



Engineering Invention

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Stanley Saitowitz/Natoma Architects, Inc.
Congregation Beth Shalom
photos opposite: courtesy Forell/Elsesser; above, Bruce
Damonte

The seismic lateral forces generated by the large mass of the bowl atop the pedestal were a challenge. The high center of mass generates large overturning forces, which argues for a deep foundation. Yet piles or piers would have been costly and disruptive, besides anchoring the mass of the structure rigidly to the earth and exacerbating the effects of ground shaking. Instead, the engineer placed the pedestal on a four-foot thick concrete raft. Dynamic analysis using records of actual earthquakes indicated that a beneficial rocking action would occur, lessening the lateral forces experienced by the structure.

Invention is the product of the imagination—the discovery, sudden or deliberate, of a way of getting something done. Invention may be a solution to a “problem” or an improvement on a situation or circumstance.

Engineering is the application of science by which properties of matter and sources of energy in nature are made useful to man. It is the useful application of science to how we live.

Both invention and engineering synthesize ideas that come from many sources. Looked at this way, invention and engineering are synonymous, exemplified in Archimedes’ screw moving water uphill, in the codices of Leonardo da Vinci, which illustrate methods of moving humans through the air, and in our generation’s development of surfaces that are “invisible” to radar and light.

In the built environment, invention in structural engineering is based on the application of mathematics, physics, the science of materials and their properties, and economics and their effects on how we live in *civitas*—in civilization. These sciences affect our infrastructure, shelter, and commerce.

Common Ground

Designers want to make ideas work. It is helpful to understand the expression of an idea, and, more importantly, it is essential that the *source* or *root* of the idea be understood. If the main ideas or goals are discussed, then there can be a meaningful exchange and dialogue, and the design process can remain fluid and malleable. Designers want to create something that works in form and in function. A realistic solution will have to address aesthetics, function, cost, and expectations, among other issues.

Effective design is founded in exploring solutions that can address more than one issue, while enhancing function or purpose. The collaboration of engineering with other design disci-



plines is fruitful when all the issues are raised from various vantage points, so that the common ground, the common goal can be identified. It is about embracing “what-if?” and finding out “why.” Addressing questions of “why” gets us closer to the root of an idea. If there are other ways of addressing that idea, then solutions can be explored.

There are numerous considerations weighed in coming to a solution—constrained budgets, limited energy sources, limited space, and short and long term performance expectations. Understanding and prioritizing each of these considerations is essential to zero in on an appropriate solution.

An Early Example and a Recent One

The development of Gothic cathedrals through the centuries was spurred by the imagination and fervor of the church and their master-builders, and executed by diverse trades of masons, carpenters, and metalworkers. The Chartres Cathedral nave soars at 38 meters (124 feet) with rib-vaults that flow down the sides of the nave to rest on clustered columns. At the exterior of the building, flying buttresses with arching arms stiffen the column-piers and direct the thrust of the canopy to the ground. This cathedral, constructed of discrete blocks of brittle material, exemplifies the refinement that occurred over centuries, evolving from massive, stacked blocks to become skeletal, so that glass and light become the primary features of the cathedral.

Form can be based on analogies found in nature. Nature is efficient and is a constant source of inspiration: ribs strengthen and reinforce thin sections around them, springs and coils move flexibly, tubes and branches are models of compressive or tension, and tap roots provide anchorage.

Santiago Calatrava, architect and engineer, combines his training in both fields and expands on them through his sketches and sculpture. His work is derived from his diverse and artistic background, and his building and bridge structures are sculptural and articulated. The proportions of his works make sense and fit together, reminiscent of their anatomical basis. In his Sundial Bridge over the Sacramento River in Redding, California, the arc of the pedestrian bridge deck is suspended from cables from a single mast that leans back to the riverbank. The angle of the mast creates a palpable visual tension from the support through the steel cables to the glass roadbed. This visual tension reflects the engineering tension as well—the cable-stayed bridge is configured in such a way that the forces on the mast and foundations are not optimally minimized. Nonetheless, those forces are addressed, and the entire bridge, from the curved abutments, the arcing walkway, and the splayed cables to the swooping cantilever mast is sinuous, fluid, and expressive.

