FORM-MAKER AND COLLABORATOR:
THE ROLE OF THE STRUCTURAL ENGINEER

BY

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ABSTRACT

Over the past century, there have existed two major types of structural engineers. Some, like Robert Maillart, contributed greatly to the advancement of new forms. Others, such as Peter Rice, produced their most innovative work in collaboration with architects. The present study analyzes the work and methodology of both groups of engineers, with the purpose of defining the common ground between them. Finally, there is a detailed discussion of the ‘form-makers’ and ‘collaborators’ in the context of the present day, in an effort to describe the basis for quality in structural engineering.

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1. INTRODUCTION

1.1 Overview

The realm of great engineers has encompassed two major groups. The first group is of structural engineers who created their own forms, such as Robert Maillart and Felix Candela. The second consists of those who pioneered innovative structural systems through their collaborations with architects; notable examples include Peter Rice, or the firm of Buro Happold.

This thesis examines the role and methodology of innovative structural engineers from both of these groups, with the goal of defining the common ground as well as the differences between them. The primary form of investigation involves case studies of one or two noted projects by each of the profiled engineers. Occasionally, it will be appropriate to examine a series of related projects by an engineer, rather than focusing on one or two, in order to gain a greater understanding of the engineer’s methodology.

Sections 2 and 3 examine the engineers and their projects in detail. Section 2 concerns the structural engineers who were “form-makers,” while Section 3 focuses on the “master collaborators.” Section 4 contains a detailed discussion that attempts to catalogue some of the similarities between the two groups of engineers. In addition, this section will explore the differences between the two groups in the context of today. Are “form-makers” a thing of the past? Have the “collaborators” become merely subservient to architects? These questions, along with related issues, will be addressed, in an effort to describe the basis of quality structural engineering.
1.2 Methodology

It is important to clarify the rationale behind the selection of the engineers or engineering firms chosen for the current paper. A set of rules was implemented:

- There was an effort to include a diverse set of engineers, who worked on many types of structures (i.e. bridges, towers, shells, lightweight structures).
- Each engineer (or firm) had to be active (had to have constructed projects) within the time period from 1900 through the present. This constraint would ensure that all the profiled engineers primarily worked with the contemporary materials of structural engineering – steel and reinforced concrete.
- Each engineer should have been a practicing professional, not merely an academic. Each engineer should have built a large body of quality projects.
- Each engineer should be internationally recognized as a pioneer in the field. This would ensure that documentation and literature would be easily available.
- Each engineer should be recognized as an engineer – not merely as an architect or builder – by the engineering community. Each engineer should self-identify as an engineer, whether or not they also embrace other roles.

Each engineer or firm’s profile will include the same set of information. This will include:

- The building types, forms, or structural systems that the engineer (or firm) is most famous for.
- The context of their education (for engineers) or the motivation behind their origins (for firms).
- The general design philosophy of the engineer or firm.
Case studies of a few major projects. Occasionally, it will be appropriate to examine the links between a series of related projects, rather than to focus on one or two – this is especially true when an engineer is known for developing a specific form. Whenever it is possible to do so, the engineer’s method of creating these forms or systems will be examined, as well as the context in which these projects were created. All of the projects must have been constructed – not merely paper studies, and must have been completed at the time of this writing.

Occasionally there would be a famous engineer who worked for an equally famous firm (i.e. Fazlur Khan, who spent his career at Skidmore, Owings and Merrill (SOM)). These engineers usually gained a reputation based on extraordinary individual achievements, and will be profiled separately from their firms. In that case, projects which were notably attached to the engineer’s name will be profiled under that engineer, while projects more attached to the corporate face will be profiled under the firm’s name. For example, the John Hancock Center of Chicago is integrally tied to Khan’s name, while the forthcoming Burj Dubai is known as an SOM project.

It may be noted that any survey of engineering history is subject to omissions and subjectivity. While this paper does not necessarily cover the most representative sample of structural engineers, it certainly attempts to present a diverse selection.
2. THE FORM-MAKERS

2.1 Robert Maillart

Robert Maillart (1872-1940) was a Swiss engineer who became famous for his pioneering use of reinforced concrete, primarily in bridges. Billington is perhaps best at explaining the unique nature of his achievements: “Maillart was the first engineer to sense that the full expression in concrete structures could be efficient (safe performance with minimum materials, economical (accountable to the public welfare or to private industry with competitive costs), and elegant all in the same construction” (2003, p. 32), and “He was the first twentieth-century designer to break completely with the masonry past and put concrete into forms technically appropriate to its properties and yet visually surprising” (1985, p. 155). Hidden in the Swiss wilderness are dozens of Maillart’s bridges, the vast majority of which are still in use, as well as the majority of his major buildings (Billington, 1985).

Maillart perfected several different forms during his career, especially the three-hinged arch (most famously in the Salginatobel Bridge) and the deck-stiffened arch (as seen in many bridges including the Valtschielbach and Töss Bridges) (Billington, 1990). His work shows an iterative quality; he improved upon his previous works when designing new ones.

As a youth, Maillart demonstrated excellence in mathematics, and received admission to the prestigious Federal Polytechnical Institute in Zurich (also known as the present-day ETH) (Billington, 2003, p. 32). It was there that he had the great fortune to come under the tutelage of one of the legendary teachers of civil engineering – Wilhelm Ritter – who was his professor for several classes: “graphic statics, stone, wood,
and iron bridges, and bridge construction” (Billington, 2003, p. 33). Ritter’s approach to structural engineering education was unique: “[He] taught the value of both experience and calculations: his lectures were animated by continual reference to full-scale, completed designs, and he unceasingly confronted his students with the fact that the creation of structures is both an aesthetic and a scientific enterprise” (Billington, 1985, pp. 152-153); “[Ritter’s] approach encouraged his students to visualize the flow of forces within a structure as well as the way in which different forms could change that flow” (Billington, 2003, p. 32). Ritter’s approach, which incorporated a visual and aesthetic sensibility into engineering design, was likely crucial in influencing Maillart’s future work.

