Integrating Secondary Goals into Structural Design

1. Design for Multiple Objectives

If managed appropriately, a second significant design requirement can be turned into an opportunity. In the design of structures, the tenets of efficiency and economy are widely pursued goals. A number of talented designers have pushed beyond these basic requirements to achieve structures that are visually elegant as well. Many historically celebrated precedents are clear, sound responses to a particular condition—a column-cantilever following the moment diagram of a wind load, a funicular truss with appropriately sized sections, or a concrete shell shape determined by form finding. When additional design requirements are added to the process, however, the solutions cannot be as straightforward, since designers may need to manage tradeoffs between competing design goals while arriving at a geometry and form that satisfy a variety of conditions.

The design of modern buildings and other structures demands the ability to synthesize multiple design goals simultaneously. This is largely true because of an increased emphasis on overall performance and design sustainability, of which structural material efficiency is only one consideration. Modern computational methods have been developed to aid the effort of effectively managing different design goals, especially in the case where multiple design goals can be quantified, simulated, and measured. Yet, though computers can be helpful in rationalizing geometry and completing performance analyses, they cannot yet generate diverse typological possibilities, prioritize different design goals, or evaluate the aesthetic expression of a structure without input. There is still no substitute for human creativity, intuition, and experience in design.

Numerous historical examples exist of structural designs that clearly derive their form from the careful consideration of multiple, simultaneous goals. Early instances include churches that rose to soaring heights and enclosed volumes with heavy stone, yet managed to allow for interiors washed with daylight. Other examples show how designers were able to attain free structural spans for large buildings while also achieving occupant comfort through the use of thermal mass and passive heating, cooling, and ventilation strategies. Recently, structural designs that pursue multiple goals include skyscrapers shaped to collect wind power or employ extensive shading systems, long-span stadiums on the leading edge of energy efficient design, and concert halls that make compelling structural gestures while also performing well acoustically. There is significant value for an aspiring structural designer in studying these precedents for inspiration.

2. The National Portrait Gallery Courtyard – Integration of Compatible Design Goals

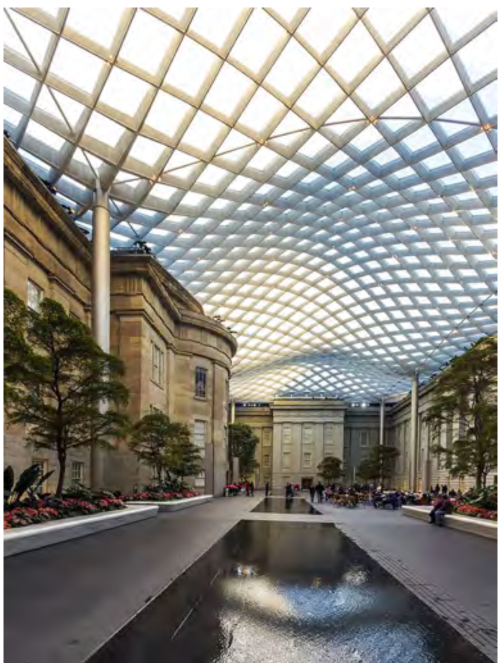

Figure 1: National Portrait Gallery Roof[1]

One example of the expert synthesis of multiple design objectives is given in the undulating, diagrid steel roof built to enclose a historical courtyard at the National Portrait Gallery in Washington, D.C[1]. Designed by Foster + Partners with Buro Happold, the structure has been widely praised for respecting its historical context while providing a visually elegant solution that creates a hushed, serene interior[2]. While considerations of structural efficiency and performance are clear drivers of the form, daylighting and acoustics also play a significant role in the success of the structure. For example, the structural member sizes that make up the grid are varied to give stiffness where it is necessary, but at the same time modulate the amount of daylighting in the space and add complex visual effects. The shape and section

[1] http://www.fosterandpartners.com/projects/smithsonian-institution/

[2] Fortmeyer, Russell. "Foster + Partners shroud a courtyard with a quiet, ethereal glass canopy for two museums at the Smithsonian Institution". *Architectural Record*, March 2008: 99-103.

properties of the structure also allow for the clean integration of sound absorbent material, which creates an acoustical effect that is normally impossible for spaces with walls made of marble and sandstone. Other design decisions reflect the management of multiple design goals, such as the upturned roof edges to direct rainwater towards drains embedded in the columns, but the ability to achieve structural efficiency, economy, and elegance while also considering non-structural aspects of the roof's performance leads to a satisfying design solution.

