MODERN EXAMPLES OF STRUCTURAL ART IN METALS

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Abstract: Many of the greatest structural artists—designers practicing at the top of their profession and achieving excellence in efficiency, economy, and elegance of their structures—from Thomas Telford to John Roebling, from Othmar Ammann to Fazlur Khan, practice primarily in the media of iron and steel. During the latter part of the 20th century and into the 21st century a handful of designers have carried on this tradition of greatness in structural art in metal. This paper sets the context for modern works of structural art in metal through a brief examination of the history of great design in metal and then examines Jörg Schlaich as an exemplary modern practitioner of the art form through a sequence of bridge and roof structures that cover the period from roughly the 1980s to the present and range in scale from modest pedestrian bridges to long span roofs for major places of public assembly. These structures are examined in terms of their structural efficiency, economy, and elegance. Elegance is interpreted here to entail ways in which the designs spring from creativity constrained by the requirements of good structural engineering; the degree to which the designs are innovative and introduce new techniques or ideas to the discipline of structural engineering; and, whether and how the designs are visually expressive of their structural function. Although impossible to quantify, the aesthetic beauty of the structures is also considered. The works of Santiago Calatrava are compared to those of Schlaich as a coda to the paper to spur greater discussion of the meaning of excellence in structural design.

INTRODUCTION

Structural engineers create large-scale public works that form the physical fabric of our civilization and yet the general public, and indeed many practicing engineers, do not have or develop a sensitivity to and appreciation for excellence in the discipline of structural design. In the 1970s and 80s Prof. David P. Billington defined in a series of articles and books (e.g. Billington 1979, 1983, 2003) structural art as a form of excellence in structural design. Works of structural art, and the designers who create them, excel not only in meeting engineering design criteria such as safety, serviceability and durability but also in meeting the near and long term needs of society and in achieving a degree of elegance that enhances the aesthetic quality of the built environment. The evaluation of structural designs in the context of structural art has usually been approached in terms of the success of designs in the Scientific, Social, and Symbolic realms, or correspondingly in terms of a specific realization in these larger domains: Efficiency, Economy, and Elegance. This framework is certainly not the only way to approach the evaluation and criticism of structural design (e.g., see Gottemoeller 2004; Troyano 2005; Muttoni 2011). Too often, works of structural design are analyzed in the public realm by architectural critics who, while well equipped to evaluate form in the context of architectural design are poorly equipped to criticize works of structural art that are highly constrained by engineering demands in ways that differ fundamentally from the constraints imposed on architecture. The structural art framework has the advantage of allowing a systematic analysis of a structural design across a modest number of categories that nevertheless cover the technical quality, service to society, and beauty of a design.

The purpose of this paper is to show that the creation of structural art was not a peculiarity of the middle part of the 20th century, but in fact has continued to occur over the decades since the publication of Prof. Billington's seminal book *The Tower and the Bridge*. The continued creation of structural art is demonstrated through an examination of the works of the German structural engineer Jörg Schlaich. Specifically, four classes of structures are described: bridges that are stiffened in novel ways; bridges with substantial three dimensionality; cable net surfaces; and grid shell surfaces. For each of these categories a sequence of structures is introduced to illustrate the ways in which Schlaich's designs are representative of structural art in that they are high quality solutions to engineering problems and achieve a sense of elegance in design. Where possible, given limited public availability of cost data, an evaluation of the economy of the designs is made.

A secondary purpose of this paper is to introduce Schlaich's works more broadly to the US structural engineering community and eventually to the general public. Schlaich has practiced overwhelmingly in Europe, specifically in Germany. To the degree that members of the general public in the US are even conscious of the quality of engineering design reflected in our infrastructure, they certainly are not aware of the excellence that can be achieved in such works by a master artist such as Schlaich. It is hoped, therefore, that broader dissemination and discussion of Schlaich's work, along with that of other contemporary structural artists, will inspire the public to be more demanding of public officials and insist that designers of public works in the US strive to create works of structural art.

