

Conceptual Transparency: Examples from the Work of Robert Maillart and Jörg Schlaich

E. M. Hines¹

¹Professor of Practice, Tufts University; Principal, LeMessurier Consultants,
Cambridge, MA 02139; PH (617) 868-1200; email: emhines@lemessurier.com

ABSTRACT

Design processes and design calculations are reviewed for the 1925 Valtschielbach Bridge by Robert Maillart and the 1998 Ingolstadt Bridge by Jörg and Michael Schlaich. This review emphasizes the importance of conceptual transparency in structural design and demonstrates the interconnected nature of theory and practice in actual design processes. It helps to establish engineering thinking as distinct from scientific or mathematical thinking, and allows detailed consideration of how structural design processes may be taught in the university. Examples from the author's own practice and teaching demonstrate the potential for learning environments where university students are introduced to the tools and disciplines essential to creating original work based on fundamental understanding of engineering concepts.

SESSION DEDICATION AND INTRODUCTION:

WHAT CAN WE LEARN FROM THE GREAT STRUCTURAL DESIGNERS?

We have assembled this session in order to honor the career of Professor David P. Billington of Princeton University, whose scholarship and voice have influenced countless members of our profession, encouraging us to seek the human stories behind the great works of structural engineering. It is through these stories that Professor Billington has conveyed to us not only the character of the great designers themselves, but also the very ideas and contexts that have made great designs possible. Our collection of perspectives on these ideas amounts to a modest *Festschrift*, recollecting the documents produced by students and colleagues to honor their mentors, documents we have stumbled across over the years working alongside Professor Billington in his Maillart Archive at Princeton.

Session Papers:

- Maria E. Moreyra Garlock: “Felix Candela and the Origins of Inspiration”
- Eric M. Hines: “Conceptual Transparency: Examples from the Work of Robert Maillart and Jörg Schlaich”
- Abbie Liel: “The Influence of Engineering Organization on Design and Construction Processes at Tennessee Valley Authority Dams of the 1930s”

The distinction between theory and practice leads many to assume that engineering design consists of following procedures generated as the results of scientific research. A closer look at the design processes for significant historical structures, however,

reveals intensive engagement between engineering imagination, fundamental principles, technical know-how and human will. Based on this insight, the session showcases some examples of compelling design processes and considers the implications for university engineering education. Attention is given to the distinction between a design process—which implies a personal way of directing creative thinking toward the solution of an actual problem; and a design procedure—which implies rote application of equations and methods. Understanding this distinction opens up possibilities for several important projects including: establishing engineering design as a creative and intellectual discipline equivalent in stature to research, working to reduce code complexity by placing emphasis on principles as opposed to rules, establishing the limits of computer analyses and their relationship to the imaginations of competent designers, and ensuring that engineering students master fundamental concepts in a way that allows them to think creatively.

INTRODUCTION

The calculations and the sketches behind the two structures featured in this paper constituted my introduction to the structural engineering design process under the guidance of Professor Billington. The stories behind both structures have proven to be durable and reliable landmarks on my professional path as a structural engineer. While these calculations and sketches were instrumental in the creation of sophisticated, original structures, they are themselves quite clear and simple. In a world enamored of complexity and computational power, where high-tech is often equated with intellectual merit, they demonstrate a higher level of thinking—one that radically distinguishes the essential characteristics of a system from the trivial—*conceptual transparency*. This power of abstraction serves a vital role in the design of large-scale structures, where failures are catastrophic and experimental prototypes are prohibitively expensive. Overlay these warnings with the imperative of economy and the desire for beauty, and it becomes clear that conceptual transparency addresses equally the need to assume responsibility and the opportunity to work creatively.

ROBERT MAILLART'S VALTSCHIELBACH BRIDGE

The chief concern of engineers is the quality of their assumptions. One of the clearest examples of this point in engineering history, as told by Professor Billington in *The Tower and the Bridge*, relates to Robert Maillart's development of reinforced concrete deck-stiffened arch bridges in the mid 1920's.