After ETH, Maillart worked for several other companies before setting up his own design and construction business (Billington, 2003). He began creating his innovative bridges only several years after graduation; at first, the clients were so skeptical of his unusual designs that they occasionally brought in Professor Ritter as a consultant. Each time, Ritter was supportive; he never found any major design changes to be necessary, even after an intensive analysis and load-test for Maillart’s first major bridge at Zuoz (Billington, 2003). As time went on, Maillart was able to demonstrate that his designs were not only structurally sound; they were cost-effective in their use of material and construction scaffolding (Billington, 1990). Unfortunately, Maillart lost his profitable business amidst the chaos of World War I, and eventually set up a small design firm (in contrast to his design-build construction firm from previously) (Billington, 2003). This did not seem to have stunted his creative ability; it was after the war that he created many of his best-known bridges, including what is widely regarded as his masterpiece, the Salginatobel Bridge.

As Maillart became a more experienced designer, he came to realize that good designs could be achieved with a good understanding of structural engineering
principles, reinforced by observation of built projects, without requiring extensive mathematical analysis (Billington, 2003). There is no doubt that he was a supremely technically proficient engineer; he was merely streamlining his earlier methods of calculation, and his bridges were all still load-tested to verify his methods (Billington, 2003).

Maillart’s legacy has been significant, especially in the minds of a younger generation of engineers (including Felix Candela, Heinz Isler, and Christian Menn). Many of them have openly embraced Maillart’s influence, as they continue to generate new forms that are widely acknowledged as structurally efficient as well as elegant and original (Billington, 1990).

2.1.1 Three-Hinged Arches: The Path to Salginatobel

The Salginatobel Bridge (completed 1930) (Fig. 2.1) has become one of the icons of twentieth-century structural engineering. At 90 meters, this three-hinged
hollow-box arch is Maillart's longest bridge (Billington, 1985). Maillart (along with a builder) won the commission in a design-build competition (Billington, 1985).

The significance of the Salginatobel will become clearer if placed in context with the works that preceded it. Maillart arrived on the engineering scene at a time when reinforced concrete was only beginning to gain acceptance. “He entered the field after the pioneers had developed useful methods for design and construction [of reinforced concrete] but before anyone had dared to invent new forms that departed radically from the aesthetic of those earlier materials [stone, wood, and steel]” (Billington, 2003, p. 32). Viewed chronologically, Maillart’s projects demonstrate his developing expertise in working with this new material, allowing him to reach the level of the Salginatobel. What follows is a selection of his three-hinged arch bridges that formed the basis for Salginatobel.

Figure 2.2. (top) Zuoz Bridge; (bottom) Cracks near abutments (Billington, 2003, p. 39)

His first major bridge – at Zuoz (completed 1901) (Fig. 2.2, top) – was “the first concrete hollow-box structure ever built” (Billington, 2003, p. 37). The deck, arch, and
walls act together to carry the loads; these three elements together form a hollow box girder in cross-section (Billington, 2003). The hollow box construction made the bridge stronger and lighter than a comparable solid stone bridge; in addition, the scaffolding would only need to carry the arch while it hardened, because the arch could then carry the walls and the deck (Billington, 2003). It was thus an economical design on several accounts. As mentioned previously, Ritter was called to conduct an independent analysis, and afterwards directed the legally required public load-testing ceremony (Billington, 2003).

It will be noted that the Zuoz Bridge does not outwardly appear significantly original, especially compared to the previously popular stone and masonry bridges. Billington notes that Maillart was still somewhat fettered by the traditional styles of design (2003). This would change after Maillart was consulted on cracks in the walls near the Zuoz Bridge’s abutments (Fig. 2.2, bottom), two years after the opening. Maillart realized that the cracks were not structurally dangerous; more importantly, “he now understood that the arch’s internal forces, while distributed over the entire box section at the crown [the center of the bridge], gradually moved down the walls to focus entirely at the abutment hinges” (Billington, 2003, p. 38). In other words, he realized that the cracked portions of the bridge were essentially useless to the structural system. This would lead to yet another competition-winning bridge, the Tavanasa (Fig. 2.3).
With the Tavanasa Bridge (completed 1905), Maillart did not merely remove the useless parts of the structure from the Zuoz; he also modified the arch’s shape to reflect the higher moments experienced at the quarter-points of the arch (Billington, 1990). Billington notes that this was the first of Maillart’s designs that could not have been built using the previously popular stone materials (1990); this was a true advancement in concrete design. Note that the ‘traditional’ (for that time) stone abutments are still present in this design. Yet even this design was judged “too radical” by the people of the time, and Maillart was not to build another hollow-box arch bridge until the Salginatobel, more than two decades later (Billington, 1990).

With the Salginatobel Bridge (Fig. 2.1), Maillart eliminated the stone abutment walls completely, creating the entire form out of concrete in a single visually continuous piece. He also shaped the cross-section of the bridge in a way that allowed its internal stresses to remain low for all loading conditions (Zalewski & Allen, 1998). Zalewski & Allen also note that he designed the Salginatobel (and probably most of his other work)
using graphic statics; this is evident in a Salginatobel design drawing by Maillart (Fig. 2.4).

Maillart continued to ruminate over his built works. Reflecting upon the Salginatobel a few years after its opening, he wrote, “Even the [Salginatobel Bridge] cannot lay claim to complete sincerity of form...It was only in the bridge at Felsegg built as recently as 1933 that I had the chance of realizing a truly logical form” (as cited in Billington, 2003, p. 60). Maillart had realized that instead of leaving the underside of the arch smooth (as was traditional), he should have articulated the moments in the arch with a slightly more angular profile (Billington, 2003), as he eventually did with the Felsegg Bridge (Fig. 2.5). The moment diagrams from two point loads – two trucks – at the quarter points of the bridge help to explain Maillart’s thoughts (Fig. 2.6) (Billington, 2003, p. 60).
2.2 Felix Candela

Felix Candela (1910-1997) was Spanish-born engineer and architect who became famous for building thin concrete shell structures derived from hyperbolic paraboloids ('hypars'). Like Maillart, Candela was keen to exploit the properties of reinforced concrete, using his knowledge of membrane theory, as well as learning from his built projects (Garlock & Billington, 2008). His shells can be seen in many places in Mexico, where he spent most of his life; among them are the Restaurant at Xochimilco, the Cuernavaca Chapel, the Bacardi Run Factory, and the Church of our Lady of the Miraculous Medal. These are all hypar-derived forms with curved edges, and belong to
Candela also built a vast number of straight-edged hypars forms (known as ‘umbrellas’) that functioned as his firm’s most profitable type of work, since they were built inexpensively with reusable scaffolding and formwork (Garlock & Billington, 2008).

