The Role of Nature in Structural Art

Aspiring structural engineers are traditionally taught to judge the quality of their work on the practical foundations of efficiency and economy. However, Billington (1983) argues that structural engineers should become ‘structural artists’ by adding an aesthetic component to their assessments. He states, “The belief that the happy engineer, like the noble savage, gives us useful things but only the architect can make them into art is one that ignores the centrality of aesthetics to the structural artist” (Billington, 1983, p. 15).

Billington stresses that efficient and economical structures are not necessarily aesthetically pleasing. Conversely, aesthetically pleasing buildings and bridges may lack efficiency or economic viability. The question explored here is how to integrate aesthetic qualities with the practical requirements of structural engineering, so that structural engineers become structural artists. A significant requisite is an effectual source of inspiration. One promising source is the natural environment. Natural forms are inherently efficient, and functional designs in nature are aesthetically pleasing. In addition, many civil structures inspired from nature are both economical and innovative.

There is also an educational benefit from drawing upon biological models. At Washington University, my fellowship responsibilities include teaching a structural engineering module to middle school students. I have found that my students learn best when I teach engineering concepts through analogies, where the analogous material is concrete, visual, and familiar. Such is the case for the comparisons I have drawn for them between man-made structures and natural forms. This experience has further fueled my interest in structural art and its contribution to structural engineers’ education.

Natural Efficiency and Beauty

Forms found in nature are shaped for maximum efficiency, transferring the required amount of force with the least amount of material. In On Growth and Form, D’Arcy Thompson suggests that the shapes of living things are largely the result of adaptation to physical forces, not behavior and diet, as many biologists believed at the time (Willis, 1995). All natural structures must resist the physical forces of tension and compression. To adapt and increase efficiency, natural forms prefer tension members because compression members have a propensity to buckle. Using the maximum amount of tension members concentrates compression into localized regions, which is utilized in the form of the spider web. The web is made of a network of tension strands, with the spider and captured prey acting as localized compression struts. Since the web must resist the same physical forces as our civil structures, the web's form provides an elegant model by which the engineer maximizes efficiency. An example is the highly efficient tent structure of Frei Otto's Olympic Stadium in Munich, Germany, where the steel wire nets are in tension and the large steel masts carry the compression (see Fig. 1).

Figure 1: Frei Otto's 1972 Olympic Stadium in Munich, Germany (Holgate, 1992, p. 74)

Efficient forms are often aesthetically pleasing. Some of the terms we commonly use to describe works of art, such as balance and symmetry, are derived from functional considerations, such as efficiency (French, 1994). In the animal kingdom, balance is connected with movement, so predators have to utilize balance, punctuated by moments of imbalance, to pursue and catch their prey. In addition, most of the animal kingdom is symmetrical, breaking symmetry only for functional reasons, like the asymmetrical claws of some crustaceans.

However, an efficient design is not necessarily an aesthetically pleasing one. Numerous structures exist that are efficient but lack aesthetic value. Connecting design to natural forms can avoid this pitfall. An important component in our aesthetic appreciation of nature is our desire to feel an emotional connection with our environment. Aldersey-Williams (2003) points out that in Jungian psychology, a wild animal often represents the Self, and we immerse ourselves in nature to nourish this connection. When organic forms inspire us, we can design efficient structures that mirror them – works of structural art that arouse our sense of harmony with our environment.

The Ludwig Erhard Haus building in Berlin, Germany exemplifies an efficient design with an aesthetically pleasing result due to its inspiration from nature (see Fig. 2). The repeated elliptical arch, inspired from the skeleton of an armadillo, is used to efficiently suspend floors over a tall atrium. The structurally efficient form evokes aesthetic pleasure because it resonates with our emotional connections with biological forms.

Figure 2: Nicholas Grimshaw and Partners' 1998 Ludwig Erhard Haus building in Berlin, Germany (Aldersey-Williams, p. 121)