Prior to introducing Schlaich's works a brief history of structural art is presented with emphasis on those structural artists who worked primarily in metal. Then a brief professional biography of Schlaich is given that emphasizes the tradition of design in which he was educated and trained. The body of the paper covers Schlaich's bridges and surfaces and the paper concludes with a brief presentation of some key works of Calatrava. Calatrava's work is provided as a short coda to the paper, in a smaller number and with less detailed analysis, primarily to provide a visual context to Schlaich's work. That is, to allow the reader to see how different designers may come to very different solutions to similar engineering problems.

TWO CENTURIES OF STRUCTURAL ART IN IRON AND STEEL (1781-1980)

The possibility for structural art arose with the industrial revolution and the beginnings of the use of modern engineering design principles applied to new industrial materials such as iron. Prior to the industrial revolution engineering did not exist as a discipline separate from architecture and construction, and though the designers and builders of pre-industrial structures such as the great cathedrals sought many of the same goals—lightness, expressiveness and beauty—as do structural artists, their work belongs to a different tradition. For the purposes of this paper, a brief review of two classes of structural art, suspension bridges and long span roofs, sets the context for discussion of Schlaich's work.

The suspension bridges designed by Thomas Telford, John Roebling, Othmar Ammann, and Leon Moisseif illustrate different approaches to the provision of adequate stiffness to the highly flexible form of the suspension bridges. Schlaich has distinguished himself partly by providing stiffness to cable supported bridges in novel and elegant ways. Consider the structures of Fig. 1, taken chronologically in the following discussion.

Telford's Menai Straits suspension bridge utilized the anchorage of the arched backspans to partially stabilize the main span—then longest in the world at 176m. Although the Menai Straits bridge did suffer a partial collapse in a wind storm after Telford's death, it is considered a success and stands and carries traffic today, 189 years after its construction. John Roebling mastered the form of the suspension bridge and, in his masterwork, the Brooklyn Bridge used a hybrid system for stiffening of the roadway that consisted of a stiffening truss and diagonal cable stays emanating from the tower tops. This hybrid, or redundant approach, is typical of Roebling's designs, and at Niagara he additionally used cable stays running downward from the deck to the cliffs of the Niagara gorge. Roebling's use of multiple stiffening systems in parallel renders his bridges more difficult to read in terms of the flow of forces yet must also be at least partially credited with ensuring the permanence and performance of his structures, which have never experienced significant problems with flexibility induced oscillations.

Othmar Ammann's George Washington Bridge was designed and constructed to have a main span of 3500 feet, twice the length of the previous record holder, the Delaware River / Ben Franklin Bridge in Philadelphia. This was a formidable technical engineering achievement in itself, yet the structure is equally important in the history of structural art for the slenderness of its deck profile and its use of metal towers. The bridge, as originally constructed and opened in 1931, carried a single level deck for automobile traffic. Ammann was able to achieve such lightness and slenderness in the bridge deck by counting on the stiffness generated by structural deadweight as predicted by the deflection theory of suspension bridge behavior (Ammann 1933). This is a classical example of the way in which technical and aesthetic excellence can intersect in works of structural art. To put it a different way, and in a way that more clearly acknowledges the constraints and priorities of structural design, Ammann's technical excellence enabled the aesthetic excellence of the George Washington

Bridge. Although the towers of the bridge were designed to carry a cast concrete cladding, the eventual appearance of the skeletal metal forms of the towers without their cladding set the stage for later works by Ammann including the Bronx Whitestone, Throg's Neck, and Verrazano Narrows Bridges, each of which express the towers more clearly than the George Washington Bridge.

