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Exploring the Ideals and Character of Structural Elegance

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Abstract

Strength is common to all structures, but high performance requires that strength be provided efficiently, as demonstrated by minimal material use. Through form optimization, prestressing and other strategies, performance is made efficient, and the structure has the potential for visual elegance. Material economy is also the source of “leanness”, an absence of superfluous mass that is key to structural beauty. Visual transparency is corollary to leanness, and structural beauty demands that non-structural elements not obscure the structural form. When a subjectively chosen structural concept is refined through analysis and judgment into an elegant final form, a unique design may appear the predestined solution to its load-bearing problem. The paper explores structures in nature, including the musculoskeletal system of the human body, as models for understanding structural beauty.

Keywords: High performance structures, gothic cathedrals, concrete shells, architecture, lightweight construction, form resistance, adaptive form resistance, internal resistance, liechtbau, human form.

1. Introduction

The Tower and the Bridge [1] and other publications by David Billington have informed and inspired the author and others who share Billington’s passionate interest in structural aesthetics. The book describes “structural art” as the product of three ideas: efficiency (minimum materials), economy (construction simplicity, ease of maintenance, and integrated form), and engineering elegance. Efficiency and economy are readily defined - efficiency measurable as the ratio of weight/area, and economy as the ratio of cost/area. In defining elegance, though, Billington faced the imposible task of defining artistic merit itself, and with limited success. He lists contrast and affinity with the structure’s context as elements of elegance, but these are only two of many ways we might define elegance (and beauty itself). This author can define elegance no more definitively than Billington. However, routine experience of the structures of nature and of our own bodies have strong parallels to our appreciation of beautiful structures that provides clues to the sources and character of structural elegance.

2. The High Performance Ambition

An expertly performed high jump (Figure 1) is one of sport’s most beautiful and iconic movements. In the contemporary technique, brought to prominence by the American Dick Fosbury, the athlete bounds towards the bar and springs from the ground to lift his center of gravity, at the same time rotating his torso until his back faces the bar. He snakes his body over it – head first, then shoulders, hips, and legs, before dropping to his back in the landing pit. Fosbury parlayed the unconventional technique to a gold medal at the 1968 Mexico City Olympics, after which it became known as the Fosbury Flop.

The name belies the beauty of a well-executed flop and its advantage over the previous standard – the straddle. A straddler clears the bar facing down, with his body parallel to the bar, so that head, torso,

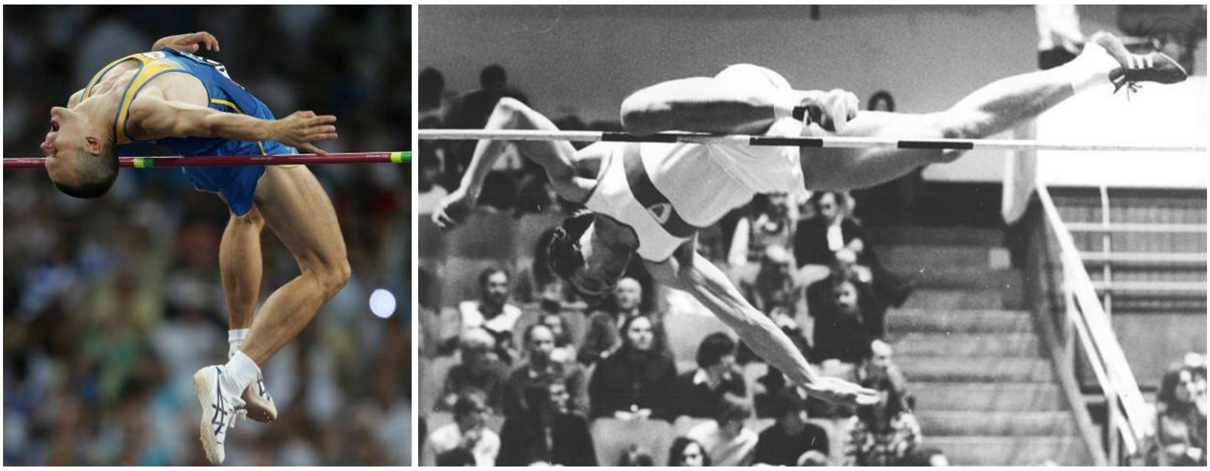

Figure 1. Well-executed flop (left) and straddle (right) high jumps. (Right image Bundesarchiv,Bild 183-S0305-0030/CC-BY-SA 3.0)

and legs pass over it nearly simultaneously. To clear the bar, the straddler must lift his center of gravity about 10-20 cm above the bar. In contrast, the backwards, serpentine movement of the flopper allows him to pass cleanly over the bar while keeping his center of gravity critical centimeters *below* it. If the jumper imparts the same upward thrust as he springs from the ground using either technique, the flop allows him to clear a higher bar. Fosbury’s gold medal jump was ungainly next to the well-honed movements of the best straddlers, but jumpers that followed him gradually refined the technique. Their skill, combined with the flop’s growing familiarity, make its best practitioners appear natural and graceful as they clear bars placed at heights well above their heads.