3. Montreal Olympic Stadium – A Discussion on Managing Tradeoffs in Design

While sometimes a single design decision can satisfy multiple requirements, it is often the case that design goals trade off directly. For example, structural efficiency and economy are often measured by quantifying the amount of structural material present in a design, and good structural designers find creative, elegant ways to minimize volumes of steel or concrete. However, in certain cases it may be advantageous to use more structural material than absolutely necessary in order to shape a building in a way that reduces heating and cooling loads. The potential tradeoff is demonstrated by a spirited debate about the Montreal Olympic Stadium between the engineer Anton Tedesko and architect-engineer Frank Moffet in a 1976 issue of *Civil Engineering*, the journal of the American Society of Civil Engineers[3]. Tedesko, with support in later letters from David Billington, argued that the architecturally arbitrary form of subtly sloped cantilevers required massive section sizes and wasted material, while Moffet commented that the lower arch slope results in smaller building volume and surface area, leading to operational energy savings[4]. Although the argument was never resolved, it highlights how contemporary architecture has raised the bar for economy, efficiency, and elegance—a modern structural designer must be able to effectively engage with these complex design considerations and manage tradeoffs with structure in order to be successful.

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[3] A. Tedesko. "Experts Slam the Olympic Structures of Montreal", *Civ. Eng. - ASCE*, December, pp. 50–54, 1976.
[4] Sommerschield, H. F. et al. "Letters: Montreal Olympic Structures", Civ. Eng. – ASCE, 47: 5-36, 1977.

Figure 2: Exterior of the Montreal Olympic Stadium

4. Conclusion

These examples show how synthesizing additional design objectives into the structural design process can lead to successful, visually compelling designs, while also demonstrating the emergence of increased multi-objective thinking in the field. If awarded the SOM fellowship, I would visit a number of structures that effectively balance or manage multiple design goals to arrive at aesthetically interesting solutions. These examples would traverse different time periods and locations, including historical masonry structures up through contemporary examples. The emphasis would be on towers, civic architecture, long-span roofs, and other structures at large enough scale to make significant aesthetic gestures and require careful consideration of overall form. While travelling, I would also make an effort to engage with design offices related to these buildings to learn more about their processes for synthesis and integrated design. I am grateful for the opportunity to be considered for this nomination, as the fellowship would be immensely valuable to my development as a structural designer.

Proposed Travel Itinerary

The structures in this proposed travel itinerary were selected because they are structurally significant and visually elegant, but also exhibit a clear design response to at least one additional objective besides structural efficiency. Although arranged geographically to illustrate how the trips will be planned, each of the structures fits primarily into one of five categories. These categories sometimes overlap, and certain structures fit easily into multiple categories, but this labeling system was created to highlight important and often dominant goals that interact with structure in the design process.

1. Structure + Energy (7)
These structures are notable for their emphasis on energy efficient operation and occupant comfort. Secondary design elements in this category include the use of thermal mass, passive heating and cooling, solar control, double facades, and others.

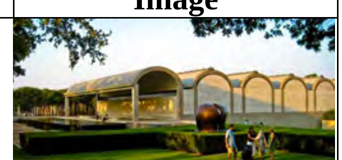
2. Structure + Daylight (8)
Structures in this category effectively integrate thoughtful shading elements and daylight management into the building form and structural system.

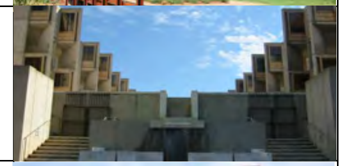
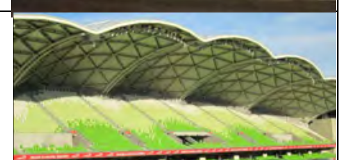
3. Structure + Site (9)
The designers of these structures responded to a significant geometric site constraint, such as spanning over railroad tracks or fitting between neighboring buildings and terrain, or found a creative way to manage wind, rain, and other elements.