The slenderness of the George Washington Bridge set an aspirational goal for bridge designers of the time both because it resulted in a beautiful structure and because it allowed great efficiency of material usage and therefore economy. The failure of the first Tacoma Narrows Bridge, designed by Leon Moisseiff, due to insufficient stiffness provided to the deck illustrates the importance of stiffness in suspension bridge design and highlight. In fairness to Moisseiff, it should be noted that the George Washington Bridge succeeded largely because of its sheer scale, leading to tremendous deadload and resulting cable stiffness. Later Ammann designs such as the Bronx Whitestone did experience problems with flexibility and required retrofits.

There also exists a tradition in the design of engineered surfaces, usually long span roofs, that can be readily identified as structural art and also informs critique of Schlaich's work. The Galerie Des Machines, built for the Paris Exposition of 1889 (the same exposition for which the Eiffel Tower was constructed) is a starting point for tracing the development of structural art in long span roofs although it is preceded by several decades by many of the great arched trainsheds of Europe, including the 1854 roof at Paddington Station in London designed by I. K. Brunel. The arches of the Galerie were made of a modern material, iron, and essentially adapted the three-hinged arch from a bridge form to a roof form. Of particular importance for the consideration of the roof of the Galerie as a work of structural art, or at least a precursor to the structural art of roofs, is the clear and dramatic expression of the hinges placed at the springing points of the roof arches (Fig. 2a). Such expression plays an important role in structural art, especially when it is expressing a structural function that is important to the performance of the structure.

An important additional advancement in the structural art of long span roofs was the development of forms that made use of three dimensional action in resisting loads, rather than simply repeating two dimensional solutions, e.g., the arches at the Galerie des Machines. Heinz Isler, working in reinforced concrete, was perhaps the structural artist who most strongly accentuated and used to his advantage the three dimensional nature of his roof shells (Fig. 2b). Isler achieved three primary advances by harnessing fully three dimensional shapes: the ability to cover spaces of essentially arbitrary geometry; high material efficiency; exceptional elegance. Schlaich, as will be shown later in this paper, accomplishes these same objectives by using steel in novel ways to create elegant, expressive and efficient surfaces.

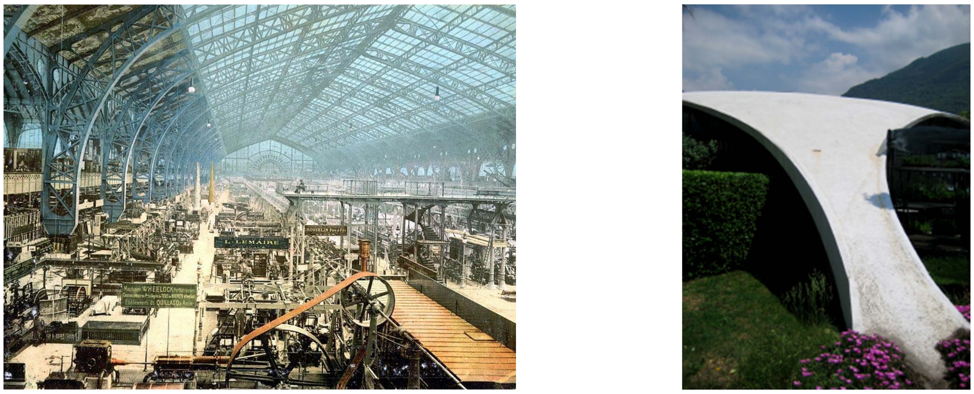
(a) Menai Straits Bridge
(Credit: Mick Knapton)

(b) Brooklyn Bridge
(Credit: Cristopher Moen)

(c) George Washington Bridge
(Credit: Arnold Reinhold)

(d) First Tacoma Narrows Bridge
(Credit: Prelinger Archives)

Figure 1: A brief history of structural art in suspension bridges



(a) Galerie des Machines
(Credit: Library of Congress)

(b) Burgi Garden Center
(Credit: Sanjay Arwade)