Robert Maillart, the Swiss bridge designer, developed in 1923 a limited theory for one of his arched bridge types which violated in principle the general mathematical theory of structures and thereby infuriated many Swiss academics between the wars. But Maillart's limited theory worked well for that special type of form. Within that category type, Maillart's theory was useful and had the virtue of great simplicity; he developed the theory to suit the form, not the form to suit the theory. In the United States, by contrast, some of our best

engineers understood the general theory well, but not understanding Maillart's specific ideas, they failed to see how new designs could arise. They were trapped in a view of an engineering analysis which was so complex that it obscured new design possibilities.(Billington 1983, 9-10)

Adherence to a general theory in this case is tantamount to the blind application of equations so often observed in the work of engineering students in fundamental classes. Maillart's much simpler approach, however, with its emphasis on new possibilities for arched bridge forms, represents the heart of creative engineering thinking—creativity not only with respect to the appearance of form, but also with respect to its engineering substance. Even Maillart's calculations were creative. In other words, Maillart recognized that there was more than one way to approximate the structural behavior of his deck-stiffened arch systems and he chose an approximation that exhibited a high degree of conceptual transparency. In the appropriate context, Maillart's calculations were entirely correct. That was precisely what angered Maillart's academic peers, and distinguished Maillart's engineering thinking. Maillart's calculations for the deck-stiffened Valterschielbach bridge, pictured in Figure 1, total 3 ½ pages. The calculations that represented Maillart's conceptual leap filled the last half page, and are shown in Figure 2.



Figure 1. Robert Maillart's 1925 Valterschielbach Bridge in Switzerland (image credit: Billington 2005).

Seldom has the point been made more clearly that the engineering genius of the work rests on the *assumption* supporting this half page, and not on the calculations themselves. Based on the full scale behavior of his previous bridges, Maillart made

the assumption that the deck and the arch deform together, and would thus carry bending moments in proportion to their flexural stiffness. Since the deck was significantly stiffer than the arch, Maillart designed the deck to carry all the bending of the system. Such a conceptual leap reflects at least the same level of intellectual quality as the creation of any general theory, and far surpasses the technical exercise of applying such a theory. From a human point of view, Maillart's conceptual leap exceeded the generalized theory in value, because it led to more economical bridges that have become artistic icons as they have remained both serviceable and durable.

The essence of Maillart's engineering calculation for the Valtschielbach bridge in Figure 2 is represented by the equation

$$M = \frac{pL^2}{2 \cdot 8 \cdot 4} = \frac{0.9 \cdot 40^2}{64} = 22.5tm$$

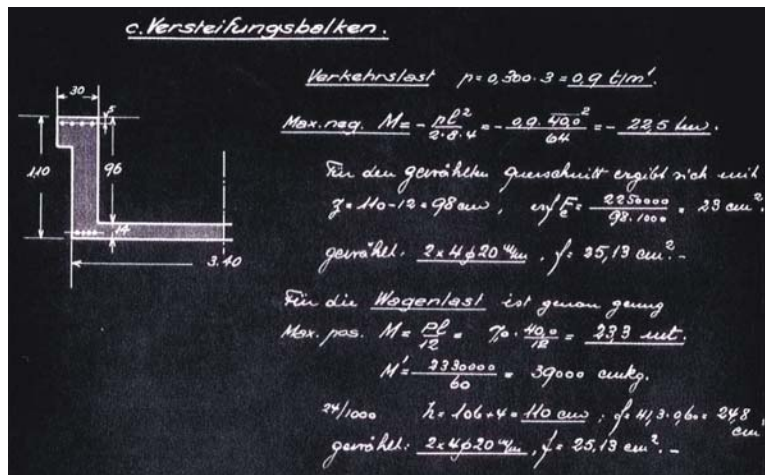


Figure 2. Robert Maillart's deck stiffening calculations for the Valtschielbach Bridge (image credit: Billington 2005).

Using the arch allowed Maillart to reduce his dead load bending moments to zero, while reducing his live load bending moments to approximately 22% of the same moments on a simply-supported beam. Figure 3 shows conceptually the Valtschielbach arch on the left and a simple beam on the right, each with a span of 40 m (131 ft). Assuming the distributed live load of 0.9 t/m (0.603 k/ft) for this example, the live load bending moments shown for the arch and the beam at the bottom of Figure 3 are 162 kft [22.4 tm] and 730 kft. This difference is impressive, but does not emphasize the relative efficiency of Maillart's bridge, which is more efficient than a simple beam by more than a factor of 8.

The top of Figure 3 shows the same spans under uniform load. For this example the same live load has been used for consistency, although it would be more appropriate to use the actual dead load, which is larger than the uniform load shown at the top of Figure 3. The moments under uniform load in the arch are zero, while in the beam they are 8 times higher than in the arch under live load.

