. Work on your capstone weekly and meet with your advisor often, that way you aren’t pulling late nights/all-nighters in the month leading up to the due date (trust me). The journey may be rough, but you will get through it and you will have gained a significant experience. As an ever inspiring fish said: Just keep swimming!
Chapter 1

The Design Competition

The Salford Meadows Bridge design competition comes as part of a Salford City Council project known as Irwell River Park (IRP). The goal of the IRP is to transform the Manchester City Region into an international waterfront destination in order to boost economic growth and development in the area. As part of the IRP, a landmark pedestrian bridge to connect The Crescent in Manchester with The Meadows in Salford was sought to aid in the development potential of a corridor between the two cities across the River Irwell. Extended details of the IRP can be found in the IRP Brochure, which can be accessed by the link listed in the Appendix.

In order to understand the design principles for this particular pedestrian bridge, it is necessary to discuss the site and context of regional development goals. There are two main sites for this project, The Meadows and The Crescent. The Meadows site, as seen in the map in Figure 2, is located on a river bend covering about 7 hectares. According to the design competition website, the site has been under development as part of a five year management and maintenance program that commenced in 2008. The Crescent site, also

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known as the Chapel Street Corridor, is the historic core of Salford and home to the University of Salford. Regeneration of this area is a key priority to the city of Salford as it will significantly contribute to the growth and development of the Regional Centre in Greater Manchester³. Surrounding areas are also under development to rejuvenate and transform Salford; plans for development can be further explored by visiting the competition website⁴.

The design competition for this landmark bridge was held in two stages, open to registered architects and engineers worldwide. Collaboration between architects and engineers was encouraged as the second stage proposals required a demonstration of engineering consideration for constructability and deliverability within the budget.

Architects and engineers were expected to follow the key design principles set out by the competition, including street visibility, landscape development, pedestrian only design, and riverbank/land supports. Bridge designs were additionally required to fit in with the city’s goals and strategies for pedestrian traffic and conservation areas.

The design competition was held in two stages. The first stage being open and anonymous, and second stage being a shortlist of 3 designs with anonymity lifted. The shortlisted designers were given further information for design and engineering considerations (as mentioned before, Stage 2 proposals required strong engineering input and full estimation). Stage 2 proposals were required to comply with the requirements of the Highways England/Eurocode Design Manual for Roads and Bridges (refer to link in Appendix for PDF). To get the community involved in the project, the Stage 2 shortlisted designs were presented at an exhibition for public consultation. Interested persons could attend and make comments on the

⁴ Ibid.
designs. These comments were made available to the judging panel before the winning design was selected\textsuperscript{5}.

The winning design, seen in Figure 3, was submitted by Tonkin Liu Architects with ARUP the engineering firm. Their sculptural design is derived from the natural landscape of the area, the meandering river, and the meadow wildflowers. It is described by the architects as a metaphor for growth, as the bridge reaches out from the meadow to the city connecting the two. The design is ambitious and unusual structurally, with a curving and twisting arch and deck. The description of the structural characteristics of the bridge is given as follows:

“Our proposal for the Meadow Bridge is a simple primary twisting arch supporting a deck made of a pair of curving torsion beams. The curvature in the arch and the sweeping deck optimizes its structural stiffness, resulting in an ultra-lightweight structure using minimal material. The hollow triangular torsion structures of the arch and deck are constructed of tailored flat 10mm mild steel plates, using contemporary digital tools in modeling, analysis, and computer-controlled water-jet cutting. The crown of the arch appears as the two torsion beams part in the middle of the deck, demonstrating how the bridge is supported. Nestled in the crown of the arch are apertures that offer a place to rest and reveals views of the river valley below.”\textsuperscript{6}

-Tonkin Liu Architects


Figure 3: Salford Meadows Bridge, Architects Tonkin Liu, Engineers ARUP. http://www.ribacompetitions.com/salfordmeadowsbridge/winner.html
Chapter 2
The Engineering behind a Design

The structural design process involves analyzing design drawings, checking code requirements, and designing the structural elements and components that will come together during the construction phase. The first part is acquiring the site information and specifications to set up parameters for the design. The next part is studying the structural engineering principles, design codes, and specifications for the type of structure to be built. Using this information, analysis of the structure can be conducted through a commercial software, such as SAP2000 (although hand calculations are still important to refine and calibrate digital models). The bending moment diagrams, shear force, normal stress, shear stress, deflections and other required performance characteristics of the structure as a whole, and as individual structural members, are obtained from this model and design of the elements can begin. This entails determining the materials to be used, the shapes and sizes of the elements, and other required design aspects and criteria. The process described above could be applied to any building or project.

Before going on to discuss any analysis, it is essential to review the terms below.

**Structural engineering**: The science and art of planning, designing, and constructing safe and economical structures that will serve their intended purposes.

**Structural analysis**: The prediction of the performance of a given structure under prescribed loads and/or other external effects, such as support movements and temperature changes.

**Axial force**: Any force that directly acts along the center axis of an object. They can be compressive or tensile depending on the direction.

**Shear force**: A force that acts parallel to a surface [V].
Shear 2-2: Transverse shear (up and down, perpendicular to the axis [V2 in Figure 4])

Shear 3-3: Lateral Shear (into and out of the plane [V3 in Figure 4])

Bending Moment: Sum of forces that tend to rotate an object off its original axis causing bending, which has the effect of tension on one side and compression on the other.

Moment 3-3: Bending moment about the strong axis (up and down [M33 in Figure 4])

Moment 2-2: Bending moment about the weak axis (into and out of the plane [M22 in Figure 4])

Torsion: Force that causes rotation or twisting of an object, typically one end in respect to the other.

Figure 4: Representation of forces acting on a 3 dimensional structural member. http://www.arch.virginia.edu/~km6e/arch721/content/lectures/lec-01/page-2.html
**Force/Bending Moment Diagram**: Graphical representation of forces and bending moments along the span of an object.

**Uniform load**: Any load that is uniformly distributed across the length of a structural member.

**Point load**: Load that is acting at a single point on a structural member.

**Deflection**: The degree to which an object or point on an object is displaced from its original position under a load.

**Compression**: State of being compressed, creating internal pressure and shortening the length of an object.

**Tension**: State of being stretched apart, creating internal pressure and elongating the length of an object, the opposite of compression.

**Fixed support**: A connection between two structural elements that does not allow any movement, translational (along the axis or perpendicular to it) or rotational movement (i.e. the bending of the object at the connection point).
**Pinned Support**: A connection between two structural elements that does not allow translation (movement along the axis or perpendicular to it) but allows rotation (bending of the object at the connection point).

![Diagram of Pinned Support Types](http://www.boeingconsult.com/tafe/structures/struct1/beams/Beams.HTM)

**Connection/Joint**: Point where multiple members are connected, either rigidly (all members have the same translation and rotation; maintaining shape under deformation and capable of transmitting forces and moments between connected members) or hinged (members have the same translation but may have different rotations; capable of transmitting forces but not moments between connected members).

**Live load**: Movable or moving loads due to the use of the structure, or non-permanent static loads; an example of this in a typical office would be people, desks, photocopiers, some move, some don’t, but none are permanently attached to the building.

**Dead load**: Load due to the weight of the structural system itself and any other materials permanently attached to it.

**Environmental load**: Loads caused by environmental effects, such as wind, snow, and earthquakes.

**Arch**: A curved symmetrical structural member spanning across the length of an opening, or obstacle (such as a river) serving as a structural support.
**Beam**: A straight (typically horizontal) structural member that is loaded perpendicular to its longitudinal axis.

**Failure**: When a structure can no longer support the designed loads and starts breaking, collapsing, falling apart. The loss of structural integrity, when a member is stressed beyond its strength limit.

**Plane structure**: Two dimensional structures, all structural members and applied loads lie in a single plane.

**Space structure**: Three dimensional structures subjected to three dimensional force systems.

**Line diagram**: Each member of the structure is represented by a line coinciding with its centroidal axis (centerline of the member).