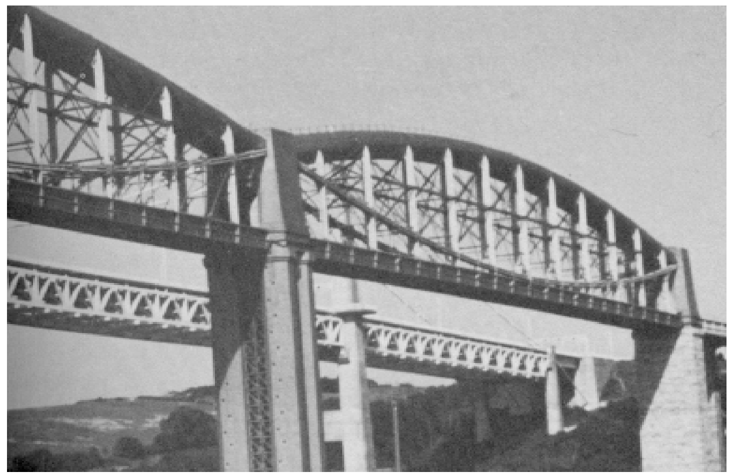

Figure 3: Isambard Brunel's 1859 Royal Albert Bridge at Saltash near Plymouth, England (Billington, p. 57)

Other Examples of Nature-Inspired Work

An arch bridge produces an outward thrust at the abutments, whereas a suspension bridge pulls them inward. A bridge could be designed by combining these concepts, so that the net force at the abutments is close to zero. This combination of actions from an arch and suspension bridge was incorporated into the structural design of Isambard Brunel's 1859 Royal Albert Bridge near Plymouth, England (see Fig. 3). The arches are iron tubes with an oval cross-section, which produce an outward thrust that balances the inward pull from the draped chains. The net zero horizontal thrust at the towers and abutments allows for an overall lighter structure when compared with an arch or suspension bridge.

This combination of arch and suspension cable has been functioning for millions of years in the structure of four-legged animals (French, 1994). The most striking example is the brontosaurus, where the legs are the towers, the belly is the chains, and the spine is the arch. The legs of the brontosaurus, like similarly designed creatures, are smaller, saving precious material, because the outward thrust from the spine is balanced by the inward pull from the belly (see Fig.4).

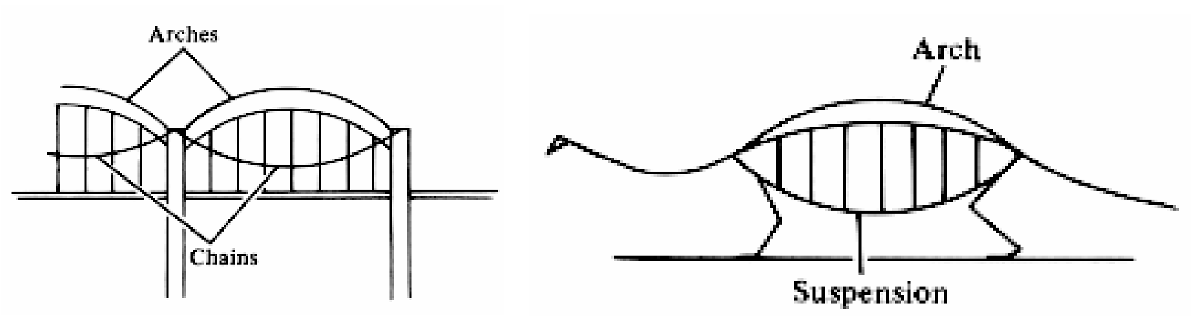

Figure 4: The similarity between the structural action of the Royal Albert Bridge and the brontosaurus (French, p. 121)

The Royal Albert Bridge imaginatively captures the efficient, appealing form of the brontosaurus. The combination of arch and suspension cable decreases the amount of material required for the towers and abutments, while the natural metaphor enhances our aesthetic appreciation.

Inspiration from nature is not only manifested in the structural design of bridges, but also in modern-day buildings, like the Swiss Re Headquarters in London, England (see Fig. 5). As described by Aldersey-Williams (2003), this structural form consists of a tapering profile, with a diagonal grid of steel beams stiffened by regularly spaced horizontal steel hoops. The form is similar to that of a sea sponge. These small aquatic creatures affix themselves to the seabed and comprise a remarkably regular geometric calcareous or siliceous exoskeleton. The Swiss Re Headquarters' form "ameliorates the wind flow, just as the sponge's shape helps