Figure 2: Structural art of long span roofs

JÖRG SCHLAICH – STRUCTURAL ARTIST

Jörg Schlaich's design philosophy can be traced directly to the development of the Stuttgart School of Building Design that created a collaboration of engineering and architecture to create lightweight structures. Schlaich earned a doctorate of engineering in 1963 from what is now the University of Stuttgart after earlier studies in Stuttgart, Berlin, and at Case Western Reserve University in Cleveland, Ohio. He also completed training as a journeyman carpenter and took classes in architecture (Holgate 1997, Bögle et al.. 2003). In 1967 he began lecturing at Stuttgart and from 1974 until 2000 he served as professor and head of a research institute for construction and structural design. In this capacity he succeeded Fritz Leonhardt.

Leonhardt was renowned for his design work in towers and bridges and, as is the case with many structural artists, was also an active educator. In the mid-1950s, as chair of concrete structures at Stuttgart, Leonhardt was responsible for incorporating a study of structures and their forms into the university's curriculum in collaboration with Curt Siegel, a professor of architecture (Trautz 2008). Leonhardt and Siegel took this collaboration a step further when, in 1964, they lured architect Frei Otto from Berlin to head the university's lightweight structures division. Otto is noted for his thorough understanding of engineering and structural shapes and his willingness to work with engineers. These collaborations deeply influenced Schlaich's career, most notably his work with Otto for the 1972 Munich Olympics Project (Trautz 2008, Schlaich 2014).

Schlaich considers Leonhardt as his mentor (Schlaich 2014) and he worked for LAP, a structural design firm founded by Leonhardt and Wolfhardt Andrä, from 1963-1979. His work during his time at the firm included his leading role in the structural design of the 1972 Munich Olympic project, a project that won worldwide acclaim and played an important role in setting the stage for his later work in the cable net form.

In 1980, Schlaich joined with Rudolf Bergermann to form Schlaich, Bergermann and Partner (SBP). The design office continues with four principals and offices in Stuttgart, Berlin, Rio de Janeiro, New York City, and Shanghai. Its tradition of academic and research collaboration with an emphasis on design of lightweight structures also continues with, for example, the firm's principal Michael Schlaich who also serves academic roles at the Technical University of Berlin (Schlaich 2014).

Throughout his career, Schlaich has engaged in academic research to support his design practice, working primarily in the topics of strut and tie modeling for reinforced concrete structures and on the fundamental behavior of cable supported structures and cable connections (Bögle et al. 2003, Schlaich et al. 2007, Schlaich & Sober 2007). He has additionally written and lectured extensively about his designs (Schlaich 1972, 2013) including defining the value of lightweight structures in terms of ecological, social and cultural points of view in addition to the core technical aspect that lightweight members should carry a minimum of bending (Schlaich 2013, Schlaich 2002). He has furthermore emphasized the importance of aesthetics in design, and similar to Billington argued that in an engineering design the aesthetics cannot be separated from the structural performance. He states this forcefully when he says, "I find it difficult to imagine a building with structural deficits as being aesthetically good" (Flagge 2003).

Bridges. Schlaich has designed dozens of bridges over the course of his career (99 are listed in a catalog of his work published in Bögle et al. 2003), ranging from small pedestrian bridges to the 475m main span Ting Kau bridge. In the context of this paper a selection from two classes of bridges is used to illustrate Schlaich as a structural artist: cable supported bridges with stiffness provided in novel ways and bridges with a strong degree of three dimensionality to their design.

The Rosenstein II (Stuttgart 1977, 29 m) and Kochenhofstrasse (Stuttgart 1989, 42.5m) bridges illustrate one of Schlaich's methods for providing stiffness for small to medium scale suspension bridges (Fig. 3). In this method, the deck is allowed to remain extremely slender by the provision of arch-shaped, pre-stressed cables that are tied vertically, from below to the deck. This approach allows extreme efficiency of material since by pre-stressing the stiffening cable Schlaich is essentially able to construct a system that provides adequate stiffness against non-uniform live load without using any inefficient members that must bear compressive or bending loads.

