Aesthetics and Physical Models

Physical models have vast potential as visual, analytical and design tools for the study and creation of aesthetically pleasing, technically challenging, efficient structures. Heinz Isler's hanging membranes, Frei Otto's soap bubbles, and Antonio Gaudí's funicular strings are all inspiring and have influenced striking structures, but it is not immediately obvious which form-finding exercises produce structurally rational works. Receiving the SOM Fellowship will allow me to study visually interesting works in Europe and the model laboratories and testing facilities from which a number of these structures emerged. I hope to use this travel to generate a catalogue of structures and the design processes that preceded them, in order to understand what form-finding techniques lead to structurally rational, aesthetically pleasing works and to observe the methodologies and complexities involved with physical experimentation. This documentation will further my study of structural art (defined here as works that are efficient, economic to construct, and elegant)[1] and inform my own future designs and contributions to the field of structural engineering.

Personal Motivation for Model Making

My undergraduate studies emphasized a two-dimensional approach to the design and analysis of structures. When posed with a design problem, the solution for a bridge was simple piers and girders and for a building a regular grid of beams and columns. While the education that I received was rigorous and provided me with valuable insight into fundamental structural behavior and the design of a particular set of members, it did not necessarily inspire creativity or elicit thinking about globally efficient forms. Rarely in my classes did we look at physical models or pictures of actual structures. I entered the field of structural engineering interested in beautiful buildings and bridges, but grew accustomed to a very conventional approach to design.

My current graduate studies are in stark contrast, as the emphasis is on studying the works of innovative, aesthetically sensitive engineers and creating conceptual designs of globally efficient forms. I

[1] This is the definition presented in David P. Billington's *The Tower and the Bridge* (Princeton: Princeton University Press, 1983), p.6.

have performed case-studies of thin concrete shells and prestressed bridges and had the opportunity to make designs for network tied arch, cable-stayed, and stress ribbon bridges, as well as a glass roof supported on a series of criss-crossing arches. I have been liberated from thinking about structures as two-dimensional objects. However, these more visually interesting structures tend to necessitate more complicated analyses and an over reliance on computer modeling. While the computer is an invaluable tool, it can compromise the development of one's physical intuition of how structures behave. After graduation, I plan on working as a design engineer and I hope to have the opportunity to design, analyze, and study physical models as a means of generating more adventurous forms and better understanding the behavior of full-scale structures.

Discipline and Play[2]

Discipline as it pertains to structural design is the understanding of structural behavior and economic and material constraints, whereas play represents an exploration of form. For elegant forms to be efficient and economical to build, discipline should accompany play. While models serve as a visual representation of the final structure they can also be used in form-finding and analysis and are an ideal way to develop structural solutions through a balance of discipline and play. The Swiss engineer, Heinz Isler engages in a design process that exemplifies this balance; his process involves generating a series of models from which the form of the full-scale structure follows. In addition, Isler views completed works as opportunities to reflect on the process of design as well as a means of checking that the predicted results are reasonably achieved. Isler states that form-finding is only "'the first link in a whole chain of investigations; the other links are [small-scale] model tests and measuring the first structure, i.e., model tests at full scale as we have it out there; these are of primary importance.'"[3] Isler's process is tied to a physical understanding of behavior, and the *Sicli Company Building* in Geneva, a free form shell with seven supports, clearly demonstrates his methodology. To develop the complex form for *Sicli*, Isler created a series of hanging models, small-scale experimental models from which he could examine shell

[2] Concept presented by Billington in *The Tower in the Bridge*, p. 213 to 232
[3] Ibid, p. 224

stresses and buckling capacity, and an architectural site model. Figures 1 to 3 exhibit models of each type.