The photo captures a well-executed flop as the jumper passes over the bar. The power of the image reflects both the physical beauty of the athlete and the elegance of his technique. He has optimized the form of his body to its task, with the backward flex in his neck and torso and precise positioning relative to the bar conveying the efficiency of his movement. His body is hard-muscled, stripped of excess, and his entire being - from outstretched arm to gaping mouth - conveys singularity of purpose in maximizing his height of clearance. He has relaxed muscular tension that does not aid in clearing the bar, and the legs that have done their work in springing from the ground stream fluidly behind him. Experts might parse his motion into dozens of discrete elements, but it is performed with a fluidity that makes it appear irreducibly simple. The aspiration of the athlete inspires us. The aspiration of structures that span great distances with minimal mass inspires us as well, and is an essential part of their beauty.

3. Leichtbau

All good jumpers are strong, but strength gets them only part way to competitive success. They must also perfect their form and technique, so that this strength is efficiently deployed to clear the bar. Unlike a competitive gymnast, the jumper gains no points for style. He is rewarded only for his performance in achieving a measurable goal, and his technique is directed towards this alone.

High performance structures, similarly, are those whose form and detailing are targeted to supporting their own weight and imposed loads efficiently. Frei Otto is best known for his work on the Munich Olympic Stadium and other tensión structures, but his academic work focused on developing the principles of “leichtbau”, or lightweight construction. In Otto’s formulation, the work capacity of a structure is defined by its “tra”: the load that it carries multiplied by the distance over which that force is transmitted to the support. Otto defined the structure’s “effectiveness” as tra/structural mass. His simple formula cannot be used by itself to evaluate the relative merits of two structures, as geometry, materials, and other variables make the demands of each design problem unique. (Supporting a load at the top of a cantilevered 10m tall mast in compression clearly requires a more massive structure than hanging the same load from a 10m long cable in tension, though both structures have the same tra.) However, Otto provides a simple expression for the goal of every high performance structure: to use the least structural mass to support a load over the required height or span.

The engineer Robert Le Ricolais, an important contributor to architect Louis Kahn's best work, aligned himself with the principle of leichtbau in his poetic evocation of the ideal "zero weight, infinite span". Le Ricolais' goal is unattainable, but in their quest to achieve it, designers sometimes create structures that satisfy unprecedented structural demands with the slightest of mass. In doing so, they may create the visceral excitement and particular beauty of high performance structures.

Engineers employ various means to create light and effective structures. The thin shells and arch bridges that are the focus of Billington's aesthetic studies are "form-resistant", or shaped to follow the most efficient load path to the support. The members of form-resistant structures are characteristically sloped, curved, or tapered to carry loads using a minimum of material. Structures as organic and exciting as Nervi's Small Sports Palace (Figure 2) may result.

Figure 2. Nervi's Small Sports Palace displays the leanness and transparency of a high-performance beauty

Variants of form resistant structures are those which change shape under the influence of an applied load in order to carry it with maximum efficiency. This strategy, "adaptive form-resistance", is demonstrated by the trampoline. Wherever the user steps, the trampoline surface deflects downward into the shape of an inverted cone with its ápex at the load point, and the tensioned, sloping surface surrounding the load pulling upward to equilibrate it. The genius of the trampoline, and of adaptive form-resistance, lies in the structure's ability to shape itself to most effectively support the load wherever it is placed on the surface. Employed frequently with flexible structures like the fabric roof used on Bigo (Figure 3) and on cable-supported glass walls, adaptive form resistance provides even greater efficiencies than are possible with its "static" form-resistant cousins built of stone or concrete.

Lightness is also achieved through "internal resistance". Rather than adjusting their shape to achieve efficiency, internally-resistant structures use prestressing to manipulate the stresses in the elements of a structure so that materials are used efficiently. Internal resistance is employed in prestressed concrete, but it is also characteristic of membrane structures and many steel applications.

Contemporary engineers are taking the pursuit of lightness a step further, using a final strategy called "load dissipation", in which the structure dampens or diverts loads, rather than supporting or resisting them. It is seen in bridge decks that are shaped for aerodynamic stability, and in skyscrapers whose stiffness is "tuned" to be out of phase with earthquake ground motions.