Candela studied architecture at the Escuela Superior de Arquitectura in Madrid, where the architectural curriculum included rigorous technical training (Garlock & Billington, 2008). Candela, however, excelled at these studies (especially in mathematics), even tutoring his fellow students and serving as an honored teaching assistant for the class on theory of elasticity (Garlock & Billington, 2008). While at the university, he became extremely interested in shells, and spent a lot of time studying independently by reading as much related literature as he could find; he would continue this self-study even later in his life (Garlock & Billington, 2008). Almost immediately after university, Candela was caught in the Spanish Civil War; he fought on the losing side and was sent to Mexico as a refugee (Garlock & Billington, 2008). It would be in Mexico that Candela finally had a chance to develop his skills: “After World War II, Mexico enjoyed a period of political stability and growth...Candela was able to take advantage of the unprecedented building boom that Mexico...underwent. In the Mexico of the 1950s, there were no restrictive codes that made thin shells difficult to build, and labor was sufficiently inexpensive that new construction methods did not unduly burden costs” (Garlock & Billington, 2008).

Candela worked for other people for several years before starting a shell building business with his brother and his friends; in the beginning, his shells were not very innovative (Garlock & Billington, 2008). He continuously learned from his built projects, and like Maillart, he believed in developing his forms based on his experience
and with "simplified calculations rather than rigorous [mathematical] analysis" (Garlock & Billington, 2008, p. 64).

2.2.1 The Curved-Edge Hyperbolic Paraboloid Shell and the Restaurant at Xochimilco

![Figure 2.7. The Hyperbolic Paraboloid (Garlock & Billington, 2008, p. 79)](image)

The hypar is a doubly-curved shape, often described as a 'saddle' (Fig. 2.7). Eventually, Candela developed hypars that could be built without ribs or stiffeners, and were extraordinarily thin (some were approximately 1.5-in-thick) as well as strong, due to their optimized forms. The advantage of the hypar was that it could be generated with straight lines – the scaffolding could be built with straight pieces of wood. His shells were carefully designed to avoid bending stresses and concentrated local forces (Garlock & Billington, 2008).

As Candela became more confident in designing and building hypars, he began to invent new forms. His Restaurant at Xochimilco (completed 1958) (Fig. 2.8), one of his most popular works, is actually formed from four intersecting hypars (Fig. 2.9). Typical of Candela’s shells, the scaffolding was created in straight lines of wood, (flexible) foam board strips were laid on top of the scaffolding (Fig. 2.10), the rebar cage was laid on top, and the concrete was poured onto the rebar cage one bucket at a time (Garlock & Billington, 2008). Although the eight ‘petals’ of the structure are identical, Candela built them simultaneously so that the forces in the structure would balance.
Figure 2.8. The Restaurant at Xochimilco (Garlock & Billington, 2008, p. 144)

Figure 2.9. Four Intersecting Hypars overlaid on One Hypar (Garlock & Billington, 2008, p. 79)

Figure 2.10. Workers Placing Foam Boards on Scaffolding (Garlock & Billington, 2008, p. 148).
Because this type of structure sends the shell forces to the groins (where the separate ‘petals’ of the roof intersect), Candela hid V-beams inside the groins of the structure, which allowed the structure to be simplified into a series of three-hinged arches for simple analysis (Garlock & Billington, 2008). The groins send the forces to the supports, for which Candela simply used his famous ‘umbrella’ structures to cup the earth (Garlock & Billington, 2008).

About twenty years later, a then young German engineer, Jörg Schlaich, built a similar shell structure in Stuttgart as a tribute. Schlaich used his shell, a temporary structure, to experiment with new materials and construction methods (Garlock & Billington, 2008). When Schlaich invited Candela to visit the project, he was surprised by the elder engineer’s generous reaction to his ‘copy’: “[Candela] laughed, clapped his hands, climbed up and jumped on it...With tears in his eyes, he said, “It feels very good to know that your own work is useful and interesting enough to bear fruit in the mind and work of some younger colleagues.”” (as cited in Nordenson, 2008, p. 143).

2.3 Christian Menn

Christian Menn (born 1927) is a Swiss structural engineer who greatly advanced the field of prestressed concrete in the design of bridges. He has become one of the world’s foremost bridge designers. His many bridges in Switzerland are strikingly original and streamlined, reflecting the work of a technically skilled engineer who has a high regard for aesthetics. Some of the most famous are the Tamins Bridge, the Felsenau Bridge, the Ganter Bridge, the Sunniberg Bridge, and the Leonard P. Zakim Bunker Hill Memorial Bridge in Massachusetts. Menn is careful to emphasize that bridge design constitutes a balancing act between four standards: “safety, serviceability,
economy, and elegance,” listed in their order of importance (Menn, 1990, p. 49). He notes that safety and serviceability are “achieved through the systematic application of scientific principles” but that economy and elegance are “achieved through nonscientific means” and depend on “the creativity of the engineer” (Menn, 1990, p. 49). Billington notes that Menn’s views on bridge design were not arbitrarily defined, but instead refined through many decades of practical experience (2003).

Menn studied civil engineering at ETH at a time when “structural analysis found itself...in the transition from descriptive graphic analysis to abstract analytic statics” (as cited in Billington, 2003, p. 167). Menn was aware of the advantages of each method, but he was influenced by the teachings of his Professor Pierre Lardy. Lardy was a teacher in the tradition of Wilhelm Ritter; although Lardy had first trained as a mathematician, he understood the limitations of relying purely on mathematical analysis for engineering design (Billington, 2003). Lardy encouraged his students to follow in the tradition of engineers like Maillart, who “placed greatest value on the graphic qualitative analysis as the simplest method to find the distribution of forces in the form” (Menn, as cited in Billington, 2003, p. 167). After university, Menn stayed at ETH to pursue his doctoral degree with Lardy; this provided Menn with some excellent opportunities for studying prestressed concrete bridge design (Billington, 2003).