**Centroid**: Center of mass of a geometric object of uniform density.

- **Xbar**: Horizontal distance of the center of mass of a geometric object along the x axis from the y axis.
- **Ybar**: Vertical distance of the center of mass of a geometric object along the y axis from the x axis.

**Moment of inertia**: Geometric property expressing a structural member’s tendency to resist bending and buckling about an axis.

- **Ix**: Property that depends on the geometric shape and its’ tendency to resist bending or rotation about the x axis.
- **Iy**: Property that depends on the geometric shape and its’ tendency to resist bending or rotation about the y axis.
**Parallel axis theorem:** Method of determining the mass moment of inertia of a rigid body about any axis given the body’s moment of inertia about a parallel axis through the object’s center of gravity and the perpendicular distance between the axes.

**Ixx:** Moment of inertia of a rigid body relative to rotation about the x-axis. Sum of each member’s moment of inertia about the x axis and its area multiplied by the distance between the y bar centroid of the rigid body and the centroid of the member squared.

**Iyy:** Moment of inertia of a rigid body relative to rotation about the y-axis. Sum of each member’s moment of inertia about the y axis and its area multiplied by the distance between the x bar centroid of the rigid body and the centroid of the member squared.
Chapter 3

Formal Analysis of the Salford Meadows Bridge

The design for the Salford Meadows Bridge submitted by Tonkin Liu Architects and Arup Engineering Consultants is unique and ambitious. The form of the bridge is unlike any standard pedestrian bridge design. Using the renderings available (see Figure 7 and 8 below) on the competition website and Tonkin Liu’s website, models were traced and created using Rhinoceros 5: Modeling Tool for Designers (Rhino) and then exported to SAP2000 for structural analysis.

Figure 7: Rendering, side view. http://www.ribacompetitions.com/salfordmeadowsbridge/winner.html
For the initial analysis, estimations of dimensions and loads were used in order to solely analyze the form. The span of the bridge was estimated using Google Earth to measure the width of the River Irwell. Scaling the span of the bridge in Rhino automatically scaled the dimensions of the rest of the model. For ease of modelling the three dimensional form of the bridge, the triangular volumes of the arch and deck were approximated by centerlines (as a line diagram), which reveals that the arch and deck connect along the midpoint. This model can be seen in Figure 9 below. Dimensions are modelled as:

- Length of arch: 112 feet
- Length of deck: 236 feet
- Height: 27 feet
However, when looking at some of the renderings of the bridge, it is drawn as though the arch cuts through the deck and is therefore connected to the deck at two points. Since this is what the renderings imply, a model of this situation was created to compare to the model of the actual behavior of the bridge depicted by approximating the centerlines. This model can be seen in Figure 10 below.
The difference between the two cases has a significant structural consequence in how the bridge behaves. Arches are elements that will transmit forces along their own axis to carry a load efficiently (entirely in compression in a well-designed arch). However, an arch only does this when it is loaded uniformly from above along the projected horizontal plane of the curve of the arch. In other words, the arch is most efficient when it is loaded at many equally spaced points as possible along the horizontal rather than at just one point. Because model A of the bridge actually connects the deck and arch at one single point, the arch in this case is acting as two beams rather than an arch (this is shown in Figure 17 where the structural analysis show high values for positive bending moment—in which case there is tension on the bottom of the member and compression on the top of the member—and low values for axial compression—which indicates inappropriate arch behavior as a true arch would experience large axial compression compared to very low bending moment). The bridge with the two loading points (as
implied by some of the renderings) looks as if it will do a slightly better job at carrying the load in arch action; model B agrees with this but it still acts more as a beam than an arch but less so than the actual behavior of the bridge (see Figure 23 where the bending moment values are lower than those for model A in Figure 17, but still considerably more significant than the compression values which would indicate appropriate arch behavior). This is accounted for by the part of the arch that extends above the deck and thus carries very little of the load.

To further demonstrate the non-arch like behavior of the bridge as proposed and compare the results to a true arch loaded in the most efficient way, a model (model C) of a hypothetical bridge where the arch is completely integrated with the deck through vertical connections across the entire length of the arch was created. Such a design is one we most often see in arch structures; for example, in the work of Swiss engineer Robert Maillart (see Figure 11 below). This model can be seen in Figure 12 below.

![Figure 11: Salginatobel Bridge designed and engineered by Robert Maillart. structurae.net](image-url)
The bridge as rendered in the design competition varies in the y-direction, meaning it has curvature in the direction up-down the river. This is also an unusual design feature as most standard bridges are symmetrical and can be analyzed in the 2D plane that spans the river. To demonstrate the structural issues that this lack of symmetry in the y-direction will create, models of each situation discussed above were modelled in a symmetric two dimensional plane as well, which can be seen in Figures 13 and 14 below.
Each of these models were then exported to structural analysis software SAP2000 and subjected to approximated loads to estimate both the weight of the bridge itself and the additional live load (pedestrians). The arch supports were assumed to be fixed as they should be embedded into the riverbanks, while the deck supports were assumed to be pinned. A deck width of 10 feet was estimated based on the renderings provided by the architects.

These initial models were created before fully detailed specifications were available from the engineers. Their primary purpose was to show the engineering impact of the proposed form and to compare alternate designs to investigate some of the more challenging structural aspects of the design as proposed. Thus, a series of conservative placeholder assumptions for the loading of the bridge were made. An 85 pound per square foot (psf) live load was assumed—this is the design live load according to the *Guide Specifications for Design of Pedestrian Bridges* published by the American Association of State Highway and Transportation Officials (AASHTO)—and a 100 psf dead load was assumed—this is a conservative assumption based on the weight of similar bridges. These values were then used to approximate a uniform loading on the bridge of 2560 lb/ft by the following calculations:

- **Live load:** \(85 \text{ psf} \times 10 \text{ ft width of bridge} = 850 \text{ lb per ft length of bridge}\)
- **Dead load:** \(100 \text{ psf} \times 10 \text{ ft width of bridge} = 1000 \text{ lb per ft length of bridge}\)
- **Scaled uniform load:** \(1.2 \times 1000 + 1.6 \times 850 = 2560 \text{ lb per ft length of bridge}\)

Load and Resistance Factor Design (LRFD) method is applied here and as such the load values are scaled by a factor of 1.2 and 1.6 respectively to increase the estimate of applied load in order to safely compare these values to the ultimate limit and serviceability limit of the structure (limit states at which the structure no longer serves its design criteria and can experience fatigue and failure). The factors (which are part of the standard U.S. building code) are determined based on the level of uncertainty about different kinds of loads. Dead load is
multiplied by a factor lower than live load as it is a permanent load based on the known weight of the materials while live loads are highly variable loads that one cannot entirely control over the life of the structure.

The initial analysis presented next is solely to compare the form of the bridge to the other design cases. As the dimensions and loads were estimated, the numbers in the analysis are to be used only to qualitatively compare the effects of the formal design and not to be taken as the actual forces and moments experienced by the bridge.

The axial force diagram, shear 2-2 and shear 3-3 diagrams, moment 2-2 and moment 3-3 diagrams, and torsion diagram for each case were obtained and scaled to the same factor to show the difference between each. Refer to Figures 15-20 for Model A; Figures 21-26 for Model B, Figures 27-32 for Model C, Figures 33-38 for Model D, and Figures 39-44 for Model E.
Figure 15: Axial Force Diagram for Model A

Figures 15 and 16 illustrate the stress analysis for Model A, showing the axial and shear forces. Axial forces are noted at various points, with maxima reaching 36.9 kips and 38.8 kips, indicating compression. Shear forces are also depicted, with maxima of 234.5 kips and 245 kips for the positive deck force, and -240 kips and -232.7 kips for the negative arch force.

