The Role of Design in University Engineering Education

EMH 04/06/10

The role of design in university engineering education is to *motivate and challenge students' fundamental understanding* of the physical world. Within academic circles it is commonly asserted that students who understand the fundamentals can design anything. As stated, this can imply that design is secondary to fundamental understanding, and reflects the lack of attention paid to design in universities. If a designer chooses to agree with this assertion, then the observation follows quite naturally that students have problems with design because they actually *do not* understand the fundamentals. My teaching experience has demonstrated to me that students are not learning the fundamentals in sufficient depth to support creative engineering thinking.

Design is relevant in the university, not because it prepares students for the working world, but because it is *motivates and challenges* students' understanding of the fundamentals in the best possible way. Design distinguishes process from *procedure*. *Procedure* implies rote application of equations that a student may or may not understand. *Process* implies a personal way of directing creative thinking toward the solution of an actual problem. Engineering process requires a philosophical approach rooted strongly in the fundamentals of the discipline. Fundamentals are not just theory, but how theory is applied in a context. This sheds light on the difference between science—which pursues general *understanding* of how existing things work; and engineering—which pursues the *creation* of new things in specific contexts (Billington 1983).

In the University, design is less emphasized than analysis perhaps due to a misunderstanding of design as less sophisticated and more procedural than analysis. The irony of this misunderstanding is that design problems have multiple answers and each answer can be arrived at in multiple ways, i.e. design demands more from human creativity than does analysis. Whereas analysis implies a definable end, the perfection of a design can be pursued indefinitely. The intellectual life of the university can benefit from consciously placing design on equal footing with analysis, provided the design in question involves multiple legitimate paths to multiple legitimate solutions.

Consider again the assertion: "If students understand the fundamentals, they can design anything." Academic agreement with this statement has supported the pedagogical philosophy engineering education hinges primarily on learning the fundamentals of math and science. This assertion, however, is based on two assumptions: 1) students understand fundamental principles after having taken math and science classes, and 2) understanding of math and science necessarily implies preparation for engagement in design. Under certain circumstances, these two assumptions may hold true. No one is better suited, however, than engineers—designers—to understand that if these assumptions do not hold true, the assertion has no value. The reason for this is that 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 Princeton Civil Engineering professor David Billington, 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)

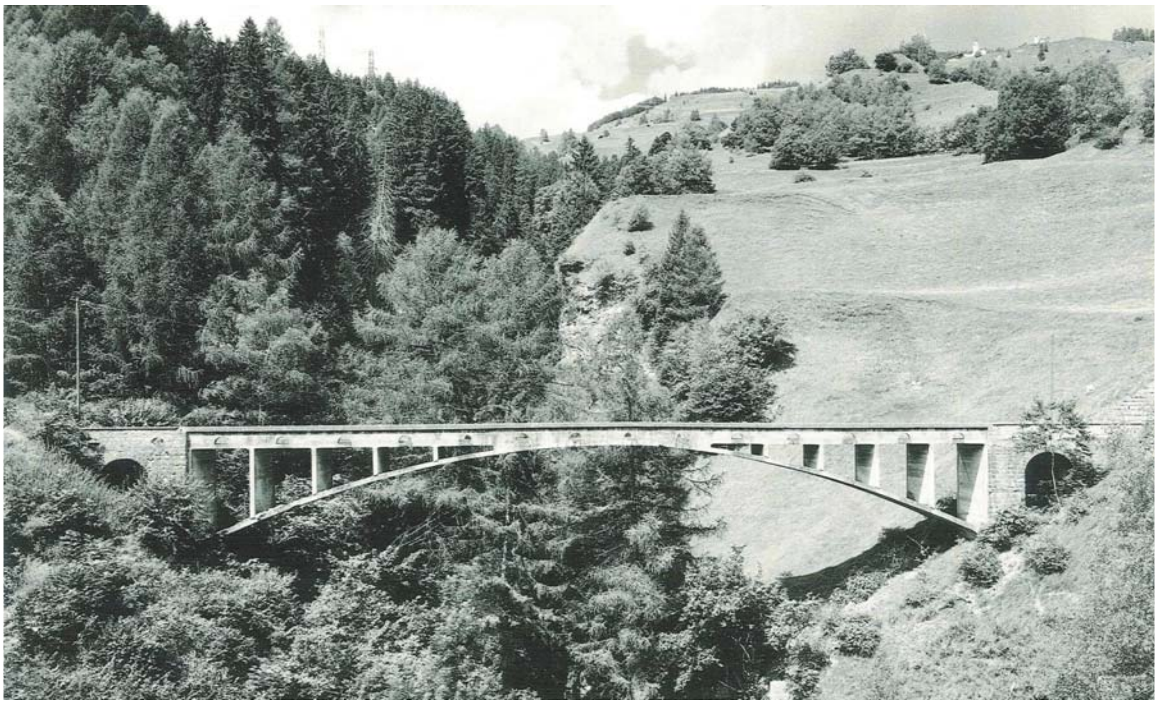

Figure 1. Robert Maillart's 1925 Valtschielbach Bridge in Switzerland (Billington 2005).