Menn soon opened his own engineering consulting firm (in 1957), and won many competitions for new bridges around Switzerland (Billington, 2003). Some of his notable earlier designs (such as the Tamins Bridge) were Maillart-inspired deck-stiffened arch bridges. Throughout his early work, Menn was beginning to incorporate prestressed concrete to generate longer spans. Eventually, Menn realized that the nature of prestressed concrete allowed it to be shaped in ways that rendered the arch unnecessary; the deck of the bridge could become the primary supporting member of
the bridge (Billington, 2003). Furthermore, there would be no more need for complicated scaffolding or formwork for the arches. This would open up a new direction in his bridge forms, which will be explored in the following section.

In 1971, Menn was appointed as a professor at his alma mater ETH, and left his private practice as required by Swiss law (Billington, 2003). However, he was still consulted on major projects from around the country, including many competition-winning designs, and many of his greatest projects came from this time. As a consultant, he would generate the general form of a bridge, as well as specify the required calculations and construction procedure (Billington, 2003).

Menn is an ardent advocate of good aesthetics in bridge design, but he cautions: “From an engineer’s point of view, it is inconceivable to accept flaws in the structural system and details or disproportionately high cost in return for architectural embellishment” (as cited in Billington, 2003, p. 192).

2.3.1 Integration of Elegance with Structure: The Way to Sunniberg

Several of Menn’s finest bridges will be highlighted below in order to explain his design methodology and the depth of his achievements.

The Felsenau Bridge (Fig. 2.11) (completed 1975) was, at 3600 ft in length, Switzerland’s longest-spanning bridge at the time of its opening (Billington, 2003). The bridge is curved in plan. Its deck (Fig. 2.12) is composed of a single hollow box girder that is partially prestressed to allow for the cantilevered slabs on either side at the top (Billington, 2003). This design with the cantilevered slabs allows the outer edges of the deck (the cantilevered sections) to be built with simple scaffolding off of the main boxes, once the main boxes have been completed (Billington, 2003).
The box girder of the deck also changes gradually in cross-sectional geometry as it nears the vertical columns below. The box gets deeper (to decrease moments at midspan) and narrower at the bottom (to coincide with the width of the supporting columns) (Billington, 2003). These details arguably add an extra dimension to the appearance of the bridge.

The Felsenau's deck is supported by pairs of thin columns (one pair is prominently visible in the foreground of Fig. 2.11). Each column is 40 ft from its partner; this generous spacing has several advantages. Firstly, this provides the deck with a high longitudinal stiffness (Billington, 2003). Secondly, it provides ample room for a scaffolding platform to be built over each pair of columns, to aid in construction. Finally,
the double-column solution allows for the bridge to appear more transparent and lightweight when viewed in elevation (looking through the columns).

![Figure 2.13. Ganter Bridge (Structurae Website)](image)

The Ganter Bridge (Fig. 2.13) (completed 1980) replaced the Felsenau as the longest bridge in Switzerland. It is situated on a challenging site, with poor subsurface conditions. Menn began by positioning the support columns at places where the soil conditions were best, and then tweaked these positions to allow for a level of visual “symmetry and uniformity” (Billington, 2003, p. 181). The most surprising property of this bridge is that it is actually a cable-stayed bridge; the cables are encased within the thin triangular walls that span from the top of each pylon to the deck. The cables provided a way to lower the moment experienced in the bridge, but had to be encased in concrete due to the curvature of the bridge in plan (Billington, 2003). The encased stays are also protected from corrosion, and experience smaller stresses due to their chemical bond with the concrete. The walls in which the stays reside are essentially prestressed concrete walls (Billington, 2003). The overall effect of the bridge is very prominent against the natural backdrop.

Menn indicated that he was continually learning from his built works. In speaking about the Ganter, he indicated that some aspects of the design could have been made more economical, and that the cross-sectional view of the pylons above the deck
appeared "heavy and clumsy" to persons driving on the bridge (as cited in Nordenson, 2008, p. 132). Nevertheless, the bridge won numerous awards for its original design.

The Sunniberg Bridge (Fig. 2.14) (completed 1999) is one of Menn’s more recent projects. Here, as in the Ganter, the site conditions already require the deck to be rather high above the ground, so the pylons do not rise much further above the deck. The most prominent part of the bridge is the integrated pylon and support column; where many cable-stayed bridges separate these two elements, this bridge joins them into one elegant piece (Fig. 2.15). These columns are also very open in shape, in contrast to the ones at Ganter. Above the deck, the pylons bend outward from the deck, and grow wider with height; this expressive detail actually also helps the deck resist bending from certain live load cases (Billington, 2003).

The cables are placed parallel to each other in the harp configuration. While this is not the most optimized structural solution, Menn believed it was crucial to prevent a visual entanglement of the cables when viewed from various angles.
The site also necessitates the bridge to be curved in plan, which Menn used to his advantage; he omitted the expansion joints on the deck because the curvature allowed for the deck to expand and contract as an arch (Billington, 2003). The presence of the cable-stays and the stiffness of the pylon allow for the deck to be very thin (Billington, 2003).

Like the Ganter, the Sunniberg Bridge has won many awards for its expressive design. It is also highly visible to visitors, as it is situated on a busy highway route and in front of a resort.

Figure 2.15. Detail of Sunniberg (Christian Menn Website)
3. THE MASTER COLLABORATORS

3.1 Fazlur Khan

Fazlur Khan (1930-1982) became one of the world’s foremost designers of skyscrapers. Khan was a strong advocate of collaboration between the architect and the engineer: “His argument for collaboration...was a reaction against the idea of the architect alone producing the visual design and the engineer merely making the work safe and inexpensive” (Billington, 1985, p. 244). This is apparent in studying the many buildings that he worked on during his lifelong career at Skidmore, Owings and Merrill (SOM) – a corporate architectural firm with a famed structural engineering department. Khan’s buildings often expressed their structure on their exterior façades; he worked closely with the project architect (often his colleague Bruce Graham) to ensure that the architectural shape would never devolve into the realm of structural inefficiency (Khan, 2004).