Figure 16: Shear 2-2 Diagram for Model A
Figure 17: Moment 3-3 Diagram for Model A

Figure 18: Shear 3-3 Diagram for Model A
Figure 19: Moment 2-2 Diagram for Model A

Figure 20: Torsion Diagram for Model A
Figure 21: Axial Force Diagram for Model B

Axial Force Diagram Model B

- Tension in the arch above the deck: 870 kips
- Relatively large compression in the deck between connection: -998 kips

Figure 22: Shear 2-2 Diagram for Model B

Shear Force 2-2 Model B

- Max shear force in the arch: 243.5 kips
- Max shear force in the deck: 187 kips
- -190 kips
- -265 kips

Figure 22: Shear 2-2 Diagram for Model B
Figure 23: Moment 3-3 Diagram for Model B

Figure 24: Shear 3-3 Diagram for Model B
Figure 25: Moment 2-2 Diagram for Model B

Figure 26: Torsion Diagram for Model B
Axial Force Diagram Model C

-173 kips
-165.8 kips
-171 kips
-151 kips

Figure 27: Axial Force Diagram for Model C

Shear Force 2-2 Model C

105.7 kips
30.5 kips
46.2 kips
-95.4 kips
-24.8 kips

Figure 28: Shear 2-2 Diagram for Model C
Bending Moment 3-3 Model C

-1,272 kip-ft
880.8 kip-ft
-1,026.8 kip-ft
725 kip-ft

Figure 29: Moment 3-3 Diagram for Model C

Shear Force 3-3 Model C

Figure 30: Shear 3-3 Diagram for Model C
Figure 31: Moment 2-2 Diagram for Model C

Figure 32: Torsion Diagram for Model C
Figure 33: Axial Force Diagram for Model D

Axial Force Diagram Model D

18.3 kips
19.3 kips
-425.5 kips

Figure 34: Shear 2-2 Diagram for Model D

Shear Force 2-2 Model D

Max shear force in the deck (positive) 195 kips 168 kips Max shear force in the arch (positive)

163.7 kips -191 kips -185 kips
Max shear force in the arch (negative) Max shear force in the deck (negative)

-149.6 kips
Figure 35: Moment 3-3 Diagram for Model D

Figure 36: Shear 3-3 Diagram for Model D
Figure 37: Moment 2-2 Diagram for Model D

Figure 38: Torsion Diagram for Model D
Figure 39: Axial Force Diagram for Model E

Figure 40: Shear 2-2 Diagram for Model E
**Figure 41: Moment 3-3 Diagram for Model E**

- Max bending moment in the arch (negative)
  - -735.6 kip-ft
  - -629.2 kip-ft
  - -2,411.8 kip-ft

- Max bending moment in the arch (positive)
  - 1,237.8 kip-ft
  - 1,092.5 kip-ft

**Figure 42: Shear 3-3 Diagram for Model E**

**Shear Force 3-3 Model E**
Figure 43: Moment 2-2 Diagram for Model E

Figure 44: Torsion Diagram for Model E
These results illustrate two issues with the real proposed design. Firstly, that the proposed design of an out of plane bridge has higher forces and experiences forces in two directions while a plane bridge has lower forces that act in just one direction. The second design issue being that the arch is loaded inefficiently because the arch is not loaded uniformly from above along the projected horizontal plane of the curve of the arch, thus acting as beams instead.

The first design issue (the out of plane forces) can be illustrated by comparing models A and B with models C, D, and E. Models A and B represent the real design of the bridge which is out of plane varying in the y-direction while their plane counterparts, respectively models D and E, represent a typical bridge design which is plane and straight along the longitudinal axis. Comparing the two dimensional (plane) models to the three dimensional (out of plane) models, the forces in the 2D models are lower. Comparing the first two model counterparts, A and D, shear 2-2 force (Figure 33) and bending moment 3-3 (Figure 34) in model D are both smaller than in model A with bending moment significantly smaller in the deck by about 50%. In the second two model counterparts, B and E, there is approximately 60% less axial compression in the arch and tension in the deck in model E than in model B. Note how the shear 2-2 force (Figure 39) in model E is smaller by approximately 55% and distributed across the structural members differently than in model B (Figure 21). There is 55% less bending moment 3-3 (Figure 40) in model E than in B. In the two dimensional bridge models, the bridge experiences no shear 3-3, moment 2-2, or torsion unlike in the three dimensional model (the actual proposal) where the curvature of the arch and deck creates forces into and out of the plane (in the y-direction, i.e. up and down the river). These results prove that a bridge designed in plane performs more efficiently than a bridge designed out of plane, as the forces are smaller generally and there are no forces in the y-direction.
The second design issue (the form of the bridge and its impact on arch behavior) can be illustrated by comparing models A, B, and C. Model A depicts the actual behavior of the bridge where the centerlines of the bridge and deck meet at one point. Model B depicts a bridge where the arch crosses over the deck, meeting each other at two points, as the renderings of the bridge implies. As discussed previously in the chapter, a well-designed arch will act entirely in compression with very little bending moment. An arch acts this way when it is loaded uniformly from above at as many equally spaced points as possible along the horizontal rather than at just one or two single points. The results for models A and B represent this behavior, as the arches here connect to the deck at one or two points respectively, thus acting as beams rather than an arch. In model A, there are large values for positive bending moment 3-3 (Figure 17) compared to low values for axial compression (Figure 15), demonstrating less arch behavior and more beam behavior. This is an inefficient use of the arch form; in fact, if this is to be the design of the bridge it would make more sense for the “arch” pieces to be straight lines rather than curves, since they are behaving as beams and the most efficient form for a beam is a straight line. Also note how in Figure 17 for bending moment 3-3, the moment in the arch peaks at the midpoint connection in positive bending. The deck also experiences a significantly large amount of bending moment at this connection, as the deck is essentially two long beams in bending.

In comparison, model B connects at two points therefore behaving slightly better than in model A which is demonstrated by the lower forces experienced in model B. However, model B still experiences large values for bending moment 3-3 (Figure 23) compared to low values for axial compression (Figure 21) demonstrating that it still behaves as beams rather than an arch. Further, the arch cutting through the deck creates large axial compressive forces in the section of deck between the two connections and large axial tension in the section of arch above the deck.
This section of arch does not contribute to the supporting action of the arch in the most efficient way, as it is in tension rather than in compression. Also, the deck forces in bending moment 3-3 (Figure 23) and shear 2-2 (Figure 22) in this model experiences a reduction of about half as the deck is now split into three shorter spans. These results show that the arch as designed is not truly an arch but is rather curved beams as it is not loaded in the most efficient way.

Both of the design issues are illustrated by comparing any model to model C. Model C experiences the smallest axial force (75% less than in model A), shear 2-2 force (55% less than in model A), and bending moment 3-3 (90% less than in model A) out of all the models and as with the other two dimensional models, it does not experience shear 3-3 force, bending moment 2-2, or torsion, as it is not an out of plane form. Due to the arch being loaded much closer to the most efficient way as explained earlier, the forces, especially bending moment in the deck, are significantly smaller, with the arch acting completely in compression. This is because the deck (which is still of course a series of beams as in the other models) is a series of much shorter beams than in the previous models and bending moment is a function of the length of the beam squared. This is why such a design (an arch loaded from either above or below at as many evenly spaced locations as practical) is most often used for arch bridges, both traffic and pedestrian. Overall, the design issues of out of plane variation and inefficient arch loading can be fixed with design alternatives presented in Chapter 5.
Chapter 4
Diving into Details