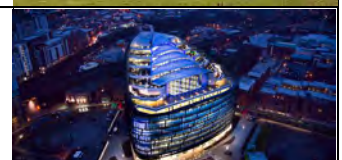
4. Structure + Acoustics (5)
These structures use a combination of shape and material integration to achieve particular acoustic effects.

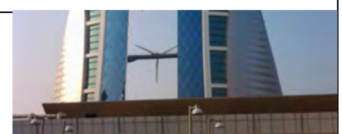
5. Structure + Low Carbon (8)
Although strongly related to the Energy and Daylighting categories, the designers of these buildings have employed innovative materials, construction processes, or building geometries to minimize the total lifecycle emissions of a building.

Office Visits
In addition to visiting the structures themselves, attempts will be made to arrange office visits with a number of the designers, as possible. Structural design that takes other architectural and performance goals into account is currently being pursued through a combination of computational tools, close collaboration between architects and engineers, and the design intuition of leading practitioners. Many firms were involved with multiple projects given in the itinerary, and could provide valuable insight into the integrated structural design process. Firms that would be contacted to request meetings include SOM, Foster + Partners, Buro Happold, ARUP, and other leaders in the field.

Leg 1: North America			
Structure	**Info**	**Reason**	**Image**
Kimbell Art Museum Arch | Louis Khan Eng | August Komendant	Fort Worth, TX 1972 Structure + Daylight	Barrel vaults help diffuse and distribute light	
National Portrait Gallery Courtyard Arch | Foster + Partners Eng | Buro Happold	Washington, DC 2007 Structure + Daylight Structure + Acoustics	Manages daylighting with member sizing; uses grid to support acoustic material	

John Deere Headquarters Arch | Eero Saarinen	Moline, IL 1964 Structure + Daylighting	Structural system becomes shading system	
Salk Institute Arch | Louis Khan Eng | August Komendant	La Jolla, CA 1963 Structure + Energy	Spanning Vierendeel frames leave space for mechanical vents; views & solar gain are balanced	
Seattle Museum of Flight Arch | Ibsen Nelson	Seattle, WA 2004 Structure + Daylight	Free clear span for displaying aircraft with integrated shading system on exterior	
Hypar Concrete Shells (Los Manantiales, Milagrosa, Cuernavaca…) Arch / Eng | Felix Candela	Mexico City, Mexico 1950-60s Structure + Low Carbon	Doubly-curved forms and reusable formwork allow for extreme material efficiency	
Leg 2: Australia and New Zealand			
Campus Reception Building, AUT Akoranga Arch | JASMAX Eng | Gandy and Roberts	Auckland, New Zealand 2001 Structure + Energy	Employs natural ventilation, thermal mass, & efficient shading strategies	
Melbourne Rectangular Stadium Arch | Cox Architects Eng | ARUP	Melbourne, Australia 2010 Structure + Low Carbon	Geodesic design reduces structure; façade mixes translucent panels with opaque insulated panels	
Magney House Arch | Glen Murcut	Bingie, Australia 1984 Structure + Site	Curved roof balances shade and sun, sheds rain while collecting water, directs breezes	
60 Leicester Street Arch | Spowers Architects Eng | AEC	Melbourne, Australia 2002 Structure + Energy	Design uses a thermal chimney to reduce operational energy	
40 Albert Road Arch | SJB Architects Eng | Connell Mott MacDonald	Melbourne, Australia 2005 Structure + Low Carbon	Building retrofit designed to achieve net-zero operation	
Leg 3: England and France			
Gothic Cathedrals (Chartres, Amiens, Reims, Bourges, Notre Dame)	Paris, France 1100-1300s Structure + Daylight	Use flying buttresses and large windows to achieve height, structural stability, and interior daylight	
Broadgate Exchange House Arch/Eng | SOM	London, UK 1990 Structure + Site	Spans a rail yard; bridge/building hybrid	