Knowledge of Properties Is Fundamental

The exploration and understanding of material properties is fundamental to structural invention—the compressive attributes and jointing limitations of masonry, concrete, and glass; the tensile and flexible characteristics of steel shapes, tendons, rods, and tubing; the lightness of thinner steel members and the limits as dictated by their geometry and crippling tendencies; the unique characteristics of wood depending on the direction of the grain and the direction of the forces; and the elastic and flexible limitations of membranes and woven materials. An understanding of the fasteners that join materials together is critical, as well. Fasteners must be compatible with respect to corrosion potential and thermal expansion rates across dissimilar materials.

An Example of Non-Transparent Form

Design of form can be realized through pure technological skill. Congregation Beth Shalom in San Francisco has a distinctive bowl resting on a pedestal; its shape includes both flat and curved surfaces, unlike a typical shell of revolution, such as a dome. The transition from level floor at the low point to nearly vertical wall at the top suggested a structural transition from a flat plate to a



above and opposite: Santiago Calatrava, Sundial Bridge,
photos by Grace Kang

deep wall beam, both in the same curved element. The curved slab is hung like a catenary ribbon from its own upper edges, which are supported by the outer ends of the side walls. These walls act as cantilevered beams, carrying gravity loads to the pedestal. A three-dimensional network of post-tensioned tendons reinforces the slabs and walls, allowing the structure to behave in this way, while limiting cracking and deflection. The form is created and expressed in the material, yet the way the form is achieved—through the network of tendons—is not transparent, contributing to the mystique of the design.

Tools to Enhance Resources

The earliest tools of structural engineering are experience-based and experimental. Some examples are deliberate and empirical, such as the construction of the dome at the cathedral in Florence, and some fall into the category of trial and error, such as the choir at Beauvais, which was intended to be the “tallest and widest” until its collapse and reconstruction. Gaudi devised forms from hanging models that created shapes, which he inverted. More than a generation ago, thermoplastic materials were loaded and isostress areas (areas of equal stress) were graphically shown with color. More recently, empirical testing with physical models that are appropriately scaled in mass and size are loaded with wind, fire, or shaking bases that simulate earthquakes. Such physical tests provide one source of information.

Another source of information is provided by computer analysis. Numerical computation is an extremely powerful tool. The speed of iterative calculations is fast, the graphic output of results can be visually revealing, enabling the engineer to perform numerous parametric studies, and the computer can be used to optimize load paths. Optimized design can also be achieved by a numerical sensitivity analysis in which a shape can be subjected to load, the stresses and deformations calculated, and the geometry of that shape automatically altered mathematically so that the stresses and deformations are minimized. Each succeeding iteration generates a form that further minimizes stresses and deformations, creating mechanical efficiency with minimal use of materials.

The effectiveness of these tools is as good as the data that goes in, and the interpretation and application of results that come out. If the information, boundary conditions, physical constraints, and material behaviors are not appropriately modeled, then the results may be misleading. An effective analysis is based on knowledge and prediction of realistic conditions. The results of analysis need to be scrutinized, compared, and tempered with physical, empirical evidence.

It's Not a Free-for-All

Creative engineering is dependent on the engineers, their resources, and their collaborators in both design and construction. Communication is essential for the best outcome. Creativity comes from broad thinking, from the ability to embrace ideas outside of the normal realm, and from the application or synthesis of those ideas to another application. Creativity may also come from the imaginative application of an existing idea to a new situation. Creativity is about knowing how to create a prototype model, knowing what to look for in the modeling, and knowing how to interpret results and refine them further.

Recognizing what aspects are fundamental to a refined solution is an important skill. From broad-based thinking, selective deliberation is required. A common thought is that there is a solution for anything. And indeed there may be. Exhibitionism can be indulged in various ways, and “brute force” will always yield a solution of sorts. However, a refined, elegant, spare, and efficient design that informs and responds to form as well as function requires thought, creativity, and discipline, freedom *through* discipline not freedom *from* discipline. Structural creativity requires both imagination and discipline, the fundamental tools of invention. ●