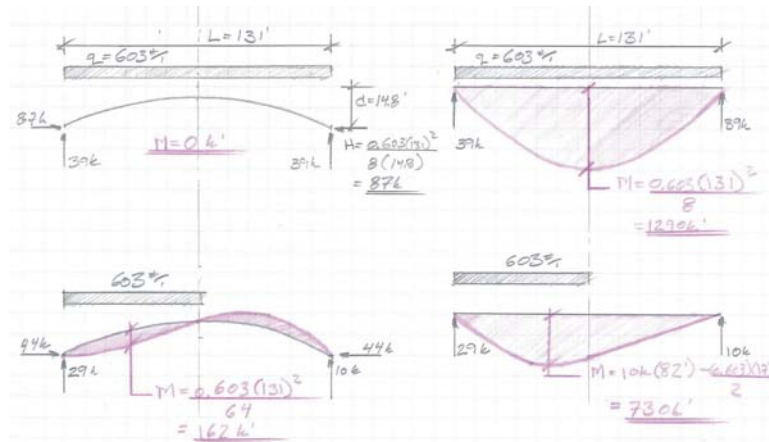


Figure 3. Valterschielbach bending moments explained conceptually.

For this example, it is most appropriate to compare maximum bending overall moments, not just maximum bending moments from a given load case. If the dead loads of the structure are just 25% higher than the live loads, then it can be demonstrated that the deck-stiffened arch reduces bending moments by an order of magnitude compared to the simple beam. See Chapter 9 of *Robert Maillart's Bridges* (Billington 1979) for a complete historical discussion of Maillart's deck stiffened arches and their relevance to the difference between science and engineering.

JÖRG AND MICHAEL SCHLAICH'S INGOLSTADT BRIDGE

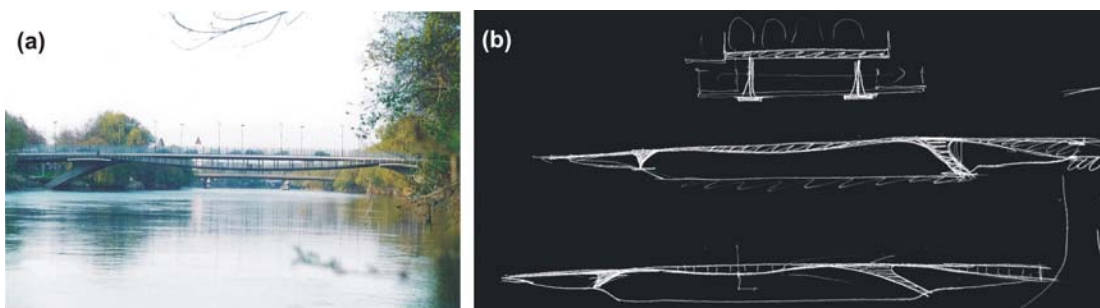


Figure 4. Danube River bridge in Ingolstadt. (a) Elevation. (b) System concept sketches.

Figure 4(a) shows the third bridge over the Danube River in Ingolstadt, Germany, which won a design competition in 1993 and was completed in 1998. Jörg and Michael Schlaich generously allowed us to photocopy many sketches from their collaborative design process for this bridge with Architects Kurt and Peter Ackermann. These sketches and several interviews formed the basis for our story of this design process and the design competition (Hines and Billington 1998). In the discussion of conceptual transparency, these sketches complement the simplicity of Maillart's Valterschielbach calculations by demonstrating the power of drawing as a language of creative expression.

One of the important early system sketches is pictured in Figure 4(b). While simple, this sketch captures the essential ideas of the proposed system: a slender deck, supported as an inverted suspension span, and longitudinally prestressed by the arching action between two raked piers. The separation between the road and the pedestrian can be seen in the section at midspan. The second elevation below shows a representation of massing with vertical supports between the cables and deck. The sketches are executed quickly in the company of collaborators. They are the standard means of communicating between designers. Yet, it is rare that we consider closely and discuss the sketches that represent the creative process. They are often considered either to stand alone as a flash of genius or to be mundane in their multitude. As representatives of hundreds of sketches developed during a design process, the sketches in Figure 4(b) and in Figure 5 show the kind of communication that is essential to the creative development of an idea in structural engineering.