Further information about the bridge regarding dimensions, cross sections, etc., was obtained through the generous correspondence of architect Anna Liu from Tonkin Liu, and structural engineers Ed Clark and Stuart Chambers from ARUP Engineering Consultants. Mr. Chambers provided a document outlining dimensions and cross sections of the bridge, a basic structural model, and advice about how to model the bridge for a novice working in the computer software. The information was a significant reassurance that the current work and models were on the correct path. He concurred with the methodology used for the initial models. The estimated dimensions for those models were found to be within 20 percent of the updated dimensional information. A few of the initial assumptions were made incorrectly such as the arch supports being pinned rather than fixed and the precise nature of the arch and deck connection, which can be seen in the lower left of Figure 45 below. It is worth noting that this design (which from the analysis in Chapter 3 we know will be more efficient than either model A or model B which were extrapolated from the architect’s competition winning entries) is significantly different from the architect’s renderings.
A new model was created in Rhino to depict the cross-sections and correct dimensions based on the document provided by ARUP. Refer to figures 46-51 for various views of this model F. From the various views presented, take note of the S shaped curvature of the deck and arch, of how the cross-sections vary from deck ends to mid-span, of how the arch cross section is integrated with the deck to form the mid-span cross-section, and how the depth of each cross section varies across its member length.
Figure 46: Model F

Figure 47: Model F, profile view
Figure 48: Model F, aerial view of deck

Figure 49: Model F, aerial view of arch
Figure 50: Model F, arch cross-section

Figure 51: Model F, deck cross-section metamorphosis
The centerlines of each volumetric shape was modeled as a line diagram and exported into SAP2000 for analysis (SAP cannot import the complicated sections and shapes modelled in Rhino, thus only a line diagram of the form can be inputted; the program takes account of the shape of the cross section in its analysis, but does not display it in the graphical user interface).

With the accurate dimensions, loads for this analysis were calculated according to the Eurocode’s Design Manual for Roads and Bridges (DMRB). Following Section 7 Standard for Foot/Cycle Track Bridge Loading, the nominal pedestrian live load was calculated by:

7.1.1 **Nominal pedestrian live load.** The nominal pedestrian live load on foot/cycle track bridges shall be as follows:

(a) for loaded lengths of 36m and under, a uniformly distributed live load of 5.0 kN/m²;

(b) for loaded lengths in excess of 36m, \( k \times 5.0 \text{ kN/m}^2 \) where \( k \) is the nominal HA UDL for appropriate loaded length (in kN/m) x 10 \( \text{L} + 270 \)

where \( L \) is the loaded length (in m)\(^7\).

The loaded length of the bridge is 97.46 meters (319.75 ft) so calculations will follow part b for the nominal pedestrian live load. According to Table 13: Type HA Uniformly Distributed Load (UDL) of Section 6.2 in the DMRB\(^8\), the nominal HA UDL for a loaded length of 100 meters is 22.7 kN/m. The nominal pedestrian live load is thus calculated by:

\[
k: \quad (22.7 \text{ kN/m} \times 10)/(100\text{m} + 270) = 0.6135
\]

Load: \( k \times 5.0 \text{ kN/m}^2 = 3.07 \text{ kN/m}^2 \)

The width of the deck varies from 3 meters to 3.5 meters to 5.5 meters. Thus an average value of 4 meters width was used to calculate the load per meter and then converted to pounds per foot as the bridge is analyzed in Imperial Units.

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\(^8\) Ibid.
\[3.07 \text{ kN/m}^2 \times 4\text{m} = 12.27 \text{ kN/m}\]

\[12.27 \text{ kN/m} = 841 \text{ lb/ft}\]

Thus the total live load for the bridge is 841 lb/ft. A live load scale factor according to the DMRB is 1.5, however to be conservative and safe, the 1.6 standard scale factor will be used in calculating the scaled ultimate load.

The dead load of the bridge was calculated by using the dimensions and cross sectional shape of the deck and arch. According to the architects, the deck and arch are to be constructed of tailored 10mm mild steel plates. With steel, it is expected that the dead load will be in the range of 2,000 to 3,000 lbs/ft. The dead load for the deck on average is calculated by the following:

Cross-Section:
2 triangles: 1.075m deep and 2.75m wide (3.526 ft deep and 9.02 ft wide)

![Figure 52: Cross section of the deck with average measurements](image)

Weight:
Length of one side of triangle: \(5.725 \text{ ft} = [3.526^2 + (9.02/2)^2]^{1/2}\)
Triangle perimeter: \(20.47 \text{ ft} = [5.725 \text{ ft}*2 \text{ sides} + 9.02 \text{ ft width}]\)

---

Thickness: 10mm (0.393 in)

Cross-section of steel: $193 \text{ in}^2 = [20.47 \text{ ft}*12 \text{ in/ft}*0.393\text{in}*2 \text{ triangles}]

Specific weight of steel: $490 \text{ lb/ft}^3$

Dead load of steel: $657 \text{ lb/ft} = [490 \text{ lb/ft}^3*193 \text{ in}^2/144 \text{ in}^2/\text{ft}^2]$

Assume about 5 inches of concrete/asphalt/wearing surface

Specific weight of concrete: $150 \text{ lb/ft}^3$

Dead load of concrete: $1128 \text{ lb/ft} = [(150 \text{ lb/ft}^3*5/12)*9.02 \text{ ft width}*2 \text{ triangles}]

Assume another 15 lb/ft$^2$ of utilities, barriers, handrails, lighting, etc.

Superimposed dead load: 271 lb/ft

Total dead load from deck: $2055 \text{ lb/ft} = [657 \text{ lb/ft} +1128 \text{ lb/ft} +271 \text{ lb/ft}]

The dead load for the arch on average is calculated by the following:

Cross-Section:

1 triangle: 0.75 meter deep and 2.75m wide (2.46 ft deep and 9.02 ft wide)

Weight:

Length of one side of triangle: $6.245\text{ft} = [2.46^2+(9.02/2)]^{1/2}$

Triangle perimeter: $15.41 \text{ ft} = [6.245\text{ft}*3 \text{ sides}]$

Thickness: 10mm (0.393 in)

Cross-section of steel: $72.68 \text{ in}^2 = [15.41\text{ft}*12 \text{ in/ft}*0.393\text{in}]$

Specific weight of steel: $490 \text{ lb/ft}^3$

Dead load of steel: $247 \text{ lb/ft} = [490 \text{ lb/ft}^3*72.68 \text{ in}^2/144 \text{ in}^2/\text{ft}^2]$

Total dead load from arch: $247 \text{ lb/ft}$

Thus the total dead load from the arch and deck including superimposed dead load on average is $2302.39 \text{ lb/ft}$. This value falls in the range expected, thus the calculations are correct.

A nominal value of $2500 \text{ lb/ft}$ will be used to be conservative and account for changes in cross sections that occur throughout the span. The scale factor for ultimate limit state for the dead load and superimposed dead load according to the DMRB Table 1 is 1.05 and 1.75 respectively. To
be conservative, the standard scale factor of 1.2 will be used for the sum of the dead and superimposed dead load. The scaled ultimate load is thus calculated by:

\[ 1.2 \times 2500 \text{ lb/ft} + 1.6 \times 841 \text{ lb/ft} = 4346 \text{ lb/ft} \]

This load was then applied as a uniformly distributed load across the deck in SAP2000. The results of the analysis are presented below in Figures 53-59.
Figure 55: Shear 2-2 Diagram for Model F

Figure 56: Moment 3-3 Diagram for Model F
Figure 57: Shear 3-3 Diagram for Model F

Figure 58: Moment 2-2 Diagram for Model F
The same design issues discussed before are still prevalent in this new model. The issue of the arch being loaded inefficiently is represented in Figure 56, where there is significantly large bending moment 3-3 compared to low axial compression. The arch in this model still behaves as two curved beams that connect to the deck at two points as in model B, however the arch is integrated into the deck cross section rather than cutting above it. This creates large forces in the arch legs and smaller forces in the deck along the length that is integrated with the arch. The forces are generally larger, in some cases almost double, on the right side of the bridge due to asymmetry of the bridge. The bridge still varies in the y-direction therefore still experiencing the issues of being out of plane.