Comparison of the two bridges shows how Schlaich's treatment of the pre-stressed stiffening arch evolved both over time and with increasing scale. In Rosenstein II, the shorter and earlier of the two bridges, the walkway follows the profile of the main suspension cables, there are no real towers supporting the cables and a single stiffening cable, centered under the deck, is provided. At Kochenhofstrasse, the later and longer bridge, proper towers are provided to allow for greater sag of the suspension cables while maintaining a relatively flat walking surface, two stiffening cables are provided in addition to arching in elevation they are splayed at the anchorages to provide lateral stiffness in addition to vertical stiffness to the span.

Although one may see an antecedent to Schlaich's use of stiffening cables in Roebling's use of diagonal cable stays above (in Brooklyn) and below (in Niagara) the deck, the arch-like form of Schlaich's cables is, to the author's knowledge, without precedent and presents a highly readable and clear expression of the structural function to the viewer of the structure. By his extensive use of cables, additionally, Schlaich manages to visually express the lightness of the bridge through the slenderness of the deck and nearly vanishing thinness of the stiffening cables.

(a) Rosenstein II
(Credit: Nicolas Janberg)

(b) Kochenhofstrasse
(Credit: Holgate 1997, pg 220)

Figure 3: Suspension bridges stiffened by pre-stressed underslung cables.

The Rosenstein I (Stuttgart 1977, 78 m) and Max Eyth See (Stuttgart 1989 114 m) also provide stiffness through the use of cables, but do so by inclining the suspender cables that run from the main suspension cables to the deck (Fig. 4). Each bridge also presents geometric constraints that make this approach to stiffness preferable to that used in Rosenstein II and Kochenhofstrasse. In each case the total bridge length is greater than in the previous examples, meaning that implementing the pre-stressed arch stiffener would likely have compromised clearance to a greater degree. In the case of Rosenstein I the placement of a single tower at midspan would have rendered the aesthetic of a pre-stressed arch cable peculiar, whereas in Rosenstein II and Kochenhofstrasse the shape of the stiffening cable mirrors the profile of the suspension cables. As in Rosenstein II and Kochenhofstrasse the use of cable geometry to stiffen the bridge means that the deck can be provided with only minimal stiffness, and in all four of these bridges the decks are extremely thin. In the case of Max Eyth See the deck is only 0.3 m thick, giving a span to thickness ratio of 380. For comparison, the first (failed) Tacoma Narrows bridge had a similar ratio of 350.


(a) Rosenstein I
(Credit: Nicolas Janberg)

(b) Max Eyth See
(Credit: Delbert F. Schafer)

Figure 4: Suspension bridges stiffened with inclined suspenders.

Schlaich has also applied his design expertise to large scale bridges. In addition to the Hooghly Bridge (Calcutta 1992, 822m total length main span 457m), the Ting Kau bridge (Hong Kong 1998, 1177 m with longest span 475 m) was one of the longest cable-stayed bridges in the world when constructed. The multiple spans pose significant design challenges in providing adequate stiffness and preventing non-uniform loads from generating large displacements that propagate across spans. Schlaich addressed this problem by tying the top of the main tower to the tower-deck intersection points of the adjacent secondary towers (Fig. 5). The resulting cable arrangement is unorthodox, but as with his smaller suspension bridges, it allows the deck to be extremely slender, with a depth of only 1.7 m. For comparison, the deck of the Millau viaduct, another multi span cable stayed bridge, has main spans of 342 m and a deck thickness of 4.7 m (Hoorpah 2002). The significant differences in the deck are also due to the cable arrangement: Millau uses a single plane of cables supporting the centerline of the deck and therefore requiring significant torsional stiffness of the deck, while at Ting Kau, Schlaich has specified four planes of cables supporting more uniformly the edges and two points near the centerline of the bridge.