Often these sketches are accompanied by simple calculations and text. Their value lies in their ability to represent clearly and accurately a dynamic process that is invisible to most students in its human character—composed of sketching, simple calculations, discussion, debate and an iterative approach to the development of an idea. I tell my students that if our imaginations were perfect, we would not need to worry about the discipline of creativity. Our ideas would come fully formed out of our imaginations. Instead, most of us harness the power of our ideas by communicating about them. We communicate with ourselves, with our colleagues, and with our critics. In this communication, we learn more about our ideas and develop them further. While it may not be possible to teach creativity per se, it is certainly possible to teach the discipline required for creative work. And the first step in teaching such a discipline is to demonstrate it by example.

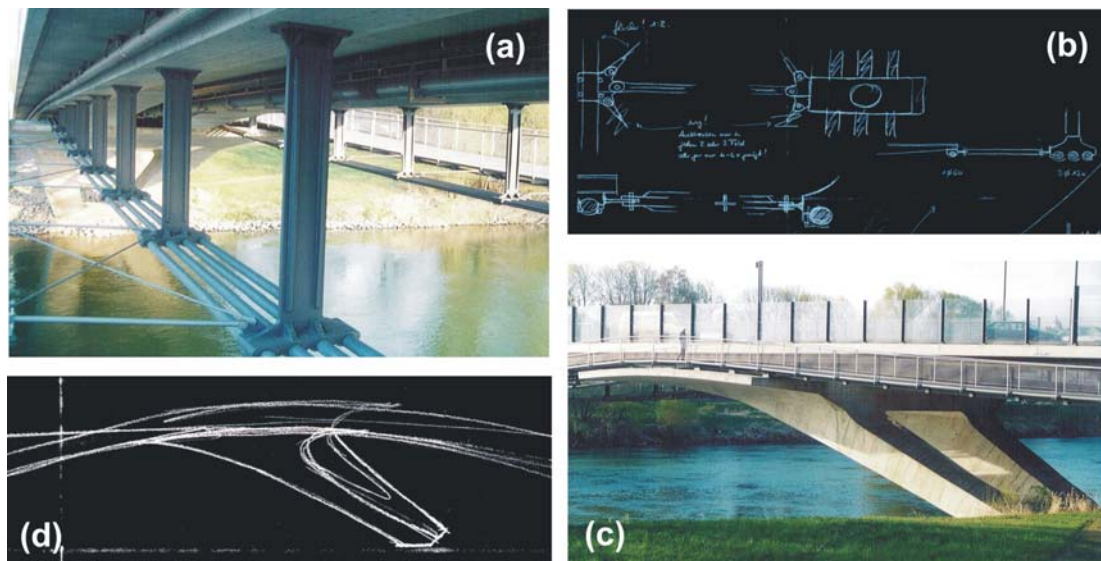


Figure 5. Ingolstadt details and concept sketches. (a) deck support on cables with bracing to pedestrian walkway; (b) concept sketches for connections between deck support cables and pedestrian walkway; (c) skewed pier with deck and pedestrian walkway; (d) pier sketch.

Figure 5 shows this discipline in further details. It is not enough simply to sketch a system. The system relies on its details, and conceptual transparency is largely concerned with the interaction between a system and its details. Figure 5(a) shows the supports between the cables and the deck, along with the horizontal ties between these cables and the pedestrian walkway. Figure 5(b) shows sketches of these details that were developed in close proximity to the sketches in Figure 4(b). Figure 5(c) shows the skewed support, which evolved to retain a high degree of plasticity from a very simple decision to skew the supports by 20 degrees. Figure 5(d) shows the early conceptualization of this support as a plastic element.

The example set in Figures 4(b) and 5 is that the creative work of engineers involves intense communication between the idea of a system and ideas for its details. This communication poses a challenge, because it is easier to fall into a habit of focusing only on the big picture or only on the details. The sketches in a design process need to be effortless because they need to be disposable. The value of any given sketch resides in its relation to all the other sketches and the design process—not in its quality as an independent work of art. The disposable nature of these sketches gives them their value—they record fleeting thoughts and ideas, set down quickly for the purpose of critical evaluation and discussion. To produce them fluently is to speak the language of the engineer. Leonardo Da Vinci's sketch books are compelling precisely because they exhibit his artistic talent not for its own sake but as eloquence in the language of drawing.

DRAWING, THE LANGUAGE OF THE ENGINEER

The concept of drawing as a language was coined by Carl Culmann in the mid 19th century as he developed graphic statics (Billington 2003, Lehmann and Maurer 2006), however for this discussion I would like to consider drawing even more broadly—as a language requiring multiple levels of abstraction, and possessing tremendous intellectual richness.