To determine if the proposed cross-section design can carry the forces that result from the form and the loading of this bridge, the centroid and second moment of area of the cross section at the maximum point of force and moment were calculated. Centroid and second moment of area are properties of a shape (just like perimeter, area, and volume) which measure respectively the center of mass of the cross-section and its resistance to bending; as a general rule, a deeper
cross-section resists more bending in the 3-3 direction and a wider cross-section resists more bending in the 2-2 direction. Using the equation for actual stress in the cross section, \( f = \frac{M_y}{I} \), where \( M \) is bending moment, \( y \) is the location of the centroid of the section, and \( I \) is the second moment of area, it was then possible to compare the value calculated to the maximum allowable stress in standard mild structural steel (45 ksi). If the calculated stress was near or greater than this value, then the cross-section would need to be deeper to carry the loads. Below is a summarization of the analysis. The triangular cross-section of the deck was simplified to straight members as in the figure below in order to calculate the centroid and second moment of area.

The centroid was calculated as follows:

- Xbar1: 21.7 in  Ybar1: 34.3 in  Area1: 26.9 in²
- Xbar2: 43.5 in  Ybar2: 34.3 in  Area2: 26.9 in²
- Xbar3: 64.9 in  Ybar3: 34.3 in  Area3: 26.9 in²
- Xbar4: 86.6 in  Ybar4: 34.3 in  Area4: 26.9 in²
- Xbar5: 54.1 in  Ybar5: 68.7 in  Area5: 42.5 in²
Xbar (total): 54 in

54 in = [(xbar1 * area1 + xbar2 * area2 + xbar3 * area3 + xbar4 * area4 + xbar5 * area5) / Total area]

Ybar (total): 44 in

44 in = [ybar1 * area1 + ybar2 * area2 + ybar3 * area3 + ybar4 * area4 + ybar5 * area5) / Total area]

The second moment of area for each member was calculated as follows:

\[ I_{x1} = 10527 \text{ in}^4 = \frac{(b \cdot h^3)}{12} \]
\[ I_{y1} = 0.35 \text{ in}^4 = \frac{(b^3 \cdot h)}{12} \]

\[ I_{x2} = 10527 \text{ in}^4 = \frac{(b \cdot h^3)}{12} \]
\[ I_{y2} = 0.35 \text{ in}^4 = \frac{(b^3 \cdot h)}{12} \]

\[ I_{x3} = 10527 \text{ in}^4 = \frac{(b \cdot h^3)}{12} \]
\[ I_{y3} = 0.35 \text{ in}^4 = \frac{(b^3 \cdot h)}{12} \]

\[ I_{x4} = 10527 \text{ in}^4 = \frac{(b \cdot h^3)}{12} \]
\[ I_{y4} = 0.35 \text{ in}^4 = \frac{(b^3 \cdot h)}{12} \]

\[ I_{x5} = 0.55 \text{ in}^4 = \frac{(b \cdot h^3)}{12} \]
\[ I_{y5} = 41531 \text{ in}^4 = \frac{(b^3 \cdot h)}{12} \]

Using parallel axis theorem, the moment of inertia for the entire rigid body was calculated as follows:

\[ I_{xx} = 78,295.17 \text{ in}^4 = \sum (I_{xi} + A_i \cdot (y_{bar} - y_{bari})^2) \]
\[ I_{yy} = 104,612.2 \text{ in}^4 = \sum (I_{yi} + A_i \cdot (x_{bar} - x_{bari})^2) \]

Using the maximum bending moment 3-3 and 2-2 from the analysis, the allowable strength along each axis was calculated by the following:

\[ M_{3-3}: (-) 19,880 \text{ kip-ft} \Rightarrow 238,557 \text{ kip-in} \]
\[ M_{2-2}: (+) 4,624 \text{ kip-ft} \Rightarrow 55,490 \text{ kip-in} \]

\[ F_{\text{strong}} = \frac{(M_{3-3} \cdot y_{bar})}{I_{xx}} = 134 \text{ ksi} \]
\[ F_{\text{weak}} = \frac{(M_{2-2} \cdot x_{bar})}{I_{yy}} = 29 \text{ ksi} \]

The maximum allowable stress (i.e. the strength) of industry standard mild structural steel is 45 ksi which is less than the actual stress calculated along the strong axis. Thus the deck cross-section will have to be significantly deeper in the vertical direction to carry the loads.

Alternatively, the plates of steel could be quite a bit thicker to improve the resistance to bending.
(i.e. increase I), but this would make the bridge heavier, which would increase moment and thus stress. Therefore, making the cross-section deeper is the more efficient (thus less expensive) way to solve this problem.

This is an important result as it underscores the consequences of awarding design competitions on the basis of architectural renderings. Even using the updated engineering drawing for the model (which is already different from the competition winning entry), this analysis shows that the bridge deck will need to be considerably deeper than drawn—leading to a significantly different appearance in the realized project.
Chapter 5

Design Recommendations

The major concerns with the design of the bridge as is, is that the curvature of the arch and deck out of plane create significant forces in two directions and the connection between the arch and deck causes the arch to behave as a series of beams. In order to address the first issue, one alternative design option is straightening the bridge to a 2-dimensional plane as in models C, D, and E. The other alternative design option is adding a straight deck path across the river which increases the stiffness but preserves the architectural integrity of the original design.

To address the second issue, the arch can either become beams as it is acting or be an arch connected to the deck in such a way that it carries the load in the most efficient way. The first alternative design option would be to convert the arch supported deck into a beam supported deck, much like a pi-frame (see Figure 61). In this case, the curved arch legs of models B and E would be converted into straight beam members (still inclined from support to deck connection). The second alternative would be designing a bridge wherein the arch is integrated with the deck across the entire length of the arch as the one in model C, which was shown to have the smallest forces of all modelled cases (see Figure 62). Also, straightening the arch to a two dimensional plane would expel shear 3-3 force, bending moment 2-2, and torsion as well as reducing all forces experienced by the arch.
In addition to the two major design issues with the overall form of the bridge, there are some details in the design that present a concern. The holes in the arch as rendered by the architects are part of the design aesthetic, and indeed engineers often remove unnecessary materials in areas of low stress to make structural members lighter and thus more efficient. However, the analysis presented in Chapter 4 shows that these holes have not been located in areas of low stress. In a square or triangular cross-section, the bending forces are carried in the top and bottom flanges of the cross-section (bending often dominates design, which is why the I-beam is an often used shape), while the shear forces are carried in the sides walls of the cross-
section (or the web of an I-beam). Thus in structural members, more material is needed in the middle of a cross-section in areas of high shear. Web stiffeners in steel I-beams are an example of this design solution (see Figure 63). However, in areas of low shear, holes can be located. This is often done in beams so MEP works can run through reducing the need for large drop ceiling space (see Figure 64). In a simply supported beam for example, shear occurs along the web of the beam and is highest at the supports reducing to zero at the midspan (refer to Figure 5 for the shear force diagram of a uniformly loaded beam). Thus in these areas of low shear stress near the middle of the length of the beam, holes or openings are acceptable.

However, the arch curves and twists over itself and experiences high shear 2-2 and shear 3-3 forces in locations where the architectural renderings indicates openings. To fully resolve this issue, a more detailed finite element analysis for the arch would have to be done in order to determine the allowable areas for holes. When asked about the holes, Mr. Chambers had stated that the presence of the holes in the arch were ignored for the conceptual design, ensuring that if they were added it would be in areas of relatively low shear. The architectural renderings however, shows the holes somewhat randomly distributed (with no discernable pattern) uniformly across the length of and the height of the arch. Figures 55 and 57 show the shear forces experienced by the arch. A distribution of openings across the arch that took into account the high shear stresses as displayed in these figures would not be uniformly distributed across the length of the arch and would show a discernable pattern. Holes would be located only in the middle of the cross-section (never near the top or bottom) and there would be no holes near the supports of the arch or the intersection of the arch and the deck. For maximum efficiency, holes would also likely change size in response to increasing and decreasing shear stress. Mr. Chambers also stated that to be 100% confident in the design, analysis still needs to be
undertaken to ensure that the stresses in the steel plates of the arch are acceptable. The implications of this disconnect between the architect’s models and the engineer’s analysis is discussed in the next chapter.