Light construction stategies are not unique to modern high-performance structures. Arches and shells are simple expressions of form resistance that are pervasive both in nature and in the stone construction of gothic cathedrals. Leichtbau, though, represents the systematic use of these strategies for structural efficiency, based on the analytical evaluation of internal stresses and the targeted and creative use of one or more high-performance design strategies. It creates a virtuous circle, in which structural efficiencies lead to lighter construction, with the reduced load decreasing the demand on the structure and facilitating further mass reduction. Leichtbau does not by itself assure elegance, but when a light structure is detailed to provide clear expression of the load path, and where non-structural elements do not visually conflict with this expression, the opportunity for beauty arises.

Light structures (and beautiful structures) are not necessarily economical structures, as high strength and durable materials, refinements in the shaping of members, the use of prestressing, and the introduction of curving structural forms bring added expense in fabrication and complications in the erection process. In addition, in the contemporary construction environment of the developed world, labor costs predomínate over material costs, and the material savings associated with leichtbau are often overridden by the added labor required to achieve its refinements. When designers push the techniques of leichtbau to their limits, though, there arises the potential for a special beauty that mirrors the beauty of the strongest and most technically proficient athletes.

4. The Lean & Organic Beauty of High Performance Structures

If we compare two jumpers with identical mechanics and the same ability to generate upward thrust, but with different weight, we expect the lighter jumper to clear a higher bar. A successful jumper must be lean, as well as strong, and the best have a compact but powerful musculature that can generate explosive force, and minimal body fat to hinder their ascent. A high-performance structure must also be lean, and it becomes so through the use of strong materials positioned exactly where required, and the absence of superfluous mass that might increase the tra of the structure. If the engineer employs form resistance or another of the high performance strategies to reduce dead load, the structure can be less strong (and less massive) and still reach the required span or height.

The forms of high-performance structures often curve to conform to the path that their loads take to the ground, and the cross sections of members sometimes vary along their length to reflect variations in internal forces. The forms of high-performance structures are typically derived from objective efforts to achieve lightness and efficiency, more than they are shaped by the conscious effort to create beauty. Horst Berger’s Denver Airport Terminal roof (Figure 3) provides an example. Cables spanning from side to side in the fabric valleys are prestressed, pulling downward on the fabric to pretensión it. Both cables and fabric are shaped to provide equilibrium under the required design prestress. While high performance mandated curvature in cables and fabric, the masts themselves are straight and plumb, to deliver the downward pull of fabric and cables to grade by the most direct path.

Just as leanness alters a building’s structural performance, it profoundly changes its visual character. Again, the athlete provides a useful metaphor. The leanness of an athlete’s body draws his skin tight to the muscle and bone beneath in a way that exposes the mass and geometry of his own biological structure. Leanness also reveals the athlete’s actions, telegraphing the tension or relaxation in each muscle and the articulation of joints in motion. In a lean structure, similarly, the delineation of form gives clues as to the path that forces take through the structure, and the bulk and shape of the beams and columns that compose a structure suggest the forces they resist. The layman may be unable to articulate the way that an athlete or a structure carries and responds to load. Each of us, though, through long familiarity with the action of our own bodies and observation of the trees and shells and other structures that comprise our world, can intuit with pleasure the way that a structure supports a load when leanness allows it to.

Figure 3. The Denver Airport Terminal’s roof design pursued lightness and efficiency, with beauty the result.

Leanness can’t be appreciated if obscured by non-structural elements like ceilings or partitions, or if structural members compete visually with mechanical ducting or other building services. A comparison of Nervi’s two Rome Sports Palaces illustrates the point. The dome form of the Small Palace is clearly articulated on both exterior and interior (Figure 2). From either viewpoint, it is easy to visualize the weight of the roof thrusting downward and outward against the sloping buttresses, which distribute the roof weight to the ground at their feet. The Large Palace roof has similar form, but a tall curving wall encloses support spaces around the building perimeter, and hides the view of the dome on the exterior (Figure 4). We can admire the sculptural geometries of the Large Palace form, but its façade masks expression of the roof’s load-bearing behavior. The effect is as if Fosbury had made his gold medal jump while wearing a bathrobe. The mechanics and height of the jump might be the same, but we would not appreciate its lovely efficiency. Arguments may be made for the architectural merit of either Nervi structure, yet it terms of their structural expression, the Small Palace elegantly reveals the behavior of its high performance roof, while the Large Palace does not.