Adherence to a general theory in this case is tantamount to the blind application of equations so often observed in engineering students completing a homework assignment in strength of materials, fluid mechanics or circuits. 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 mathematics was creative. And in the appropriate context, this creative mathematics was absolutely correct. That was precisely what angered Maillart's academic peers, and precisely what distinguished Maillart's engineering thinking. Maillart's calculations for the deck-stiffened Valtschielbach 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. Seldom has the point been made more clearly that the *assumption* on which this half page rests, and not the page of calculations itself, constitutes the engineering genius of the work. 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 far exceeds 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

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

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 demonstrates the consequences of this.

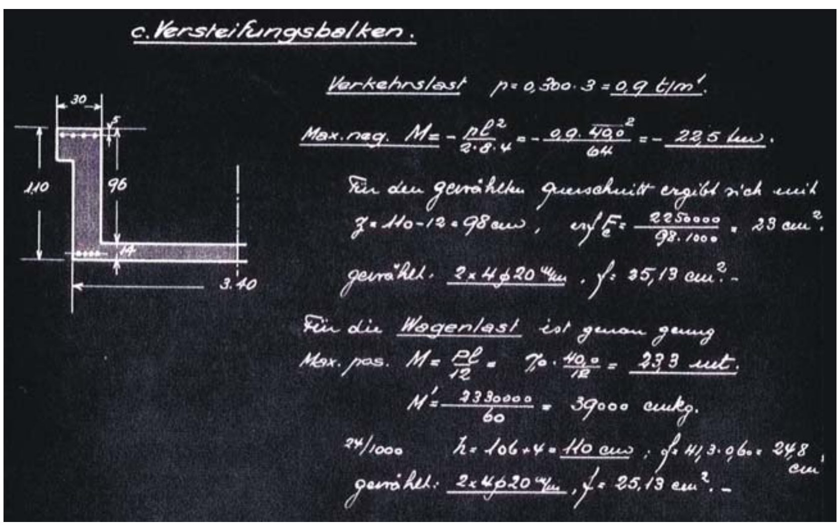

Figure 2. Robert Maillart's deck stiffening calculations for the Valtschielbach Bridge (Billington 2005).

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 not 4.5 times better than a simple beam but more than 8 times better.

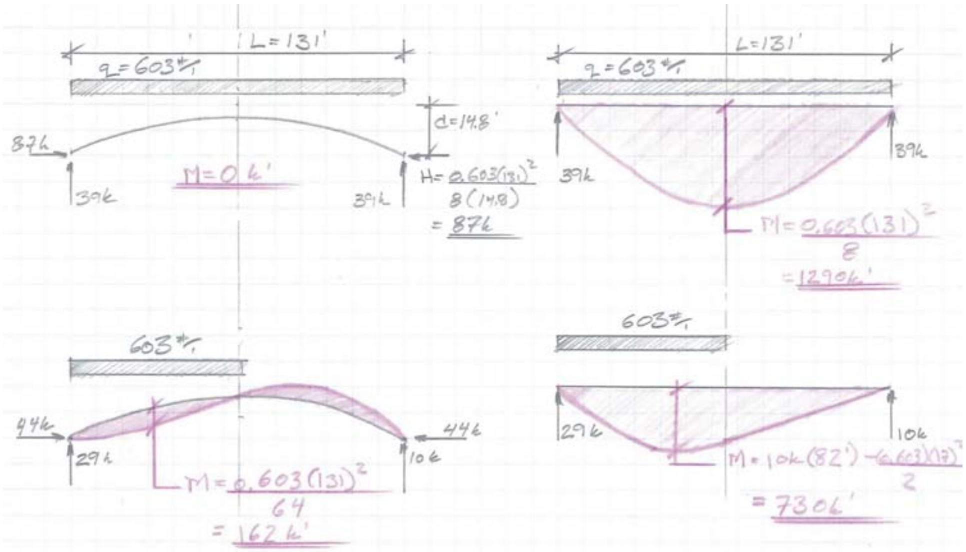

Figure 3. Valtschielbach bending moments explained conceptually.