Khan was adept as using both concrete (as seen in his Onsterie Center in Chicago) and steel (most famously in the John Hancock Center and Sears Tower, both also in Chicago); he also pioneered and refined many new structural systems for towers, especially the ‘trussed tube’ (used for the Hancock) and the ‘bundled tube’ (used for the Sears). His achievements were significant because they came at a time when the conventional construction methods for tall buildings were becoming costly and inefficient as the building heights increased above a certain level (Khan, 2004).

Khan was born in Bangladesh (then East Pakistan) and began his engineering studies at Calcutta Bengal Engineering College. Shortly after graduation, he received two highly competitive scholarships – a Fulbright, and a government scholarship – which allowed him to advance his studies of structural engineering at the University of
Illinois. In the three years covered by his scholarships, he earned an astonishing two master's degrees (in civil engineering, and in theoretical and applied mechanics), as well as a doctoral degree (Khan, 2004). Immediately after his graduate studies, Khan worked at SOM in Chicago for two years, upon which he returned to Bangladesh, with the aim of applying his new knowledge to the improvement of his homeland (Khan, 2004). However, it soon became apparent that bureaucratic and political hurdles would prevent him from receiving a job that would allow “[an] opportunity for the progressive thought that he desperately longed for...[After two years] fear of a slow, intellectual death began to haunt him” (Khan, 2004, p. 38). Khan made a sorrowful decision to return to the US (where he immediately returned to SOM), but in later decades he would increasingly use his expertise to contribute to humanitarian causes in Bangladesh (Khan, 2004). Khan would stay with SOM for his entire career, eventually becoming a partner.

Khan’s legacy can be seen through the fact that the structural systems that he worked on have become conventional systems for tall buildings since the days when he first propelled them to the forefront (Khan, 2004).

3.1.1 The John Hancock Center

The John Hancock Center (completed 1970), apart from enduring as one of Chicago’s tallest and most iconic buildings, was also perhaps Khan’s favorite of his works (Khan, 2004). More importantly, the tower spoke of a significant level of collaboration between architecture and engineering: “The structural clarity of the architectural design confirmed the active role that structural engineering innovation could assume in the evolution of high-rise architecture” (Khan, 2004, p. 105).
At 1,127 ft in height, the 100-story tower houses 2.8 million square feet of office and residential space. An initial design had called for two smaller towers – one for the offices, and one for the apartments (Khan, 2004). Architecturally, there were issues with a two-building scheme; the architectural design team (led by Graham) noted that natural light and views would be compromised by two such closely-situated buildings, among other things. Khan realized that a single-tower solution could be built economically if a radically new structural system was used (Khan, 2004).

Prior to the Hancock, it had already been established that a tall building could resist lateral loads and minimize interior column use if the exterior faces of the building could be designed to bear load (especially lateral loads). For one of Khan’s previous buildings, the Chestnut-DeWitt Apartments (completed 1963 in Chicago), this was accomplished with the use of a grid-like system of closely-spaced exterior columns working in conjunction with deep spandrel beams – a “framed tube” design (Khan, 2004, p. 103).
What Khan proposed for the Hancock was both structurally and visually distinctive (Fig. 3.2). Khan, who also taught at the Illinois Institute of Technology, had helped one of his students develop a lateral-load-resisting system for tall buildings using exterior diagonal bracing (Khan, 2004). This structural system, which came to be known as the ‘trussed-tube,’ would require much less steel than a ‘framed-tube’; the ‘trussed-tube’ would not require closely-spaced columns, because the various components could interact intelligently. The multistory diagonal brace worked to carry and distribute both gravity and lateral loads, and minimized the shear-lag effect; the columns and diagonals also carry minimal bending (Khan, 2004).

Khan held fast to his design concept despite initially skeptical comments from peer review engineers, several of which offered their services as the main structural engineers on the project (Khan, 2004). Eventually, SOM decided to allow Khan to continue developing his concept. As design proceeded, Khan worked with the rest of the architectural design team to develop a tapered profile that would both benefit from the new bracing system as well as provide for programmatic requirements (the
apartments were to be located near the top of the building, while offices, which required larger floor spaces, were located below) (Khan, 2004). The team also worked out the dimensions of the building in order to resolve the geometric constraints between the building taper, the angles of the diagonal braces, and the required floor-to-floor heights (Khan, 2004). In the apartment levels, the architects and engineers worked to hide ceiling beams inside partitions or other room separators to allow for more open ceilings and a more luxurious space for residents (Khan, 2004).

Khan realized that the connections between the ends of the diagonal braces and the rest of the frame would be crucial to the entire system working effectively; he thus worked closely with the steel fabricators on the connection design and erection procedure (Khan, 2004). Complicated connections were to be welded before arriving on site, and on-site connections were primarily bolted to speed construction and reduce labor costs (Khan, 2004). Wind tunnel tests were used in aiding the design, but at the time there was no specified code for motion perception in tall buildings (Khan, 2004). Khan’s team had to rely on data taken from other tall buildings, and Khan even performed a few qualitative tests on his own to better (Khan, 2004).

A final major contribution by Khan should be noted. During schematic design, the architects proposed eliminating the top-most set of diagonal braces, so that the residents in those (more luxurious) apartments would have completely diagonal-free windows. Khan was extremely opposed to this idea; he felt strongly that the building’s rational aesthetic was at stake, and that the structure would no longer appear logical to the eye (Khan, 2004). Although he knew that the structure of those top floors could be tweaked to allow for the omission of these braces, he opposed this design change by slightly exaggerating the structural importance of those braces (Khan, 2004). His arguments worked, and the braces were retained.
The diagonals themselves have become a famous idiosyncrasy of the building. Even today, the windows with the diagonal braces running across them have been known to attract higher rent than the ‘regular’ windows.

3.2 Peter Rice

Peter Rice (1935-1992) was an Irish-born structural engineer who rose to prominence as one of the most creative engineers of his time. During his career, he worked on numerous innovative projects with many high-profile architects, becoming close collaborators with several of them (most notably Renzo Piano and Richard Rogers). Among the diverse projects that he worked on were the Sydney Opera House, the Centre Pompidou in Paris, the Pavilion of the Future for Seville’s 1992 Expo, the Lloyd’s Building in London, La Villette in Paris, the Kansai Airport outside Osaka, and the Menil Collection in Texas. His contributions to the advancement of both structural engineering (and by association, architecture) earned him numerous accolades. As a testament to his ability to work with other disciplines, he was awarded the esteemed Royal Gold Medal for Architecture from the Royal Institute of British Architects (RIBA); Rice was one of the few engineers to ever receive this award.