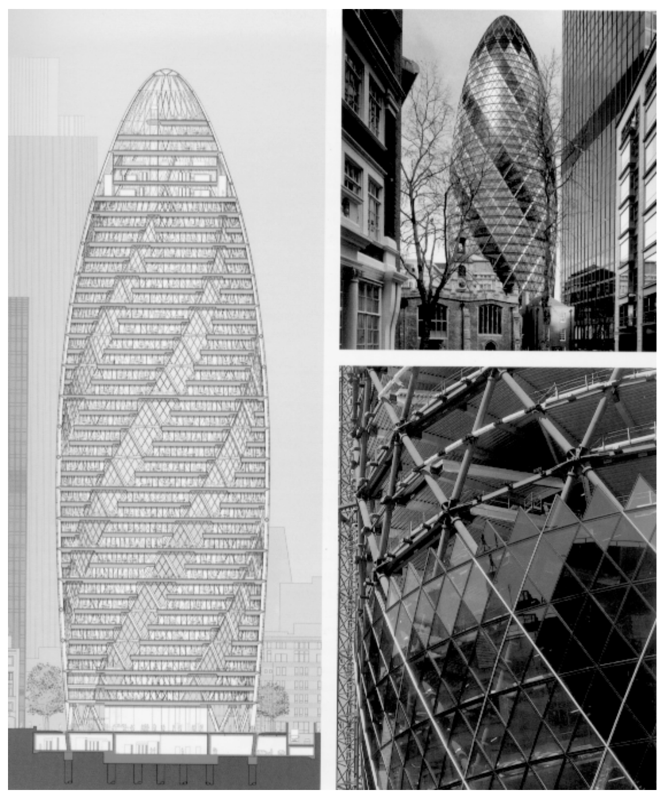

Figure 5: Ove Arup & Partners' 2003 Swiss Re Headquarters in London, England (Aldersey-Williams, p. 99)

water flow round it" (Aldersey-Williams, p. 98). Compared to a rectangular form, the skyscraper's tapering profile reduces ground-level wind speeds. The elegance and beauty of the structure is a typical byproduct of a design modeled after an efficient biological form.

Economy

There is no guarantee that efficient structures, which are economical in conserving material, will be economical overall. If an efficient structure is difficult to construct, it can be costly. Thin concrete shells, for example, are efficient but usually costly. In addition, economic considerations depend on the social setting – the specific time and place. Labor costs may vary from place to place, and from one era to another. Other variables, such as the experience of the contractor and workers, affect the cost of a structure. Overall, the structural engineer must strive for efficient structures, but keep in mind economical factors that may require altering the design.

Fortunately, many nature-inspired structures are economical as well as structurally efficient. The Britannia Bridge, designed in 1850 by Robert Stephenson (see Fig. 6), exemplifies a practical, uniform structure which facilitated construction to decrease cost. However, the similar-in-scale Royal Albert Bridge, which mirrors the structural action of the brontosaurus, was less costly, having been evoked by a more efficient, organic, and "highly expressive form" (Billington, p. 55).

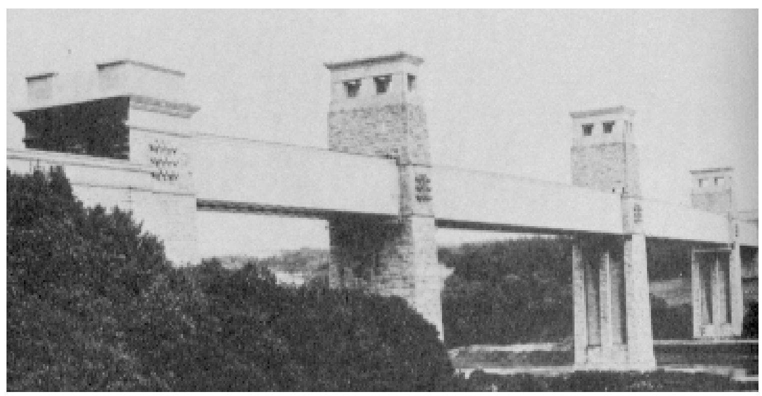

Figure 6: Robert Stephenson's 1850 Britannia Bridge in Wales (Billington, p. 58)

Future Possibilities

The Royal Albert Bridge and the Swiss Re Headquarters building are innovative structures. Their forms are unique to their areas of application, largely because of their connection with nature. In structural engineering, nature provides endless possibilities for inspiration that can spark innovation. One exciting future possibility is to use fluids as structural elements (French, 1994). Earthworms and slugs rely on fluids inside their bodies to handle compression. Currently, the stability of thin structural skins of rockets relies on internal fluid pressure, but this innovative idea could find a dominant role in the design of buildings and bridges.

The qualities of structural art – aesthetics, efficiency, and economy – are all desirable attributes of structural design. Using innovative ideas inspired from nature, structural designers can become structural artists, significantly contributing to the growth and artistic enrichment of the profession.

References

Aldersey-Williams, Hugh. (2003). Zoomorphic: New Animal Architecture. New York: Harper Design International.

Billington, David P. (1983). The Tower and the Bridge: The New Art of Structural Engineering. New York: Basic Books, Inc., Publishers.