The thickness of the steel plates to be used is also of concern. The tailored 10mm mild steel plates are thin in comparison to standard cross sections for a structure of this scale. An increase in the thickness of the material would add to the strength and stiffness of the bridge and would not greatly hinder the architectural goal of the bridge looking like a lightweight structure, although it would make the bridge considerably heavier, thus requiring an even deeper cross-section to carry the load.

![Figure 63: Example of web stiffeners in a steel I-beam. http://www.whatsonttheare.com/2012/03/07/stiffeners/](http://www.whatsonttheare.com/2012/03/07/stiffeners/)

![Figure 64: Example of holes in steel I-beams for MEP works. http://www.steelconstruction.info/Service_integration](http://www.steelconstruction.info/Service_integration)
Chapter 6
The Design Process and the Role of the Engineer

As discussed briefly, the lack of early collaboration between architects and the engineers in the design process leads to complications further along in the project, especially during construction. The design process, specifically the process for design competitions, is typically architect led, with no significant consideration of the technical aspects. The resulting designs are judged by a panel mainly made up of significant individuals in architecture and governing bodies that host the competition. Often, the selected winning design has to undergo significant changes in order to be constructed leading to a product significantly different in appearance (and sometimes much more expensive) than the design proposed. This issue not only costs time and resources, but it imposes costs on society whose tax funds are used for the project (if a public work, as many design competitions are). The more significant the changes are, the more costly. However, such problems can be avoided by simply integrating technical considerations early on in the design process.

The Salford Meadows Bridge design competition was open to both architects and engineers and collaboration was encouraged. The winning design was submitted by a team of architects and engineers, albeit being architect led. However, issues between design and structural viability and constructability are not insignificant as seen in the results from the structural analysis. With the architects leading the project, it is possible that the engineers had little say or influence on the formal design decisions as their input was a required component for Stage 2. As can be seen by the Stage 1 submission in Figure 65 below, the form of the bridge
remained similar to the final design with differences in the cross sections of the deck and arch and the Meadows side landing.

Looking at the document provided by ARUP in Chapter 4, there are differences in the engineer’s models and the architect’s. Firstly, note how in the engineering model, the arch cross section does not twist over itself. Secondly, note how the arch does not cut through the deck; rather, it is integrated into the cross section of the deck. Also, the arch is of solid cross section in the engineer’s model. Although analysis of the acceptability of the holes is not yet completed, the final proposed design still includes the holes. As can be seen from the structural analysis of the Salford Meadows Bridge, the arch experiences relatively high shear both perpendicular to the axis and into and out of the plane (model F, Figures 55 and 57) meaning that placing holes in the arch as planned will be complicated and take much more technical consideration. The twisting of the cross section of the arch as it extends over the river is also included in the final proposed design when such twisting was not analyzed by the engineers. This disconnect between the engineer’s analysis and the proposed design goes to show that the design process of design
competitions is not foregrounding these kinds of technical considerations until after the design is selected.

In design competitions, there is no guarantee that the design will win; thus there is little incentive to do such complex technical analysis for the proposal. However, when engineers are included in the conceptual design process, the result can be a design that is innovative but more buildable within the budget and timeframe allowed, wherein technical analysis was integrated from the very beginning. Many successful firms practice such early collaboration, one of the most prominent being the architecture and engineering firm Skidmore, Owings, and Merrill (SOM). At this firm, collaboration is described as “fundamentally interdisciplinary” by its associates\(^\text{10}\). Their most famous collaborative designs are groundbreaking and innovative structures in which the architecture and structure are one and the same, including the Burj Khalifa, currently the tallest building in the world, the Sears Tower (now Willis Tower), the former tallest building in the world, and the One World Trade Center (refer to Figure 66).

In regards to a design competition for SPG Shanghai, Eric Long, Associate Director and structural engineer at SOM has described the non-traditional approach SOM takes towards competition design where “because we work together so hand in glove, the analysis we do is based upon experience and intuitive understanding about the way things work, so for us it’s just a natural thing to involve structural as well mechanical engineering in these proposals.”

Such a holistic design approach has proved successful, where the design proposed is the design that is built within the estimated budget and schedule. Not only that, collaboration can allow for innovative and creative design solutions, where both the architecture and engineering is challenged. In an article for Architectural Design, associates at SOM affirm this by stating that “This spirit of architectural and engineering collaboration feeds the development of conceptual and technical invention to this day at SOM, leading to new structural and architectural paradigms.”

Another firm that successfully practices collaboration between architects and engineers is Foster + Partners. Collaboration is integral to the firm’s mission as stated on their website on “What We Do” tab:

“Foster + Partners understands that the best design comes from a completely integrated approach from conception to completion. We have a strong creative team, in which structural and environmental engineers work alongside the architects from the beginning of the design process. By doing so, we believe that they can learn from one another and combine their knowledge to devise wholly integrated design solutions. The design teams are supported by numerous in-house disciplines, ensuring that we have the knowledge base to create buildings that are environmentally sustainable and uplifting to use.”

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Xavier De Kestelier, a Partner at Foster + Partners, describes the collaboration process as one where there is constant communication early on between the architects and engineers; “We always try to get engineers involved really early…It’s not like we make the shape we want and then give it to the engineer to figure out how to make it stand up—it’s always a conversation.” The product and benefits of this kind of design process is evident in many of the projects at Foster + Partners, one being the Hearst Tower (see Figure 67). This office building is an example of a structure in which the architecture and engineering cannot be separated; the triangulated diagrid form of the structure serves as its architectural expression as well as an environmental initiative. The tower satisfies the three design ideals of efficiency (uses 20% less steel than a conventional frame, energy savings from green building initiatives), economy (less material required, recycled material, and reduced time for construction due to prefabrication), and elegance (unique expression of creative and innovative design). The challenge to the design of the Hearst Tower was integrating the original base of the building and creating a connection between the old and the new. The new tower is linked to the base in such a way to give the impression that the tower is floating weightlessly above the old building. Without early collaboration between the architects and engineers, it would be safe to assume that the current design would not have been developed, as it is the result of a ‘wholly integrated design solution’.

The benefits of early collaboration are abundantly evident. Many of the remarkable, ambitious, and groundbreaking structures in the world today are the result of architect and engineer teams. Henry Petroski, the Aleksandar S. Vesic Professor of Civil Engineering at Duke University and licensed Professional Engineer, researches the interrelationship between success and failure in design. On the Walt Disney Concert Hall (see Figure 68), he comments that

“Frank Gehry’s complex design might never have risen off the drawing board were it not for engineers and technical professionals working in collaboration with the architect… The Disney Concert Hall’s art and architecture may be more apparent than its science and engineering, but the building relies on both to succeed.”

Going along with the argument that collaboration pushes innovation, Petroski states

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“Architects and engineers with strong creative capacities working together can change the look of things and change the way we look at things. The collaborative architect-engineer team of Bruce Graham and Fazlur Kahn, which gave Chicago the John Hancock and Sears towers, epitomized this” adding further that “Artful structural expression that does not rest on firm technological foundations can be a disaster.”


The Salford Meadows Bridge is an ambitious design, just as many of the projects described above are. The difference is that the success of these projects depended on the collaboration between the architects and engineers from conception to completion. The bridge is a whole, one entity; thus the process of design should be holistic wherein the engineers and architects work together to create a single product. Rather than treating the engineering as a requirement of the process, integrating engineering into the process by treating it as equal to the architecture (which it is, because structural engineering principles influences the design and form) creates opportunities for the realization of ambitious and innovative design ideas. The issues arising from the design of the bridge and the disconnect between the engineers’ and
architects’ work would be nonexistent if the design was approached as a wholly integrative process.