However, even more revealing is this excerpt from his acceptance speech for that award: “If I have a philosophy, if I have a belief, it is the contribution that we can make and the contribution that we should make, is not to be quasi-architects. People often call me an architect-engineer, that’s a lot of rubbish, I am an engineer, plain and simple” (as cited in Brown, 2001, p. 6). Rice did not ever believe that he was crossing the realm into architecture, a profession for which he had tremendous respect. And yet he believed in expanding the narrow confines of the traditional engineer’s role; he
rebelled against the conventional image of an engineer as a ‘number-cruncher’ (Brown, 2001). What made Rice stand out from his peers was his ability to combine his supreme technical skill with creative solutions that not only allowed his architect partners to realize their designs; Rice’s collaboration arguably augmented the finished product. In an obituary in The Independent, Piano is quoted describing Rice as “like a pianist who can play with his eyes shut; he understands the basic nature of structures so well that he can afford to think in the darkness about what might be possible beyond the obvious” (as cited in Rice, 1994, p. 179).

Peter Rice grew up in a provincial village near Dundalk, where his father, noting his aptitude for mathematics, encouraged him to pursue the more practical profession of engineering (Rice, 1994). Accordingly, he studied civil engineering at Queen’s University Belfast, and undertook post-graduate studies at Imperial College, after which he joined the firm Arup full-time as a structural engineer (Rice, 1994). Rice would stay with Arup for the rest of his life, rising through the ranks to Director (Brown, 2001). Simultaneously, he formed several partnerships with various architects or engineers; the most enduring one of these was the firm of RFR, which he formed with the architect Ian Ritchie and the engineer Martin Francis in 1982 “to try and combine architects and engineers in equal partnership” (Rice, 1994, p. 183).

Also of interesting note is that after several years at Arup (mostly spent laboring over the Sydney Opera House), Rice spent a sabbatical year as a visiting scholar at Cornell University, where he studied “the application of pure mathematics to engineering problems” (as cited in Brown, 2001, p. 13). This is just one example of how Rice was an engineer who never wanted to stop learning, and brought his sense of inquisitiveness to his work over his entire career.
3.2.1 Centre Pompidou (Beaubourg)

The Centre Pompidou (Fig. 3.3) in Paris was Rice’s second major project at Arup, after the Sydney Opera House. It was also perhaps the project that first established him as a respected engineer in his own name.

Figure 3.3. Centre Pompidou (Centre Pompidou Website)

The project, completed in 1977, was conceived by a partnership between architects Renzo Piano and Richard Rogers, as the winning competition entry for a new arts and culture center. Arup had supported Piano & Rogers during the competition stage of the project, and Rice became the lead structural engineer on the project as the scheme evolved into reality (Brown, 2001). In his memoir (1994), Rice provides a detailed account of his involvement, without failing to give credit to many others – both his colleagues and his junior engineers – that contributed to the various elements of the project.

The building itself required “future flexibility,” (long spans for clear floor-space that might receive very irregular loading), and had the unusual feature of carrying nearly all of the services (i.e. ventilation ducts, electricity, etc.) and circulation systems on the
façade (Rice, 1994). These challenges would require an innovative structural system that would not conflict with the architectural intent. Rice was particularly sensitive to the design’s integration with the public and lack of traditional austerity, in contrast with other arts centers or museums, and his work on the structural detailing reflects this sensitivity. He realized that the structure would be highly visible to the end-users of the project (a detail of the façade is shown in Fig. 3.4), and thus much effort would have to be spent on detailing the structure so that “the building would be read as tactile and unintimidating: something with a human quality” (Brown, 2001, p. 49).

Rice mentions that his team submitted several schemes to the architects, before consensus was reached on a cast-steel system centered around gerberettes, which will be explained below (1994). His reasoning for using cast-steel, an unusual choice, reflected his desire to bring an element of craft to the structure (in order to ‘humanize it’), as well as his desire to innovate new uses for existing material and work with new
material (Brown, 2001). His team worked extensively with the steel manufacturers to ensure that the cast-steel pieces would be of the required strength and quality (Rice, 1994).

It was the idea of using gerberettes (Fig. 3.5) – a specially shaped connector beam – that finally allowed Rice’s team to develop the final structural system (Fig. 3.6) (Brown, 2001). The gerberettes allowed for the interior trusses to be integrated with the exterior gerberette-column bracing system (Brown, 2001); as Saint notes, the gerberettes “do a structurally critical job and are therefore engineers’ details” (2007, p. 384). The gerberettes also allowed the outermost plane of columns (most visible to passerby) to be extremely slender because they essentially vertical tension ties (Rice, 1994). The gerberette itself changes in cross-sectional shape (Fig. 3.7) so that it articulates how the loads are being carried (i.e. the gerberette is deeper where it receives a large moment at the inner column, and the web becomes thicker where it

Figure 3.5. Detail of Connection at Gerberette (Rice, 1994, p. 32; annotations by the author)

Figure 3.6. Cross-Section Through Building Showing Structural System (Rice, 1994, p. 32)
receives more shear) (Brown, 2001). It is clear that the complexity of the gerberettes would have made it impossible for them to be formed as rolled sections (Brown, 2001); this shows how Rice’s team took advantage of the qualities of cast steel.

Figure 3.7. Gerberette Detail (Brown, 2001, p. 53).

Some days after the Centre Pompidou was opened to the public, Rice noticed an elderly lady sitting next to a gerberette: “I watched her for a while, just sitting quietly, stroking the side of the gerberette, she was not afraid, not intimidated and she was on the fourth floor. And I thought that if somehow, by introducing elements like that, we can make people...feel comfortable, it proved to me that the thing that really matters is to introduce elements and materials into buildings in a way which reflects their real nature...It was worth it” (Rice, 1994, p. 46).