French, Michael. (1994). Invention and Evolution: Design in Nature and Engineering. New York: Cambridge University Press.

Holgate, Alan. (1992). Aesthetics of Built Form. New York: Oxford University Press.

Willis, Delta. (1995). The Sand Dollar and the Slide Rule: Drawing Blueprints from Nature. New York: Addison-Wesley Publishing Company.

Proposed Travel Itinerary

My interest in structural design inspired from natural forms would be enhanced by a more thorough visual experience of works of structural art. I want to concentrate on those works that exhibit a clear connection with organic forms, even if the designers did not express a conscious focus on nature as their source of inspiration.

Numerous examples of structural art exist in Central and Western Europe, with many of these structures possessing solid links with natural forms. The most resonant relationships that I intend to study in depth are:

- Spider webs – membrane and tensile structures
- Honeycomb and the structure of virus proteins – domes and ribbed shells/vaults
- Soap films – minimally-surfaced shells and organic curves

I also plan to include innovative bridges and buildings that reveal other biological connections. For all visited structures, my goals are to analyze the qualities that distinguish them as structural art, and test the validity of my perception of their connection with natural forms.

I have listed below the buildings and bridges in the order I intend to visit them. The designer and year are provided, along with my perception of their link with organic forms. As I travel, I expect to discover more works of structural art that exhibit clear connections with nature. These additional buildings and bridges will further enrich my understanding of structural art.

I also hope to meet with engineers from Ove Arup & Partners in London to discuss the structural design of the Swiss Re Headquarters, whose form resembles that of a sea sponge (see Fig. 5 in "The Role of Nature in Structural Art"). This innovative skyscraper especially sparked my interest in the possibilities of biologically-inspired structural design.

Spain

Madrid:

- The Zarzuela Hippodrome Roof – Torroja (1935) – *Soap film*

Barcelona:

- Sagrada Familia Cathedral – Gaudi i Cornet (1930) – *Termites and clay structures*
- Collserola Tower – Ove Arup & Partners (1992) – *Spider web and trees*
- Montjuic Communications Tower – Calatrava Vells (1992) – *Trees*

France

Bordeaux:

- Bordeaux Law Courts – Ove Arup & Partners (1998) – *Soap film*

Loubaresse:

- The Garabit Viaduct – Eiffel (1884) – *Trees*

Lyon:

- Lyon Airport Station – Caltrava (1994) – *Animal ribcage and anteater*

Gannat:

- The Rouzet Viaduct – Eiffel (1869) – *Trees*

Paris:

- Notre Dame Cathedral (1180) – "*Divine Proportions*"
- Bourse de Commerce – Brunet (1811) – *Honeycomb*
- Eiffel Tower – Eiffel (1889) – *Trees*
- The Orly Dirigible Hangers – Freyssinet (1921) – *Animal skeleton*
- C.N.I.T. – Nervi (1958) – *Honeycomb*
- IMAX Theatre – Chamayou (1985) – *Virus protein and honeycomb*
- Clouds of the Great Arch of La Defense – Ove Arup & Partners (1989) – *Spider web*

Switzerland

Geneva:

- Sicli Company Building – Isler (1969) – *Soap film*

Eisten:

- The Ganter Bridge – Menn (1980) – *Spider web*

Graubunden:

- Zuoz Bridge – Maillart (1901) – *Trees*
- Salginatobel Bridge – Maillart (1930) – *Trees*

Chiasso:

- Magazzini Generali Warehouse Shed – Maillart (1924) – *Animal skeleton*

Tavanasa:

- Tavanasa Bridge – Maillart (1905) – *Trees*

Zurich:

- Giesshubelstrasse Warehouse – Maillart (1910) – *Trees and mushroom*
- Swiss Air Force Museum – Isler (1987) – *Soap film*
- Stadelhofen Station – Calatrava Valls (1990) – *Animal ribcage*

Bern:

- Schwandbach Bridge – Maillart (1933) – *Soap film*
- Wyss Garden Center – Isler (1961) – *Soap film*
- Indoor Tennis Center – Isler (1979) – *Soap film*

Italy

Turin:
- Exhibition Hall – Nervi (1949) – *Honeycomb*

Orvieto:
- Orvieto Hangers – Nervi (1935) – *Honeycomb*

Rome:
- The Pantheon – Rome (124) – *Honeycomb*
- The Gatti Wool Factory – Nervi (1951) – *Honeycomb*
- The Little Sports Palace – Nervi (1957) – *Honeycomb*
- The Large Sports Palace – Nervi (1960) – *Honeycomb*
- Stazione Termini – Nervi (1967) – *Animal ribcage*
- Rome Olympic Stadium – Italprogetti (1967) – *Spider web and bone structure*
- Papal Audience Hall – Nervi (1971) – *Honeycomb*
- Auditorium Parco della Musica – Piano (2002) – *Scarab beetle*