Figure 1: *Hanging form*[4]

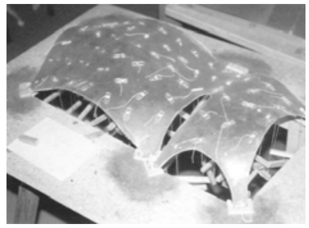

Figure 2: Sicli small-scale model[5]

Figure 3: Sicli site model[6]

Concerns about long-term behavior led Isler to monitor the deflections of *Sicli* for almost twenty years after its completion.[7] Performance of the completed structure (Figure 4), not the complexity of the analysis, dictates a structure's success. Isler, like other great structural artists relied on physical intuition gained from first-hand, observation.

Figure 4: Aerial View of the Sicli Factory[8]

Research Plan

The most successful works of structural art often involve innovative design processes. My research seeks to explore the design processes underlying the structures that I visit, and not just the completed works. Specifically, I plan to visit model laboratories in Spain, Switzerland, and Germany; wind tunnels in Denmark, Norway, and England; and buildings, bridges, and roof coverings in those six countries that have emerged from these facilities. I will therefore study completed works with regards to the following:

1. **Design process**: I will evaluate the role that form-finding, physical experimentation, and computer analyses played in the development of each design and note how the final structure reflects these different techniques.

[4] Figure 1 is from David P. Billington's *The Art of Structural Design: A Swiss Legacy (*Princeton: Princeton University Art Museum, 2003), p.146.
[5] Figures 2 and 3 are from John Chilton's *The Engineer's Contribution to Contemporary Architecture: Heinz Isler (*London: Thomas Telford Publishing, 2000), p. 99.
[6] Ibid, p. 96
[7] Ibid, p. 99
[8] Ibid, p.97

2. **Aesthetic impact**: At the small-scale one can observe the interplay of rational structural forms and aesthetics. However, only at the full-scale can one truly appreciate the designer's considerations of forces, proportioning, and site. Through these observations I will assess how a structure's form adheres to the ideals of discipline and play. This will include an evaluation of the differences in the visual impact of the small-scale and full-scale structures and the extent to which the small-scale model is able to convey the aesthetic vision of the full-scale structure.
3. **Long-term durability**: I will evaluate the current condition of each structure and its success at performing its intended purpose. When possible, I will visit structures with the engineer and/or architect responsible for the design and discuss with him/them how the structural behavior compares to results predicted by small-scale testing and has informed the designer's personal process of form generation.

My objective is to study works of structural art and the models from which they were derived. I wish to use this opportunity to improve my physical intuition as I seek to determine what form-finding techniques and analyses produce structurally rational, aesthetically pleasing structures and what new roles models may play in the future. The insights gained will allow me to better collaborate with architects and contractors as I strive in the future to get interesting forms, such as concrete shells, built by means of innovative use of materials and construction techniques. Receiving the SOM fellowship will allow me to pursue my goals and make positive contributions to the field of structural design.

The first component of my research seeks to trace the developments in form-finding that occurred in Spain and carried over and matured in Switzerland where a tradition of graphical design and analysis techniques already existed. Second, I intend to investigate the various lines of form-finding and modeling that have evolved in Germany. Finally, I plan on studying the newest developments in wind tunnel testing occurring in England, Denmark, and Norway. My goal is to study visually interesting works and the models from which these works were derived. I plan on meeting with leading designers while visiting their model laboratories, testing facilities and structures, so that I can develop my own ideas about how physical form-finding and experimentation can be best utilized by designers today.

I intend to first travel to Spain and then to Switzerland, Germany, England, Denmark, and Norway. Rather than list the structures in the order that I plan on visiting them, I list the individuals or institutes (from here on referred to as the individual) of interest within each country followed by a chronological listing of the works by that individual or institute that I would like to visit. A few notes regarding my itinerary: first, individuals listed in red text are those who if available, I plan on visiting. As of now, I have not contacted any of the individuals on my list. However, I have been in contact with prominent engineers in the United States, who have worked with or personally know a number of the individuals that I have listed and have agreed to help me arrange meetings. Second, many of the works that I attribute to a single individual are products of collaboration between a number of parties. Third, not all of the works listed by an individual have been developed directly from a model. For example, Jörg Schlaich has not created physical models for all of his works. These structures will still allow me to study how models of previous structures have helped inform the individual's process of design and also serve as an interesting comparison to works that have been derived directly from physical models. Lastly, architectural models serve as important visuals during the design process and will be observed whenever possible.