In this case, the role of the structural engineer is that equal to the architect’s, one of a creator and artist. Without the engineering, the design will never be realized as the engineers are the ones who make it happen. As renowned architectural educator, Mario Salvadori famously once noted “There can be structure without architecture, but no architecture without structure.”

It is an engineer’s duty to assure the structural integrity of a design for the safety of the public. There should be an active discussion between the architects and engineers that acts as a positive feedback loop, constantly improving the design architecturally and technically till optimization. Hans Schober, a lead engineer for Schlaich Bergermann und Partner (a leading German engineering firm that practices expert collaboration with many prominent architects), states that

“When we work together, it is often the case that the architect has different ideas about the structure than those of the engineer, and it stimulates the engineer to innovate. In turn, when the architect takes input and learns from the collaboration about good structural ideas, the architect is also stimulated by the engineer. If you don’t exploit this potential, you miss a lot of new ideas and opportunities…it is very important that both disciplines work together from the very beginning.”

Neither the architects nor the engineers are wrong or are to blame for the problems arising with the proposed bridge design. The current design competition process lends itself to the production of designs focused on aesthetics in order to win. As mentioned previously, there is little incentive to spend the time and money in order to complete complex technical analysis for a design that is not guaranteed to win the competition. With the current process, the engineers and architects did what was sensible and economical to win the competition. The technical problems that arise from the Salford Meadows bridge design are a result of this contemporary

design competition process. By upgrading to a collaborative design process, there will be less problems to resolve with the proposed design. Not only that, the proposed design that wins will be the structure that is realized as inherent technical validity assures a buildable structure. Although there may be higher initial costs and time spent on technical analysis, the money and time saved from avoiding the design and construction issues that can occur down the road as discussed throughout this project are worth practicing collaboration from the very beginning of the design competition process. As Ove Arup, founding engineer of the ARUP firm, said

“Great architecture can be created from a tortuous structure or at an inordinate cost, but it would be greater still if structural clarity and ease of construction could be added to its virtues.”

and that

“In our work as structural engineers we had—and have—to satisfy the criteria for a sound, lasting, and economical structure. We add to that claim that it should be pleasing aesthetically, for without that quality it doesn’t really give satisfaction to us or to others.”

With a collaborative process, the design of the Salford Meadows Bridge may have been formally different, but no less ambitious or innovative. When it comes to design competitions, the traditional approach has proven to lead to designs that are not structurally viable and have to be redesigned or designs that are not easily constructible, both of which impose costs on society and politics and take time to resolve. Thus, the approach to design for design competitions needs an upgrade. By that, the role of the structural engineer is at the table in the conceptual design conversations with the architects, not after the major formal and design decisions have already been made.

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It seems reasonable to assume that contemporary practices of the design process would be further advanced now than it was in ancient times as in Ancient Rome. However, current design practices seem to have taken two steps backwards instead of forwards. Christian Menn, revered bridge engineer and designer, takes note of and criticizes this regression in design. Menn believes in a design philosophy (inspired by fellow Swiss bridge engineer Robert Maillart who is discussed later) where aesthetics grounded in technical principles drive the design. Having designed some of the world’s most iconic and innovative bridges like the Zakim Bridge in Boston, MA.(see Figure 69) and the Ganter Bridge in Switzerland (see Figure 70), Menn’s words on design are worth heeding.

As he argues in the Felix Candela lectures, the fundamental objectives of the art of building have been disintegrated by a separation of duties. The once optimal synthesis between functionality, aesthetics, safety, and economy, has separated into the goals of the architect, the goals of the structural engineer, and the goals of other experts such as policy makers, planners and developers, real estate, and mechanical engineers.

“However, in ancient times, as in the Middle Ages, the engineer was generally not a specialist. He worked with the architect and often with the craftsman, and was likened to a master builder. But it was always the engineer in his capacity as master builder who made possible the success of the architect and the craftsman, not the other way around. The Roman architect, engineer, and writer Vitruvius, in his Ten Books of Architecture, stated that structural safety was the most important goal of architecture.”

“First of all, natural science is only one pillar of our profession...Like architecture, but perhaps to a lesser extent, structural engineering requires practical experience, innovative ideas, imagination, fantasy, and art. This is the second pillar of our profession, which is important and has nothing to do with analytical investigations, although in structural engineering, creativity and art cannot be separated from natural science and must build on knowledge gained through scientific research.”

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“The present tendency toward banal bridge engineering, even in prestigious projects, has led to the placing of architects, often so-called star architects, above bridge engineers. These architects, who consider bridge design only as a hobby or market slot, are convinced that they can design bridges even though they have no structural knowledge. Certainly authorities, the public, and, unfortunately, even engineers themselves believe that. Today there are those who submit bridge designs by picture book. Such proposals are sometimes judged by an incompetent jury, and awards are granted despite the fact that structural principles or costs have not been taken into consideration. Such a design procedure would be completely unacceptable in architecture or the fine arts.”

“Today, renowned architects try to achieve a balance between functionality and aesthetics, paying less attention to economic considerations and structural issues. In contrast, engineers regard the satisfaction of structural safety requirements at the least possible cost as the most important sign of quality, and they view any functional deficiency as a failure. They leave all problems of careful shaping to “others,” like architects, politicians, interest groups, etc. This dissimilar perception of the fundamental objectives of the art of building led to an unpleasant estrangement and polarization between architects and engineers.”

- Christian Menn, Felix Candela Lectures

Architecture has elevated to the superior practice that receives the prestige and acclamation. While architects create the idea, it is the structural engineer that turns the idea into a physical reality. The two disciplines go hand in hand. As Vitruvius (Roman author of arguably the most influential founding texts of the discipline, was architect, civil engineer, and military engineer in the first century) stated, “structural safety was the most important goal of architecture.” However, current design practices disconnect the two. The architect primarily focuses on functionality and aesthetics while the engineer focuses on structural safety and economy. As Menn argues, while seemingly on opposite sides of the spectrum, these objectives are dependent on each other. A design may be functional and beautiful but if it is not structurally safe or economical, it will not be realized. A design that is safe and economical, but

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24 Ibid.
25 Ibid.
not functional or aesthetically pleasing, provides satisfaction to no one as Ove Arup had said. The Salford Meadows Bridge as proposed is aesthetically pleasing, but as the analysis has shown, it is not structurally viable. Therefore, the proposed bridge design will never be built and realized until the design is adjusted and achieves both objectives.

Many magnificent works of ancient times are the result of the integration between engineer and architect. Taking the Duomo in Florence for example, wherein Brunelleschi was the architect and engineer (Figure 71), the Pantheon, possible due to engineering yet regarded for its architecture (Figure 72), and the Pont du Gard, where engineering principles drove the design (Figure 73). As reflected in *Collaborations in Architecture and Engineering*,

> “Ever since the Industrial Revolution, the proliferation of specializations required to realize a work of architecture, has continued apace with an expansion of disciplinary knowledge, capabilities, and tactics. There are good reasons for this, of course: modern society requires new, widely diverse programs and building types, and an ever more complex range of technologies are available for the design, construction and maintenance of buildings. But it is worth reminding ourselves that as the professions of the architect and engineer diverged, they also became more reliant on one another for their disciplinary expertise while working towards common goals in the form of safe, habitable, beautiful buildings.”

Increasing specialization and considerations in modern structures has separated the once combined role of designer and engineer into the goals of several professions. These goals however, are dependent on one another. One must think that only good things can result from these professions working together towards completion of a single product. As the great architectural historian and critic Viollet-le-Duc stated,

> “A little reflection will show us the interests of the two professions will be saved by their union...Whether the engineer acquires a little of our knowledge and love for artistic form...or whether the architect enters upon the scientific studies and adopts the practical methods of the engineer; whether both thus succeed in uniting their faculties, knowledge,

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and appliances, and thereby realize an art truly characteristic of our times, the result cannot fail to be advantageous to the public and creditable to the age.”