Expression of thought through language is creative. Creativity involves choice. Intellectual disciplines contribute to creative work when they facilitate judgments required to make choices. Engineering requires the command of three primary languages:

1. The written word and spoken word communicate action—a narrative of what has happened, is happening or will happen.
2. Mathematics communicates quantity.
3. Drawing communicates substance—a real object that is best understood by its appearance is communicated as an ideal through drawing.

University culture clearly recognizes the value of the written/spoken word and mathematics as forms of communication, and the act of acquiring a liberal education involves the extensive use of these languages. Drawing, on the other hand, has often been misunderstood outside of the fine arts, and in engineering has been branded as a

technical discipline. As a form of communication however, drawing is similar to writing, speaking and mathematics: it requires skill, but it also requires intellectual depth. In fact, the two are inextricably linked.

Similar to written and oral communication, the audience matters tremendously. For presentation to an owner, realistic appearance is often helpful. For communication with architects, realistic appearance is also valuable, but can be tempered with abstraction and style in a manner that facilitates a collaborative, creative process. For contractors developing an estimate, depicting quantities and the general level of complexity are helpful. For contract documents more detail is generally more helpful. It requires experience and thoughtfulness, however, even with the most powerful computer modeling systems, to develop contract drawings that are well coordinated. Providing information that is incorrect can be more harmful in the context of a contract than not providing any information.



Figure 6. Lobby Renovation, 100 High Street, Boston, Massachusetts. (a) Before: two levels of retail space at base of 28 story building (photo credit: CBT Architects). (b) After: two-story lobby with structural glass wall hung from cantilevered third floor.

In order to provide contract information in a manner that is consistent and easily understood by an expert, engineers have developed several abstractions such as weld symbols, elevation marks, tolerance numbers and typical details. These abstractions, while often communicated in the form of drawings, are generally not comprehensible to a person who does not speak this language.

In order to provide context for the characteristics of drawing discussed above, I will discuss two recent lobby renovations in Boston and their role in my teaching the 3rd-

Year structural systems design course at Tufts University. Figure 6 shows before and after photos of a lobby renovation completed with CBT Architects at 100 High Street in Boston in the spring of 2009. The former entrance to the building in Figure 6 was located at 150 Federal Street. The lobby renovation consisted of removing three bays of slab framing from the second story in order to create a new 2-story high lobby with a structural glass façade by W&W Glass/Pilkington Planar.

Figure 7 shows the framed area before and after the slab was removed. Since the new glass wall was to be hung from the cantilevered third floor framing, reinforcement of the columns prior to demolition of the slabs required not only considerations of column stability under 28 stories of building dead and live loads, but also of column flexural deflections and their effect on cantilevered slab deflections.



Figure 7. Lobby Renovation, 100 High Street, Boston, Massachusetts. (a) Before: columns and cantilevered girders reinforced prior to removal of three 30 ft x 30 ft bays. (b) After: three bays of slab framing removed, and column reinforcement completed.

Figure 8(a) shows original sketches and calculations developed during concept design of this slab removal. While it may seem natural that sketches, calculations and word occupy the same page of work (as do also graphs and tables often times), it is important to note that many students are not educated to communicate in this kind of language. At the top of Figure 8(a) is a sketch of the plan, which gives context and which will become the primary form of communication in later contract documents. Also listed are the assumed loads. These loads are deliberately simple, and their importance lies in the fact that they allow this communication to stand alone, without reference to other documents. This makes the work easier to check and to discuss with colleagues. For columns supporting a fully-occupied 28-story building, it

became important to be able to check both the relevant assumptions and calculations many times, with many different colleagues. The intellectual merit of the problem lay in distilling the problem down to its essence—to make it so simple that the unconscious could continue to consider the problem at all hours—so simple that one could wake up in the middle of the night and check the work at bedside. The analysis on the lower portion of Figure 8(a) is a simple, single degree of freedom moment distribution, which could be carried out on half a page. A sketch of the physical system, with moment diagrams drawn directly on top of the sketch helped to facilitate this level of conceptual transparency.