Figure 4. The elegance of Nervi’s Large Sports Palace roof is obscured by competing elements on its exterior.

Revealing or obscuring a structure’s connections and other details also changes its visual impact. In designing Bigo, a waterfront canopy in Genoa, Italy (Figure 5), engineer Ove Arup (in collaboration with architect Renzo Piano) sought economy and ease of construction. Their design had another ambition, though - the athletic expressiveness derived from clearly articulating the structure’s load path. All structural members are exposed on Bigo, and detailed in a manner that makes it easy to follow loads from roof to grade. This begins with the pretensioned fabric roof, whose weight and pretension join with wind and other applied loads to pull downward on the four arches that span over the fabric. The arches are in turn held up by the arrays of suspension cables that attach to them and rise to the tops of the two tall tapered masts. In the close up on the right of the figure, the suspension cables (to the right of the mast) attach to steel gathering plates, which are linked in turn to the mast top. The overturning effect of the suspension cables is equilibrated by the counteracting pull from the stabilizing cables (to the left of the mast.) The tensions in both the suspension and stabilizing cables pull down on the mast, which carries this compressive load to grade.

Figure 5. Bigo's structural elements are all exposed, and clearly display the load path.

Bigo's details reinforce the clear expression of the load path, at the same time embodying all of the leanness of a fine high performance structure. The photos show a subtle increase in the diameter of the masts towards the center of their length, as required to prevent buckling, while at the same time minimizing the bulk at the mast ends. A further refinement is seen in the gathering plates which collect the suspension cables at the mast top, where the large circular cutout in the middle reduces both the the visual and actual mass of the plates.

The forces in the members of a structure vary constantly along their length, and designers of high-performance structures select carefully articulated forms and details that express the load path. They may vary the cross-sections of members along their length, in the way that an animal bone varies in stoutness from one end to the other in response to the varying forces that the leg of the living animal needed to resist along its length. This places these designers at odds with colleagues designing more conventional structures, who employ uniform cross sections and repetitive detailing to reduce the cost of construction labor (and their own design costs.)

Structures of the natural world are nearly infinite in variety, and respond in ingenious ways to the widely varying loads imposed by natural life. The diversity and cleverness of natural structures make them frequent models for engineered structures. Those who design vertical columns that split into sloping branches may describe them as “trees”, while the curving roof forms pioneered by Candela and others are called “shells”, in recognition of the sea shells and egg shells they suggest. Designers of curving glass walls stabilized by steel cable nets draw inspiration from spider webs.

The familiarity that all of us have with both these natural structures and the musculoskeletal structures of our own bodies provides a means for non-professionals to appreciate the behavior and beauty of high-performance structures. It also provided the means for designers of an earlier era (who lacked contemporary analytical tools) to understand and explain their work. They frequently turned to the human body as a model of how their structures carried load. When completed in 1890, the Firth of Forth railroad bridge (Figure 6) was the first long span bridge built entirely of steel. To demonstrate to the public how the bridge spanned the large chasm, the engineers used three men as props to create the iconic photograph seen on the right. The torsos of the men seated to either side of center represent the cross-braced supporting towers of the bridge displayed on the wall behind them.   Each of these "supporting" men extends one arm (braced by a sloping strut) towards the center of the bridge to support the "suspended" man seated between them. In order that the weight of the suspended man not topple the supporting men, the latter extend their outside arms (again braced by sloping struts) to ropes which are lashed to stacks of bricks. The bodies of the supporting men are balanced symmetrically between the suspended man in the center and the bricks to either side, so that they can bear their load comfortably. Their arms are straight, suggesting the tension tugging at their elbows and shoulders, but we can imagine that the muscles in their arms are relaxed. Their spines are straight and relaxed, as well, and their faces bear no strain. The ease with which they support their load provides a vivid representation of the high performance structural behavior of the Firth of Forth bridge itself.