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As Menn states, structural engineering is built on two pillars: natural science AND creativity. Structural engineering is not restricted to just natural science as current education and training fails to emphasize\(^{29}\). Renowned engineer, Robert Maillart, proved with his works that creative and innovative thought as an engineer is possible, but it must build on or derive from the technical and mathematical. His Salginatobel Bridge is a prime example (Figure 11). The beauty of the bridge arises out of the new form derived from technical principles and material properties.

Robert Maillart designed forms based on three major design ideals: efficiency, economy, and elegance. He achieved efficiency by designing forms that used as little material as required with a large factor of safety, resulting in light and thin structures connected by integration of

form. The Salginatobel bridge uses 35% of the material needed in a solid arch. In achieving efficiency, he also achieved economy. The less material used, the lower the cost. He also achieved economy through integration of the building process in design considerations. The arch would be cast over wooden scaffolding first and once set, the arch could carry the rest of the structure without need for support. Elegance comes from the “maximum personal expression of the designer’s vision consistent with efficiency and economy.” Maillart achieved elegance through a close relationship between the technical and the visual. His creative and unique vision were expressed in conscious design choices dealing with efficiency and economy. His works are an expression of a single design personality that evolves over time. He modifies design and adapts styles out of an understanding of the engineering science behind it, aiming to satisfy the three design ideals of efficiency, economy, and elegance. As David Billington states, “Maillart’s concept arose out of the sum of his past experience and thought. But our analysis of his technique shows that his concept was highly disciplined by technical principles. He did not achieve beauty by avoiding, hiding, or denying technique.”

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33 Ibid.

David Billington and Christian Menn set out to prove that engineers have the freedom to incorporate personal style and creativity in engineering design without compromising the design ideals of economy and efficiency. Aesthetics are not something that strictly applies to architects. Many innovations in structures are derived from the imagination of the engineer, such as the works of Robert Maillart and Felix Candela (see Figure 74 for an example of Candela’s work on innovative shell structures).

![L’Oceanogràfic Building](http://architizer.com/blog/luis-barrahan-mexican-modernists/)

**Figure 70:** L’Oceanogràfic Building, engineered and designed by Felix Candela.

It was their imagination in design consistent with the ideals of efficiency and economy that allowed them to move forward to new forms with new materials. There is a belief that “only the architect can make them (structures) into art”, and that engineering is governed solely by efficiency and economy.\(^\text{35}\) However, engineering design does have room for creativity, but this creativity is derived from the discipline. Elegance is derived from engineering principles. The result: “structural art grounded in the understanding of engineering science.”\(^\text{36}\) Although the design competition for the Salford Meadows Bridge encouraged collaboration between architects

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\(^{36}\) Ibid.
and engineers and required engineering input (however only to assure satisfaction of the design
code), the innovative forms proposed were not grounded in technical validity from the design
conception. As Ove Arup stated, “Designing is not a science, it is an art—but an art confined by
the nature of its medium and the aims to be achieved.”37

Implementing these ideas into the current design process requires the two parties to be
open to collaboration. This however should not start in firms, but rather in the education of
engineers and architects. As Menn argued, the current education system for architecture and
engineering is why the objectives of each are separated into the creative and the technical
respectively. Building an atmosphere for collaboration early on, where the students learn about
and build a mutual respect for and understanding of each other’s professions before going into
practice will vastly improve the design process and the resulting structures. Ove Arup also
criticizes the current system stating that

“This division has done a great deal of harm, because it has diverted attention from the
fact that all structures must be submitted to the threefold discipline of functional,
aesthetic, and structural or technological organization.”38

Sinéad Mac Namara, Associate Professor of Civil Engineering and Architecture at
Syracuse University, and Clare Olsen, practicing architect and Assistant Professor of
Architecture at Cal Poly San Luis Obispo, write in their book on collaboration between the two
professions that

“Engineering curricula don’t often provide many opportunities for open-ended design
despite the fact that the real world is full of these sorts of problems. By the same token,
architecture curricula require varying amounts of technical course work, but through
interdisciplinary collaborations, students benefit greatly from conceptualizing projects
with a higher level of technical proficiency. These synergies enhance both architecture

37 Arup, Ove. *Architects, Engineers, Builders.* The Alfred Bossom Lecture to the Royal Society of the Arts, London,
March 11, 1970.
38 Ibid.
and engineering programs by enabling students to design innovative projects with real-world possibility”\textsuperscript{39}.

As can be seen, collaboration between architects and engineers has long been argued by some of the most successful professionals in the fields. If these individuals and firms are successfully designing the world’s most groundbreaking, innovative, and magnificent structures because they practice collaboration, then there is a lesson to be learned here by those who are already in practice and those in education and academia.

Chapter 8
The Last Word: A Reflection

What this capstone aimed to do was not critique the architects or the engineers of the Salford Meadows Bridge, but rather critique the process of design. What the structural analysis of the bridge exemplifies is the lack of technical, specifically structural, consideration in the design of the bridge. The disconnect between the engineer’s and architect’s work displays the lack of early collaboration in the communication and expression of architectural desires and structural needs between the two. Such collaboration though is not required by the design competition process; no one can blame the architects and engineers for not doing what would be considerable additional labor, if it would not help them win the competition. In a design competition, where the proposed design is what is expected by the judges, government, and public, the consequences of this disconnect and lack of early collaboration between the architects and the engineers can be significant as was the case for the Sydney Opera House. In order to address the issues with the contemporary design competition process, perhaps changes to the regulations to include technical and engineering validity in design or more stringent budgeting for construction should be required. As a matter of civic duty, more engineers should serve on the judging committees and be vocal in the public debate about design and planning. There is a process that works better than the one that modern education and increasing specialization champions. As has been exemplified by many of the world’s leading design firms, collaboration leads to innovative design solutions that work.

Throughout this capstone, I have learned a great deal about the interconnectedness between architecture, engineering, and design, as well as the consequences of design decisions on construction, society, economics, and politics. On this journey, I have gained skills in drawing
and analysis software programs, developed better engineering judgment and technical understanding, and expanded my view of what an engineer’s design ideals are. My original college goal was to major in architecture in order to create things that would inspire people, but I switched to engineering due to my mathematical interests. I still retain an interest in architecture and its history, but my passion for turning ideas into physical realities is possible through structural engineering. I did have doubts throughout college about whether I made the right decision and whether I should have been an architect, but due to what I have discovered through this capstone, I am certain I have made the right choice. One of my reservations about engineering was that I would not have the freedom to be as creative in design, that I would get bored of designing the same types of structures over and over again. However, after learning the history of engineering, the design principles of creative and technical integration, and the practice of collaboration from engineers and architects whose work I look up to, I know that I will be happy working as an engineer. That is, working at a firm that practices collaboration, where I can be creative and be challenged to innovate working alongside the architects in design. Not by working at a firm where the architects get to be creative in design and I just have to analyze their work to make sure it stands up.

I am thankful to have gained this sense of certainty and exposure in the field I intend to work in. The journey of completing this capstone has certainly been transformative. Getting started and figuring out what I wanted to do my capstone on was a challenge. At first, I planned to do a structural design of a building that was already designed and planning to be constructed. However, I was unhappy with that kind of stereotypical engineering project. Then in the spring of my junior year, I took the honors class HNR 360: Structures and Innovation with Professor Mac Namara. I asked her for advice on my capstone and shared my interests with her; she talked
about her interests and her book on *Collaborations in Architecture and Engineering*, which epitomized my interests in architecture, engineering, and creative design. I became very excited about the possible projects I could do in this topic with her as my advisor and decided to drop the project I had planned. I am very grateful Professor Mac Namara agreed to be my advisor and even more grateful for the mentorship she has provided me along this journey.

Overall, I could not be more proud of this capstone and the experiences I have gained from it. I am now confident in my aptitude to continue my education in structural engineering and am enthusiastic about working in design consulting in the future. The lessons I have learned will always stay with me and I am more than eager for the opportunities to share and talk about my research with professionals in the field.
Works Cited


Appendix