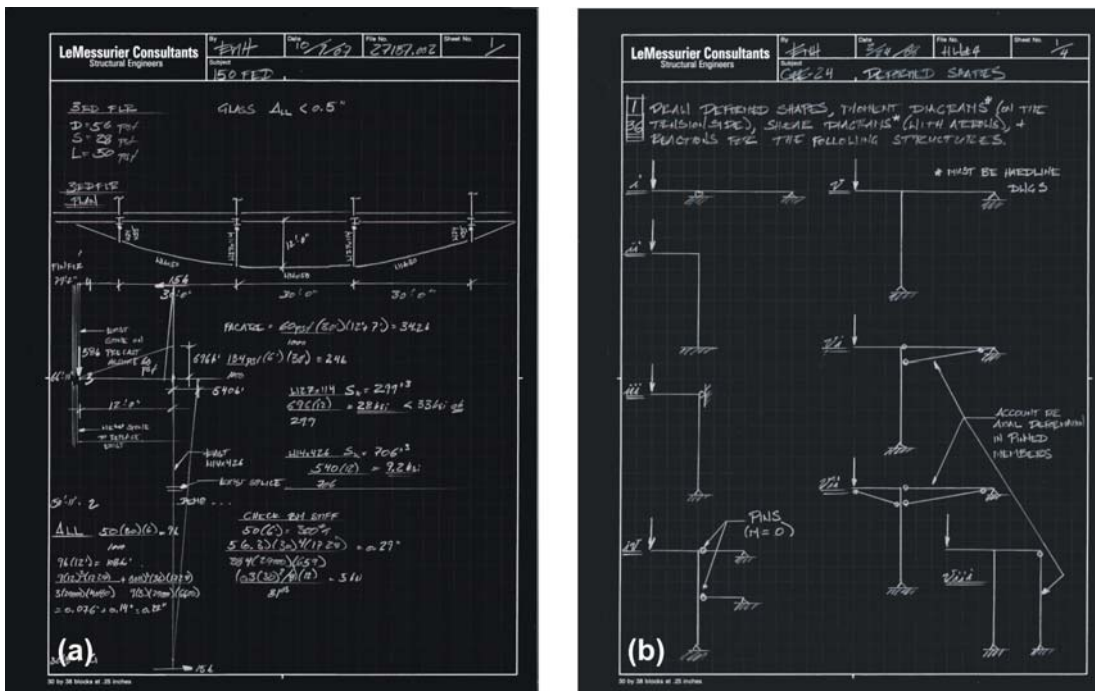


Figure 8. Lobby Renovation, 100 High Street, Boston, Massachusetts. (a) Initial analysis of third floor framing to support hung glass wall. (b) 3rd-Year structural systems homework assignment reflecting the parametric investigation of system behavior completed prior to final design.

Figure 8(b) shows a series of exercises assigned to 3rd-Year structural engineering undergraduate students at Tufts University based on a parametric investigation that followed the calculations in Figure 8(a). The object of the investigation was to determine the stiffening effects due to a range of possible reinforcement schemes for the cantilever and its beam and column back-spans. I learned from assigning this series of problems that there was a significant difference between how I saw these simple sketches versus how my students and teaching assistants saw them. I saw several variations on one theme—a cantilever with a backspan. The variations entailed different types of backspans resulting in different levels of rotational stiffness at the root of the cantilever. My students, however, saw eight different problems, with little or no conceptual thread running through them.

When I solved these problems in Figure 8(b), the moment diagrams and axial force diagrams yielded significant insight into system behavior—even before I calculated any numbers. From the principle of virtual work, more area under these diagrams implied more system flexibility. In other words, the diagrams appear more simple than they actually are—this speaks to the subtlety and effectiveness of their abstraction. Only an expert can see all they have to offer. And to an expert—they facilitate a powerful understanding. A similar observation was treated extensively by the National Research Council in Chapter 2 of their summary of education research entitled *How People Learn*.

Experts' abilities to reason and solve problems depend on well-organized knowledge that affects what they notice and how they represent problems... The fact that experts are more likely than novices to recognize meaningful patterns of information applies in all domains, whether chess, electronics, mathematics, or classroom teaching... Because of their ability to see patterns of meaningful information, experts begin problem solving at “a higher place.” (NRC 2000, 48)