3.3 Buro Happold

Buro Happold was founded in 1976 by Sir Edmund Happold (1930-1996), a structural engineer who had worked on ground-breaking projects at Arup. Buro Happold has since become a leading multidisciplinary firm that provides an array of building engineering services (as well as infrastructure and environmental services) with a staff of 2000 spread across 25 international offices. The firm strives to provide quality
engineering services in conjunction with innovation and sustainability. Some notable projects include the Great Court of the British Museum in London, the Millennium Dome in Greenwich, the Al Faisaliah Complex in Riyadh, the Sheffield Winter Gardens, the Danish National Opera House, and the Genzyme Headquarters in Massachusetts.

The firm has collaborated with a number of notable architects, engineers, and inventors (including Norman Foster, Shigeru Ban, Frei Otto, and Chuck Hoberman) on a diverse assortment of unconventional project types. The firm’s commitment to collaboration is grounded in Edmund Happold’s personal view of engineering: “A world which sees art and engineering as divided is not seeing the world as a whole...[structural design should] achieve elegance as well as value; elegance in the mathematical sense, meaning economy as well as appropriateness. Appropriateness (or function) + economy = value” (as cited in Rappaport, 2007, p. 67).

Buro Happold’s structural engineering department has been particularly successful, especially in the field of lightweight structures. From its early days, the firm has been involved in extensive research in lightweight structures and new materials (Rappaport, 2007). The firm has also developed Tensyl – a piece of software for designing tensile structures. With Tensyl, perhaps the most useful feature is its ability to “map flat panels on a curved surface” – thereby making it possibly to create complicated curvilinear surfaces with flat pieces of material (Rappaport, 2007, p. 70).

3.3.1 The Great Court Roof at the British Museum

The British Museum in London began an extensive renovation in 1999, a commission that Foster and Buro Happold won in 1994 (Rappaport, 2007). In addition to structural engineering services, Buro Happold also provided building and fire services, as well as project planning services for the project. The centerpiece of the
work was to be a new roof for the Museum’s central courtyard. At the time of its completion (in 2001), the Great Court roof (Figs. 3.8 and 3.9) was the “largest covered courtyard in Europe” (Rappaport, 2007, p. 76).

The project required the engineers (led by Mike Cook and Stephen Brown) to develop a design that would satisfy the architect’s desire for a lightweight roof covering while preserving the historic architecture of the central domed Reading Room (in the foreground in both Figs. 3.8 and 3.9) as well as of the surrounding buildings (Rappaport, 2007). The new roof was to preserve sightlines to the dome from the
exterior of the building, and avoid imposing dangerous loads onto the existing buildings (Hart, 2001b).

The roof is a glass and steel “lattice shell” structure (Rappaport, 2007). In the center, it is supported and laterally restrained by a concrete ring that rests on a set of 20 columns surrounding the Reading Room (Hart, 2001b). These columns, which carry the loads straight to the foundations without applying load to the Reading Room, are hidden behind the Reading Room’s new limestone cladding (which was part of the renovation by Foster) (Hart, 2001b). At the outer perimeter of the roof, where it abuts the surrounding buildings, the roof rests on a sliding beam system that does not translate any lateral loads to the existing buildings (Hart, 2001b).

The overall geometry of the roof was form-found with various techniques, including soap-film analysis and consultation with Bath University on deformations and stress levels (Hart, 2001b). The engineers developed a nonlinear analysis program that described the roof mathematically, so that they could examine the roof’s structural behavior after any changes to the shape (Hart, 2001b). The gridwork of the roof itself is composed of a network of slender hollow-box high-grade steel beams welded at high specifications; the steel grid supports triangular glass panels whose dimensions were also found with geometric nonlinear analysis (Hart, 2001b).

Upon its opening, the Architectural Record raved that the new courtyard was “breathtaking…a masterpiece” (Hart, 2001a). It has become a new centerpiece for the Museum.
4. DISCUSSION

4.1 The Common Denominators

In studying these stellar examples from both groups of structural engineers, one becomes aware of the similarities between many of them. They all received strong engineering educations, and became technically proficient in their fields of expertise. Although the core responsibility of a structural engineer is to make things ‘stand up,’ the engineers discussed above demonstrate the inadequacy of this narrow label. As Rice wrote, “In the minds of the public and of other professionals, the engineer is associated with unimaginative dull solutions” (Rice, 1994, p. 21). The best engineers bring a level of creativity to their work, yet never in a way which detracts from structural integrity. This creativity can exhibit itself in several directions, which include, but are not limited to: the form of the finished work, the efficiency of the structure, the ease of construction, and the economy of cost. This kind of creativity transcends the artificial segregation of form-makers and collaborators. Rice, in his work with the cast-steel gerberettes, was almost certainly thinking of Maillart’s understanding of concrete; Rice praises “the [incomparable] expression of the nature and character of concrete form in the bridges of Maillart” (Rice, 1994, p. 77).

There are additional similarities regarding their work outside of professional practice. Many eminent engineers also teach at institutions of higher education – besides Khan and Menn, Sir Edmund Happold was also a professor at Bath University for many years. Continuing in the tradition of these pioneers, engineers from firms like Arup, Buro Happold, and Simpson Gumpertz & Heger, among many others, are known to teach at various universities and colleges. Engineers like Maillart and Candela have
also produced scholarly writings that have enduring value to younger generations of engineers. In addition, many of these engineers have become involved with professional organizations and helped to revise or create engineering codes to promote better designs. All of these items speak to the engineers’ sense of responsibility to the engineering community.

4.2 The Form-Makers in the Context of Today

The ‘form-makers’ profiled above do not constitute an exhaustive list, but similarities begin to emerge quite easily. The engineers apply their exceptional understanding of structures along with an understanding of aesthetics, construction, and economics, to achieve original forms. These engineers have the ability to infuse their work with subtle innovations based on structural articulation; they do not first create an unusual shape and then try to make it work. Many of these engineers were also master-builders who managed their own construction company, or worked with trusted builders.

Some of these engineers benefited from the context in which they first started pioneering their work, as Maillart did with the advent of reinforced concrete and Candela did with the building boom in Mexico. The structures that they worked with were also quite suited to experimenting with new forms; these form-makers tend to “design bridges, towers, and vaults where the use is less intensive for individual people and more so for cars, industry, and large coverings over stadiums, auditoriums, or hangars” (Billington, 2003, p. 32).