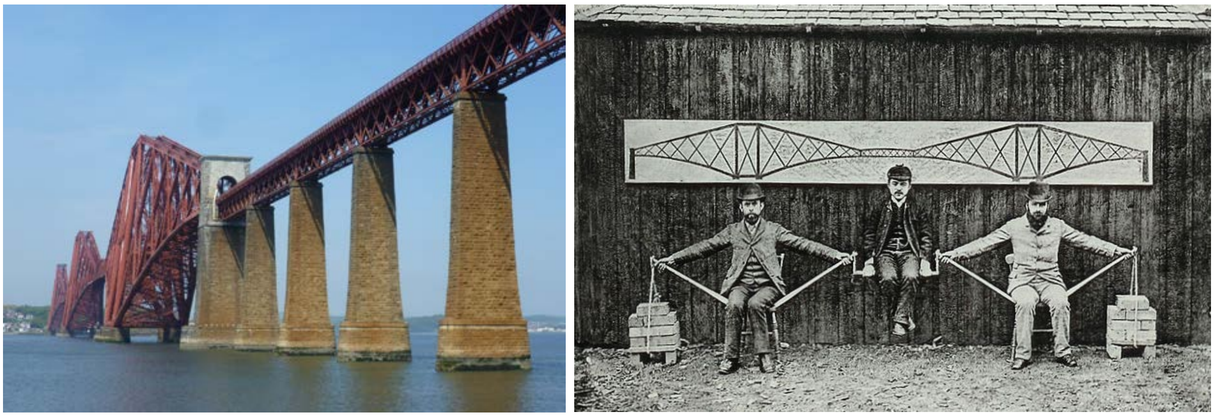

Figure 6. Human "members" were used go model the load-bearing action of the Firth of Forth railroad bridge.

5. The Pursuit of Perfection

In *The Tower and the Bridge*, Billington makes a powerful case for the subjective nature of the design choices of the select group of engineers he crowned "structural artists", and for the elements of personal style with which they worked. Billington is not incorrect, but the principles of high performance design suggest an aesthetic that relies equally on a search for "ideal" form. The architectural critic Ada Louise Huxtable eloquently captured this quality in her 1960 Nervi monograph [3]. "It is possible even for the layman to feel tension and compression, the direction of forces, and the inevitable, *correct* relationship of structure to shape", she wrote. "The fusion of structural function and abstract form creates a kind of building that is so fundamentally *right* that most other architecture seems superficial beside it." Her terms "correct" and "right" (emphasized by the present author) suggest that structures of exceptional beauty are as much the outcome of the designer's search for the ideal solution to a particular problem of loading and span as they are products of personal expression.

Rationalizing the special nature of any mode of beauty is impossible, but Nietzche's yearning "to see as beautiful what is necessary in things" provides a further clue to the aesthetic appeal of beautiful structures. Structure is the most necessary element of architecture, providing support for a building's plumbing and mechanical "organs" at the same time that it gives shape to its roofing and façade "skin".

The forms of both gothic stone cathedrals and concrete shells are founded in the simple goal of efficient load bearing – an objective more fundamental and enduring than the complex artistic and programmatic forces that drive most architectural design. Architectural critics may argue incessantly about the relative merits of particular schools of architectural practice and particular works, but there seems an unalterable quality to the structural forms of the engineering masters. How might the arch of the Salginatobel Bridge (Figure 7) be improved? Most of us prefer unblemished admiration.

Structural designers who have created work of enduring beauty have done so through a commitment to perfecting form similar to that demonstrated by elite athletes. The principal is demonstrated most clearly in the slender forms of gothic cathedrals. Cathedral designers lacked the means to provide tensile reinforcement across the joints between the stones that formed their structural skeleton, so, in order to avoid explosive failure, they were compelled to shape structural members so that the load path always fell within the member cross section.

Figure 7. Robert Maillart's contrasting concrete arches at Salginatobel (left) and Schwandbach (right).

In examining most structures, an observant structural engineer will consider the design possibilities not chosen, perhaps imagining the supporting arches with steeper or shallower slope than its designer selected, or suggesting that the arch itself be replaced by a beam or a truss. To engineers and other critical observers, the examination of most structures is an intellectually and creatively active process. The experience of examining a masterful high performance structure, though, is less one of critical engagement than of serenity in the presence of something much like perfection. An engineer might surmise the presence of a great work by the absence of his usual desire to tinker with or change it. Speaking of his contemporary Robert Maillart, shell architect Felix Candela said, "he did possess that rare quality of being able to challenge the conventional wisdom and come up with the obvious solution, one, nevertheless, which nobody could think of before" [4].

This paradox - challenging conventional wisdom to arrive at a perfect and obvious solution – is amply illustratedby Maillart's Schwandbach Bridge near Hinterfultigen, Switzerland (Figure 7), where the bridge deck, straight in elevation but curved in plan to align with the roadway approaches, is supported by an arch which is straight in plan but curved in elevation. This design, bold and unlikely in conception, appears so perfect in its finished reality that it is difficult to imagine a change to the design, or at least one that would not be a defacement of its well-integrated beauty. The nature of structural elegance, in combination with the genius of Maillart, led to a design that is unique in conception, but executed with such skill and elegance that it appears to be the inevitable solution to the design problem.

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