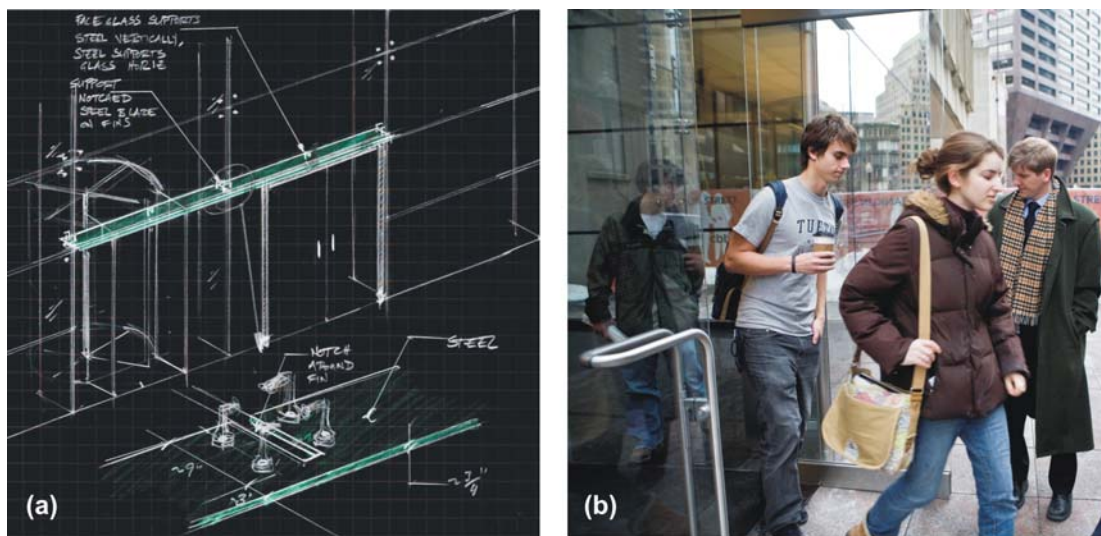


Figure 9. Lobby Renovation, 225 Franklin Street, Boston, Massachusetts. (a) Engineer's sketch of steel reinforcement for glass door header. (b) 3rd-Year Tufts University students walking through the doors depicted in (a) (photo credit: Tufts University).

Figure 9(a) shows a sketch for another structural lobby renovation at 225 Franklin Street in Boston. I developed this sketch during a coordination meeting with the architect, the glass installer and the general contractor. During the meeting, the sketch helped our team to align our interests with regard to developing an extremely light steel header that could be attached to the glass system. Both the system and the details were important to all parties involved, and the actual engineered header system ended up resembling this concept sketch very closely. Figure 9(b) shows my 3rd-Year students walking out of this doorway after having toured the new 225 Franklin Street Lobby.

CONCLUSION: THE ROLE OF DESIGN IN UNIVERSITY ENGINEERING EDUCATION

The role of design in university engineering education is to *motivate and challenge students' fundamental understanding* of the physical world. Design is relevant in the university, not because it prepares students for the working world, but because it is what *motivates and challenges* students' understanding of the fundamentals in the best possible way. Design requires a personal way of directing creative thinking toward the solution of an actual problem, and has little use for rote application of equations that a student may or may not understand. Design requires a philosophical approach rooted strongly in the fundamentals of the discipline, which is the necessary foundation for conceptual transparency. Fundamentals are not just theory, but how theory is applied in a context. To separate theory from practice is to ignore context—and hence to forsake what is most human and most wonderful in engineering.

REFERENCES

- Billington, D.P. (1979) *Robert Maillart's Bridges*, Princeton University Press, Princeton, New Jersey, 146 pp.
- Billington, D.P. (1983) *The Tower and the Bridge*, Princeton University Press, Princeton, New Jersey, 306 pp.
- Billington, D.P. (2003) *The Art of Structural Design: a Swiss Legacy*, Princeton University Art Museum, Yale University Press, New Haven, CT, 211 pp.
- Billington, D.P. (2005) *Civ 262: Structures and the Urban Environment*, Powerpoint Lectures, Department of Civil and Environmental Engineering, Princeton University, Princeton, New Jersey.
- Hines, E.M. and Billington, D.P. (1998) "Case Study of Bridge Design Competition," ASCE Journal of Bridge Engineering, 3(3), Aug., pp. 93-102.
- Lehmann, C. and Maurer, B. (2006) *Karl Culmann und die graphische Statik: Zeichnen, die Sprache des Ingenieurs*, Ernst & Sohn, Berlin, Germany, 207 pp.
- National Research Council (2000) *How People Learn: Brain, Mind, Experience and School—Expanded Edition*; J.D. Bransford, A.L. Brown and R.R. Cocking, editors; National Academy Press, Washington, D.C., 374 pp.