SPAIN (Approximate stay: 1 week)

Antonio Gaudí created models for the purpose of form-finding (funicular strings). Restored versions of his models are on display in the Gaudí Museum at Sagrada Familia.

Casa Vicenes	Barcelona	1888
Palau Güell	Barcelona	1889
Güell Cellars	Barcelona	1897
Casa Calvet	Barcelona	1904
Casa Batlló	Barcelona	1906

Casa Bellesguard	Barcelona	1909
The School Roof next to Sagrada Familia	Barcelona	1909
Park Güell	Barcelona	1914
Còlonia Güell	Barcelona	1916
Sagrada Família	Barcelona	1926*

*Gaudi worked on this structure until his death in 1926. It is scheduled to be complete in 2026

Eduardo Torroja established model laboratories (including one at the **Instituto Téchnico de la Construcción**) across Spain and performed small-scale model testing.

Market Hall	Algeciras	1934
The Zarzuela Hippodrome Roof	Madrid	1935

Frontón Recoletos	Madrid	1935
Instituto Técnico de la Construcción	Madrid	Various

SWITZERLAND (Approximate stay: 3 weeks)

Robert Maillart utilized graphic statics and full-scale testing.*

Stauffacher Bridge	Zurich	1899
Magazzini Generali	Chiasso	1924
Valtschielbach Bridge	Donath	1925
Salginatobel Bridge	Schiers	1930
Landquart River Bridge	Klosters	1930

Spital Bridge	Adelboden	1931
Schwandbach Bridge	Hintetfultigen	1933
Töss River Bridge	Wüflngen-Winterthur	1934
Arve River Bridge	Vessy	1936

* While graphic statics is not a three-dimensional modeling technique it is a physical analogy and the predecessor to model-making in Switzerland.

Hans Hauri helped Pierre Lardy set up a model laboratory at ETH in the early 1950s based on observations made at one of Torroja's labs.

Heinz Isler used physical form-finding (pneumatic, flow, and hanging membrane reversed forms) and small-scale testing to inform his designs.

Pneumatic Forms

Eschmann Company Factory	Thun	1958
COOP	Wangen bei Olten	1960

Flow Forms

Kilcher Company	Recherswil	1965
Bürgi Garden Center	Camorino	1971

Other

Wyss Garden Center	Solothurn	1962
Heilig-Geist-Kirche	Lommiswil	1967

Hanging Membrane Reversed Forms

BP Service Station	Deitingen Süd	1968
Sicli Factory	Geneva	1969
Tennis Hall	Düdingen	1978
Tennis Hall	Heimberg	1979
Heimberg Swimming Pool	Heimberg	1979
Brugg Swimming Pool	Aarepark	1981
Bruchl' Sports Centre	Solothurn	1982
Aircraft Museum	Dübendorf	1987

Christian Menn has utilized graphic statics in his bridge design.

Crestawald Bridge	Crestawald	1959
Valserrhein Bridge	Uors	1962
Tamins Bridge	Reichenau	1963
Nanin	Mesocco Valley	1967
Cascella	Mesocco Valley	1968

Felsenau Bridge	Bern	1974
Ganter Bridge	Brig	1980
Chandoline Bridge	Chandoline	1989
Sunniberg Bridge	Klosters	1999

GERMANY (Approximate stay: 3 weeks)

Heinz Isler with Michael Balz: Michael Balz is an architect who has worked with Isler as well as completed his own designs inspired by the work of Isler.

Hanging Membrane Reversed Forms

Ballet Salon	Stetten	1976
Stetten Open-air Theatre	Stetten	1976
Grötzingen Outdoor Theater	Grötzingen	1977

*Isler did not assist Balz with this work.

Pneumatic Form

*Bösiger Office**	Langethal	1998

Frei Otto was the first director of the Institute of Lightweight Structures (ILEK) at the University of Stuttgart and used physical form-finding (soap bubbles, i.e. minimum surfaces) to develop tensile structures.