Figure 5: Ting Kau bridge (Credit: Baycrest)

Typically bridges are two dimensional, carrying relatively straight roadways with super and substructures that are collinear with the roadway. Certainly there are cases where bridges take on three dimensional aspects such as curved viaducts or in mountainous terrain, but Schlaich has employed three dimensionality in surprising and playful ways in some of his small to medium scale bridges, and has stated that pedestrian bridges "need not be as straight as highway bridges are. They may even swing a little to make one feel that they are alive" (Billington 2003).

The Kelheim bridge (Kelheim 1987, 61m) is a curved plan suspension bridge with inclined towers that illustrates the ways in which Schlaich uses three dimensionality within the constraints of equilibrium to accommodate geometric site constraints. At Kelheim a clearance of 7.6m was required, but approach slopes could not exceed 10% (SBP 2014, Figure 6a). A curved bridge allows the bridge to be of sufficient length to achieve the required clearance, while keeping the entrance to the deck ramps at the riverside. Several details of the structure are also interesting including the use of guyed, inclined towers that clearly express the equilibrium configuration of the two tension members (the guys and the main cable) and the compression member (the tower). The curvature of the deck also increases its effective torsional stiffness and allows the vertical suspenders to support only the inside arc of the deck, creating a remarkable visual expression for pedestrians crossing the bridge.

Schlaich extended the use of plan curvature in suspension bridges in the Liberty/Reedy River bridge (Greenville, South Carolina 2004, 61m, Fig. 6b), his only work in the US, and the doubly curved Gahlensche Strasse bridge (Bochum 2003, 130m, Fig. 6c). The Reedy River bridge is similar to the Kelheim bridge at first glance but has important differences in the way the curved structure achieves equilibrium. At Reedy River the suspenders support the outer arc of the deck and the towers are inclined away from the center of curvature of the deck. The deck, an open section only 0.25m thick is visually open and light while also expressive of the minimal materials used in constructing the bridge. The double curves at Gahlensche Strasse also serve to enhance the torsional stiffness of the deck, meaning that only one edge of the deck need be supported by the suspenders, and the geometry of the towers and suspenders is such that no guys are required. While similar claims about inclined towers and equilibrium have been made regarding other bridges with inclined towers, at Gahlensche Strasse the validity of the claim is supported by the extreme slenderness of the tower, which would not be possible if significant bending forces were present. Finally, the Ripshorst bridge (Ingolstadt 2001, 184m total length main span 55m) shows that while Schlaich prefers the cable as a structural member most able to achieve and express lightness and efficiency he is equally able to effect three dimensional structural art in the compression form of an arch.

(a) Kelheim bridge
(Credit: SBP)

(b) Liberty/Reedy River bridge
(Credit: SBP)

(c) Gahlensche Strasse bridge
(Credit: Nicolas Janberg)

(d) Ripshorst bridge
(Credit: SBP)

Figure 6: Three dimensionality in Schlaich's work

Roofs and surfaces: Cable nets. Schlaich has also applied the concept of lightweight design using tension elements to create structural art with surface structures. Structural engineers most often design surfaces to serve as roofs, and Schlaich has done so in many cases, but Schlaich has also designed cooling and observation towers using lightweight tensile structures.

The first class of surface structures presented is that of the so-called cable net. In a cable net, a network of pre-stressed cables takes on stiffness against bending and in-plane loads. By choosing the geometry of the network and the pre-stressing forces correctly, it is possible to turn an assemblage of cables with essentially zero bending stiffness individually into a system that can serve as a roof or wall structure, or even in other more surprising ways! As with his cable supported bridges, Schlaich designs for efficiency by using the cable as the primary load supporting element. The geometry and pre-stressing of the cable nets allows bending forces to be converted to tensile forces and the nearly complete absence of compressive forces means that elements can be extremely slender since member buckling need not be considered.