One asks if the work of form-makers, or ‘structural artists’ as Billington calls them, is still possible in today’s world. While economics were a factor in these designs, they were still not necessarily the cheapest options available. It appears that the bottom
line has become a pressing constraint, especially in the United States. In addition, the training and practice of engineers and architects has become too specialized and divergent. This will be further discussed in a later section.

4.3 The Delicate Role of Collaborators

The past century has seen an increased separation between the professions of architecture and structural engineering. It is hardly a coincidence that lists of notable structural engineers during this time show a gradual trend towards fewer form-makers and more collaborators. Especially in recent times, it becomes clear that any discussion of structural engineering cannot escape mention of its brother profession of architecture. The collaborative engineers highlighted above each possessed a good deal of respect for the architectural profession. The best collaborative engineers were interested in understanding the context, function, and concept of their architects’ designs, and could therefore contribute in ways that benefited or even enhanced those designs.

How do the structural engineers of today, who belong primarily to the ‘collaborators,’ view their role on a project? Hanif Kara, a founding director of Adams Kara Taylor (which is known for its extensive collaboration with high-profile architects), believes that good collaborative structural engineering “is about becoming an expert, not about becoming a second-rate architect. Yet he stresses the importance of retaining “an empathy for architecture and space” (as cited in Gendall, 2009). This echoes the words of Rice.

Saint acknowledges the strange, contradictory role occupied by engineers in today’s society; they are blamed for failures yet without really being credited for successes (2007). For many typical contemporary projects, the engineering component
has been relegated to obtaining a structural system – a ‘solution’ – that will allow the architectural form to become a reality. The question becomes very quickly whether the collaborative engineers have actually become subservient to the architects’ structurally impractical forms. The irony, of course, is that some engineers seem to thrive on the challenges that come with unusual architecture: “When the structure of a building is distorted or hidden to comply with a designer’s imaginative bidding, as in the architecture of Gehry, Hadid, Koolhaas or Libeskind, a resourceful engineer can find creative challenges galore to address. For Cecil Balmond, the [Arup] engineer who has worked closely with several of these neo-expressionists, “the computer opens a door and gives unparalleled freedom to explore – the result is a bewildering and mind-bending free-for-all where anything goes”” (Saint, 2007, p. 428).

Saint believes that the new structural challenges brought by extreme architectural designs may not necessarily be a bad thing: “The relationship between architect and engineer becomes about the end of ‘subservience’ and...[the beginning of] one artist going hand in hand with another, or perhaps egging the other on” (2007, p. 428). Perhaps this is the unavoidable direction in which innovative structural engineering is proceeding. And yet it might be wise to remember the structural honesty that engineers like Maillart and Khan believed in.

4.4 The Way Forward

Today’s traditional educational system for structural engineers does not specifically propel them to become either great form-makers or great collaborators. Clearly a good technical background is an essential first step for any engineer. Engineering schools generally perform adequately in this respect. However, that is also
where the school's teaching stops. More is necessary to encourage more students to aspire towards the careers of Robert Maillart or Peter Rice.

Beginning students are given exercises that can be neatly analyzed. However, eventually, the professors should begin to challenge the students with more open-ended problems to sharpen their engineering intuition. For example, a photograph of a complex building on campus could be shown to the students, and there could be a discussion about what kind of structural system might be employed. Existing built structures should be discussed in the classroom with more frequency. Too often, the study of structures does not extend beyond the sterilized, simplified structures shown in textbooks.

There is also less emphasis on graphic statics than there was in the past. Graphic statics allows for a more physical grasp of the interaction between forces and forms. Ultimately, students should be comfortable with understanding the structural differences between different forms. This kind of emphasis was clear in the lecture notes of Professors Wilhelm Ritter and Pierre Lardy of ETH. A recent textbook by Zalewski and Allen (1998) advocates graphic statics as an effective way of teaching structures to both architects and engineers. In addition, a historical review of past notable structures should be included in the curriculum on some level. Billington, who was trained as a civil engineer, had never even heard of the works of Robert Maillart until after he became a professor. It is telling that the people who introduced him to Maillart’s legacy were not engineers, but architects (Billington, 2003).

Another key issue is the lack of dialogue between civil engineering and architecture departments in many universities. Students need to be shown that their future professions are not practiced in isolation, but are inextricably linked with those of others. It would be beneficial for more interdisciplinary classes or projects to be
arranged by the faculty. In addition, both engineering and architecture students should be introduced to the construction side of the industry as early as possible. A cursory site visit or two during the many years of school is only a bare minimum. An effort should be made to impart the complexity of bringing a built project from beginning to end, including the coordination that is required from multiple disciplines. Currently, this side of the engineer’s role is typically first shown to students during extracurricular internships.

Needless to say, good designs – taken here to mean designs that look and function well, are structurally reasonable, are easily constructible, and financially efficient – can only come about if real integrated design becomes the norm. True integrated design can only come about if the various disciplines are brought together at the very early stages of design. This is especially true for structural engineers. By collaborating with an architect from the schematic design phase, the engineer has the potential opportunity to ease the design away from inefficient use of material or labor, thereby creating savings for the client. The engineer, by having input from the very beginning, can also attempt to avoid becoming subordinate to the architect, as is often the case.

Finally, it is appropriate to comment on the current tools of the trade. Today’s engineers have become familiar with the various design codes as well as with an ever-proliferating array of software. These are very useful tools, and are creating all kinds of possibilities for the building industry. However, the danger is that familiarity with these tools can lead to a complacency that supplants engineering intuition. Engineers need to preserve their knowledge of structural behavior amidst these new distractions. It is worth noting the example of the famous shell designer Heinz Isler, who maintains that
he can still mentally work out the stresses in each of his shell designs during the short walk from his study to the tearoom (Chilton & Isler, 2000).
5. Conclusion

“The engineer’s profession has become more and more centered on science...the creative side of structural engineering has continued to decline...structural engineering requires practical experience, innovative ideas, imagination, fantasy, and art,” says Christian Menn (as cited in Nordenson, 2008, p. 125). Menn is lamenting more than the dearth of new form-makers; he is arguing that structural engineering is moving towards a purely technical discipline. After examining the structural engineer’s role as embodied by some of the greatest engineers of the past century, it is clear that the structural engineering, at its finest, requires creativity in approach and execution.
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