Venafro:
- M&G Ricerche Research Lab – Samyn & Partners (1991) – *Caterpillar*

Foggia:
- Padre Pio Pilgrimage Church, San Giovanni Rotonda – Piano (1991) – *Spider legs*

Venice:
- St. Mark's Cathedral (829) – *Sea urchin*

Belgium

Marche-en-Famenne:
- Comptoir Wallon des Materiaux Forestiers de Reproduction – Samyn & Partners (1995) – *Virus protein*

Brussels:
- Atomium – Waterkeyn (1958) – *Iron molecule*

Germany

Dusseldorf:
- Green House – Lippsmeier und Partner (1975) – *Honeycomb*

Cologne:
- Gaudi Musical Theatre – IPL (1996) – *Animal ribcage and spider web*
- RheinEnergie Stadium – SBP (in progress, completed in 2004) – *Spider web*

Frankfurt:
- BMW Pavilion – Sobek (1995) – *Spider web*

Neckarsulm:
- Aquatoll Dome – SBP (1990) – *Virus protein*

Stuttgart:
- Mercedes Benz Design Centre – Piano (1998) – *Fish fins*
- Stuttgart Airport Departure Hall – Schlaich (1991) – *Trees*
- Garden Exhibition – Schlaich, Bergermann und Partner (SBP) (1977) – *Soap film*
- Social Center for the Federal Mail – SBP (1989) – *Soap film*
- Roof of the Gottlieb Daimler Stadium – SBP (1993) – *Spider web*
- Bridge at Lowentor – SBP (1992) – *Spider web*
- Lookout Tower Killesberg – SBP (2001) – *Spider web*

Rust:
- Geodesic Dome at Europa Park – Mero-Raumstruktur (1989) – *Virus protein*

Munich:

- Olympic Stadium – Otto (1967) – *Spider web*
- Munich Ice Rink Roof – SBP (1984) – *Spider web*
- Ludwig Erhard Haus Building – Nicholas Grimshaw and Partners (1998) – *Armadillo*
- Carport of the Waste Management Company – SBP (1999) – *Spider web*
- DG Bank Building – Schlaich (2001) – *Honeycomb*

Berlin:

- Sony Center Forum Roof – Ove Arup & Partners (2000) – *Spider web*
- Schluterhof Roof, German Historical Museum – SBP (2002) – *Honeycomb*

Hamburg:

- AOL Arena – SBP (2000) – *Spider web*
- ZOB Hamburg – SBP (2003) – *Honeycomb*

Denmark

Copenhagen:

- Great Belt East Suspension Bridge – Birdsall (1998) – *Spider web*
- Oresund Bridge – Rothne (2000) – *Spider web*

United Kingdom

London:

- Crystal Palace – Paxton (1851) – *Water lily*
- Paddington Station Roof – Brunel (1854) – *Animal ribcage*
- Waterloo International Terminal – Nicholas Grimshaw & Partners (1993) – *Caterpillar*
- London City Hall – Ove Arup & Partners (2002) – *General aquatic creatures*
- Swiss Re Headquarters – Ove Arup & Partners (2003) – *Sea sponge*

Stansted:

- Stansted Airport Terminal – Ove Arup & Partners (1992) – *Honeycomb*

Cambridge:

- Schlumberger Research Centre – Ove Arup and Partners (1986) – *Spider web*

Newcastle:

- Global Garden – MacDonald (2000) – *Trees and honeycomb*

Manchester:

- Corporation Street Footbridge – Ove Arup & Partners (1999) – *Soap film*

Wales:

- Great Glass House of the Wales Botanical Gardens – Foster and Partners (2000) – *Honeycomb*

Bodelva:

- The Eden Project – Nicholas Grimshaw and Partners (2001) – *Virus protein*

Plymouth:

- Royal Albert Bridge – Brunel (1859) – *Brontosaurus*

Singleton:

- Jerwood Gridshell – Cullinan (2002) – *Honeycomb and beetle/armadillo*

Edinburgh:

- Forth Rail Bridge – Fowler and Baker (1890) – *Bison*

Glascow:

- Scottish Exhibition Conference Center – Foster and Partners (1997) – *Armadillo*