Now is an appropriate time to introduce the idea of economy in at least a qualitative sense. A major challenge in constructing tension structures is the design and manufacture of reliable connections. Schlaich's exceptional use of cables in his structures has been facilitated by the advent, towards the end of the 20th century of processes leading to reliable and cost-effective cable connections (Bögle et al. 2003). This observation stands as an important reminder to designers in metal that there is indeed art in the design of an efficient, elegant, and economical connection, and that in fact the making of great large scale works of structural art is not possible without equal or greater attention paid to the connecting details.

Although this paper began with Schlaich's work in bridges, his development as a structural artist using primarily cables as his medium began with a roof structure: the Olympic Stadium in Munich (1972, Fig. 7a). Schlaich was placed in charge of the design of this system as a 32 year old engineer and did so in collaboration with his early influence Frei Otto (Schlaich 2014). If one considers only the surface containing the cable net itself, a cable net roof is almost vanishingly thin (the cables are not more than one or two centimeters in diameter), yet the roof system must also consist of a weather barrier which can dramatically change the visual aspect of the structure. Properly designed, cable nets are particularly well suited; however, to carrying glass as the weather barrier, and the use of glass in many of Schlaich's cable nets results in clear expression of the overall lightness of the structure. Two examples (Figs. 7b,c) show how Schlaich has pushed the use of the cable net beyond the roof application originally envisioned at Munich. The Killsberg Tower (Stuttgart 2001, 43m high) uses cable nets in a manner similar to the Schmehausen cooling tower of 1974 but to stabilize and provide exterior support to an observation tower. No cladding is required in this application and the cable net has been somewhat distorted to have diamond rather than square cells. The Lowentor Bridge (Stuttgart 1992) uses a cable net to support a walkway, forming to the authors' knowledge the only cable net supported bridge in the world. While at first glance the cable net support appears rather large compared to the slender profile of the walkway, further inspection reveals that the walkway meanders in plan and undulates in profile in ways that would not be obviously attainable with standard piers, arch, or suspension systems.

A meaningful point of comparison for Schlaich's cable net work in the history of structural art is the series of thin shell concrete structures designed by Heinz Isler (Fig. 2b). Each designed thin, membrane structures primarily to cover or enclose large areas. Isler designed compressive membranes using reinforced concrete in a way that allowed essentially arbitrary geometry and extreme slenderness (often around 10cm, Billington 2003) while Schlaich has used tension membranes and cables. The use of cables allows a transparency that is not possible in concrete, and yet the overall forms, particularly the strong use of double curvature share much in common.

(a) Munich Olympic Stadium (Credit: SBP)

(b) Lowentor bridge
(Credit: Nicolas Janberg)

(c) Killsberg Tower
(Credit: Delbert Schafer)

Figure 7: Cable net structures

Roofs and surfaces: Grid shells. The grid shell is the other major form Schlaich has used in his design of surfaces, and the grid shell differs substantially from the cable net in that the primary load carrying members are compression struts. When these compression struts are arranged in square panels, as is often the case, they do not form a stable structure until stabilized by pre-stressed diagonal cables inside each panel. Therefore, most of Schlaich's grid shells can even be seen as lightweight systems that rely on tension to function properly.

The simplest form of the grid shell essentially forms a barrel vault over an area (Fig. 8a, roof over Roman ruins in Badenweiler, 2001, 40m span), though since the grid shell is composed of slender struts the vault can be rendered transparent by the use of glass as the roofing material. Although the barrel vault is an ancient form, Schlaich has adapted the singly curved barrel vault in surprising and effective ways. The roof of the Hauptbahnhof in Berlin uses two intersecting vaults to cover an area of 29000 sq m. with a longest span of 66m. To accommodate the geometry of the site Schlaich has flattened the arch of one of the vaults and added supplementary, but very light, cable-based trusswork below the compression member of the arch of the vault (Fig. 8b). Schlaich has also shown that the grid shell form of the barrel can be warped and sculpted in ways not available for vault designers working in stone or brick, but that are evocative, in their complex curvature, of the forms Isler created in thin shell concrete (Figs. 8c,d, Museum of the City of Hamburg, 1989, 14-17m span and DZ Bank building, 1998). The DZ Bank building is of particular interest for those curious about the interplay of architecture, engineering, and sculpture since the main component of the interior of the atrium formed by the grid shell is a large scale sculpture by Frank Gehry.