Dance Pavillion at the Federal Garden Exhibition	Mannheim	1957
Munich Olympic Stadium	Munich	1967
Multipurpose Hall and Restaurant at the Federal Garden Exhibition	Mannheim	1975
Mechtenberg Bridge	Gelsenkirchen	2003
Schwarzbach Bridge	Gelsenkirchen	2003

Werner Sobek is the current director of the ILEK.

BMW Exhibition Facility	Frankfurt	1995
Rhoen Clinicum	Stuttgart	1997
Rothenbaum Stadium	Hamburg	1999

Audi Motorshow Stand	Frankfurt	1999
Sony Center	Berlin	2000
Munich Highlight Towers	Munich	2005

Ekkehardt Ramm is a professor at the University of Stuttgart. His research includes computational form-finding. His work will be contrasted to physical form-finding.

Jörg Schlaich has created kinetic models and performed large-scale model testing.

*Hamburg Swimming Center Hypar Shell**	Hamburg	1967
Europahalle at Karlsruhe	Stuttgart	1984
Neckarsulm Swimming Pool Roof	Stuttgart	1984
Ice Skating Rink Cable Net Roof	Munich	1985

Neckarsulm I & II	Stuttgart	1985
Kelheim	Stuttgart	1987
Museum Courtyard Roof	Hamburg	1989
Railway Station	Ulm	1993

Gottlieb Daimler Stadium	Stuttgart	1993
Kieler Hörn Folding Bridge	Kiel Bay	1997
Bridge within Deutsches Museum	Munich	1998
DZ Bank Building Cable Net Roof	Berlin	1998
Glassroof Bosch-Areal	Stuttgart	2001

Schlüterhof Roof, German Historical Museum	Berlin	2002
Airport Stuttgart Terminal 3	Stuttgart	2004
Olympic Stadium Berlin	Berlin	2004
Berlin Main Station	Berlin	2006
Assorted Pedestrian Bridges	Stuttgart	Various

* Designed by Schlaich while he was working at Leonhardt, Andrä und Partner

DENMARK (Approximate stay: 1 week)

Force Technology performs wind tunnel testing.

COWI has performed wind tunnel testing and structural monitoring.

Farø Bridge	Vordingborg	1984
Storebælt East Bridge	Sprogø	1998

Øresund Bridge	Copenhagen	2000

NORWAY (Approximate stay: 1.5 weeks)

Norwegian University of Science and Technology performs wind tunnel testing.

Per Tveit created small-scale models during his initial work with network-tied arches.

Steinkjer	Steinkjer	1963
Bolstadstraumen	Bolstadstraumen	1963

Åkvik Sound Bridge	Åkvik Sound	2001

**Design by Stephen Teich and Stefan Wendelin. Both completed their Master's theses with Tveit*

AAS Jakobsen A/S has performed wind tunnel testing and full-scale wind monitoring.

Helgeland Bridge	Sandnessjoen	1991
Askøy Bridge	Bergen	1992
*Osterøy Bridge**	Tunes	1997
Raftsundet Bridge	Lofoten	1998

*Bømla**	Bergen	2001
*Storda Bridge**	Hordaland	2001
Sundøy Bridge	Nordland County	2003
Brandanger	Norway	2004

***Haug & Blom-Bakke A/S** performed retrofit and/or check of design

ENGLAND (Approximate stay: 1 week)

RWDI Anemos performs wind tunnel testing of structures.

Ove Arup & Partners has used RWDI's wind tunnel to test some of its recent structures.

Millenium Bridge	London	2000
Swiss Re Headquarters	London	2004

Moorhouse	London	2004
London Bridge Tower	London	2009*

*Expected date of completion, currently under construction

SOM, London has tested buildings in RWDI’s wind tunnel.

201 Bishopsgate and the Broadgate Tower	London	2008*

Pan Peninsula	London	2009*
Crossharbour	London	2010*

*Expected date of completion, currently under construction