Schlumberger Test Center Arch | Hopkins Architects	Cambridge, UK 1985 Structure + Site	Free, unobstructed movement of the crane; translucent roof for views	
Sainsbury Centre Norwich Arch | Foster + Partners Eng | Anthony Hunt and Associates	East Anglica, UK 1978 Structure + Daylight	Integrated structure, envelope, and louvers for managing daylight	
One Angel Square Arch | 3DReid Eng | Buro Happold	Manchester, UK 2013 Structure + Energy Structure + Low Carbon	Uses thermal mass, daylighting, and double facades to achieve high BREEAM rating	
Stansted International Airport Arch | Foster + Partners Eng | Peter Rice	Stansted, UK 1991 Structure + Low Carbon	Lightweight roof, mechanical equipment in the undercroft frees roof for natural daylighting	
Great Glasshouse Arch | Foster + Partners Eng | Anthony Hunt and Associates	Carmarthenshire, UK 2000 Structure + Low Carbon	Lightweight structure collects rainwater and warms greenhouse with passive solar heating	
Wembly Stadium Arch | HOK/Foster Eng | Mott Stadium Consortium	London, UK 2007 Structure + Acoustics	Designers tuned acoustics to match game day atmosphere of older, historic stadium	
Leg 4: Central Europe			
Cologne Cathedral	Cologne, Germany 1200-1400s Structure + Daylight	Uses flying buttresses and large windows to achieve height, structural stability, and interior daylight	
Munich Olympic Stadium Arch\Eng | Frei Otto Günther Behnisch	Munich, Germany 1972 Structure + Site Structure + Acoustics	Structure is solar, aerodynamic, hydrologic, luminous, and acoustic form	
Tamedia Office Building Arch | Shigeru Ban Eng | Creation Holz GmbH	Bern, Switzerland 2013 Structure + Low Carbon	Innovative use of wood structure at office building scale	
Maillart Bridges (Salginatobel, Schwandbach) Arch/Eng | Robert Maillart	Switzerland 1930/33 Structure + Site	Geometrically manages different load cases; integrating curve with deck-stiffened arch	
Berliner Philharmonie Concert Hall Arch | Hans Scharoun	Berlin, Germany 1963 Structure + Acoustics	Pioneered a new acoustic form (vineyard style) that became frequently employed in the design of concert halls	

Linz Design Center Arch | Thomas Herzog Eng | Klaus Daniels	Linz, Austria 1994 Structure + Energy	Grid is oriented for daylighting; natural ventilation scheme is meshed with aerodynamics of the envelope	
Leg 5: Japan			
Tokyo Internat. Forum Arch | Rafael Viñoly Eng | Structural Design Group	Tokyo, Japan 1996 Structure + Site	Footprint follows train tracks that mark the edge of the building site	
Kansai International Airport Arch | Renzo Piano Eng | Arup	Osaka, Japan 1990s Structure + Energy	Truss profile driven by interior aerodynamics, using the underside of the ceiling as an open air duct	
Yoyogi National Gymnasium Arch | Kenzo Tange	Tokyo, Japan 1964 Structure + Acoustics	Curved shape of the suspension roof improves acoustic performance of space	
Yusuhara Wooden Bridge Museum Arch | Kengo Kuma Eng | Katsuo Nakata	Yushuhara, Japan 2011 Structure + Low Carbon	Contains innovative structural uses of wood, a low-carbon material	
Leg 6: Middle East			
World Trade Center Towers Arch / Eng | Atkins	Bahrain 2008 Structure + Site	Building shape guides wind towards integrated turbines	
Abu Dhabi Central Market Arch | Foster + Partners Eng | Halvorson & Partners	Abu Dhabi, UAE 2014 Structure + Daylight	Sliding panels seasonally adjust air and sunlight; solar façade derived from regional vernacular	
Cayan Tower Arch / Eng | SOM	Dubai, UAE 2013 Structure + Site	Wind load and solar gains are reduced compared to a rectilinear building of the same height	
Burj Khalifa Arch / Eng | SOM	Dubai, UAE 2009 Structure + Site	Shape sheds wind around structure and prevents the creation of vortices	

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