(a) Badenweiler Roman Bath
(Credit: Brücke-Osteuropa)

(b) Berlin Hauptbahnhof
(Credit: Delbert F. Schafer)

Hamburg City History Museum
(Credit: Wolfgang Meinhart)

DZ Bank
(Credit: SBP)

Fig 8: Grid shell roof structures

A note on cost and economics: Quality criticism of structural designs requires consideration of the economics of the design, construction and maintenance. In the authors' experience teaching and writing about structural design it has proven challenging to find reliable cost figures in the public domain, even for bridges that are usually publically financed and owned by public authorities and governments. Even when cost data can be found publically available it is often challenging to decompose the cost of design and construction of the bridge structure from the total project cost, which may include ancillary costs even in excess of the superstructure cost. Although a full analysis of the cost of the structures show here is beyond the scope of this paper, there is evidence that the Ripshorst Bridge (Fig. 6d) is cost competitive with other bridge types of similar span and function. Specifically, the Risphorst bridge has a reported cost of 1600 euros/sq.m. (or approximately $208/sq.ft.) which sits squarely in the middle of the range of costs associated with similar span bridges (Josat 2002).

These data come from a report on German bridges, but the California Dept. of Transportation in the USA has reported a cost range of \$100-\$300 / sq. ft. for a wide range of bridge types used in California (Caltrans 2014). Surely the Ripshorst bridge cannot be considered 'typical' in any way, yet Schlaich has managed a design that, while it might not win on a lowest-initial-cost basis, is clearly competitive with other, less expressive solutions. Indeed, the primary intent of this note on costs is to show that beautiful structures, when created by a structural artist, need not come at a steep cost premium. In fact, if they do, they probably are not examples of structural art.

SANTIAGO CALATRAVA – POSSIBILITIES FOR COMPARISON

It is nearly impossible to evaluate works of structural art in isolation from other works of the same designer or from similar works by other designers. To close this paper with a prod to further thought and investigation, two structures designed by Santiago Calatrava are presented, without analysis or conclusion, as potential points of comparison with Schlaich's work. The Sundial Bridge in Redding, CA (Fig. 9a) is a single span cable stayed bridge with elements of three dimensionality stemming from the placement of the tower of the centerline of the bridge and the single cable supported span. Oriente Station in Lisbon (Fig. 9b) is a rail station roof constructed using steel and glass and therefore ripe for comparison to the Hauptbahnhof of Schlaich in Berlin.

(a) Sundial Bridge
(Credit: Chad K.)

(b) Oriente Station
(Credit: Joao Pimentel Ferreira)

Fig. 9: structures of Santiago Calatrava

CONCLUSIONS

Jörg Schlaich is one of the most prolific and accomplished structural designers of the last 50 years, and his work has received widespread attention (although more so in Europe than in the US). He was chosen as an exemplary structural artist to illustrate that the practice of structural art in metals is alive and well, and that even in the past few decades new forms are being created in both bridge and roof domains. What exemplifies Schlaich as a structural artist is his attention to structural efficiency through the use of light weight cable supported structures and his desire to clearly and elegantly express the structural function of his designs. Although cost assessments are challenging to make given the paucity of publically available data, there is evidence that Schlaich's designs are fully cost-competitive with other more mundane designs. Though Schlaich's work has been both prolific and highly varied, four classes of structures have been defined here as exemplifying his success as a structural artist: suspension bridges, curved bridges, cable nets, and grid shells.

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