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 larger dead load. 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. For this example, it is most appropriate to compare maximum bending overall moments, not just maximum bending moments from a given load case. Clearly, 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.

The example of the deck-stiffened arch described above by Billington addressed the second assumption discussed in the introductory paragraph: *understanding of math and science necessarily implies preparation for engagement in design*. American designers were not stimulated by the general theory to think creatively about bridge forms. The arch bridge near the Delaware water gap in New Jersey pictured in Figure 3 makes this point very clear.

Figure 3. Arch bridge near the Delaware water gap, by L. Bush and G.J. Ray, 1916 (Billington 2005)

The first assumption discussed in the introductory paragraph: *students understand fundamental principles after having taken math and science classes*, is readily called into question when working with Junior or Senior level engineering students on any engineering problem that they have not seen before. For instance, students in a Junior level structural systems class at Tufts University were asked to find the maximum deflection of the two asymmetrically loaded simply-supported beams shown in Figure 4. Note that the term "simply-supported" is a technical term describing the boundary conditions of the beam. These boundary conditions of a pin on one end and a roller on the other end allow the reactions and internal forces of the beam to be determined by Statics.

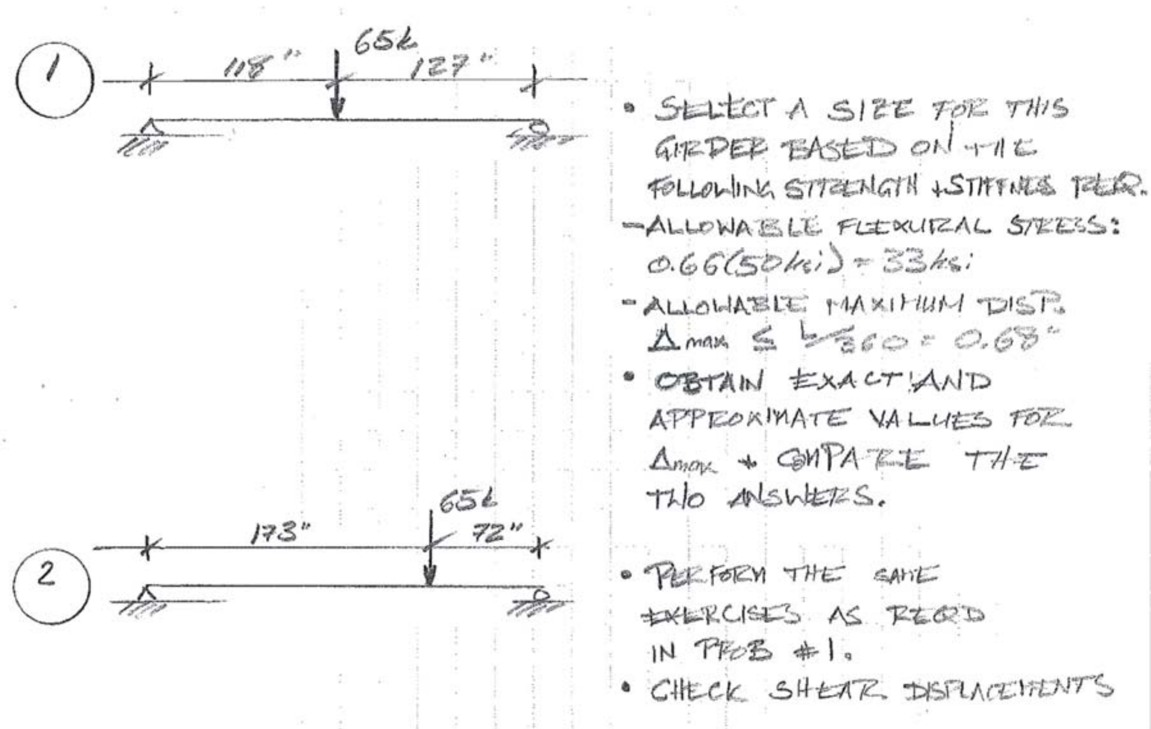

Figure 4. Simply-supported beams with an asymmetric point load.

The assignment asked for an "exact" and an approximate assessment of the maximum deflection. The word "exact" is written in quotes to express the irony of this word if it were to be applied to a real beam where the real boundary conditions and possibly the real loads had already been idealized. Students who remembered enough of their course in structural analysis from the previous semester were able to get the exact solution after engaging significant calculation. Their successful recognition that the maximum deflection of the beam in Figure 4 does not occur at the location of the point load, but rather slightly toward the center of the span from the point load, indicated some familiarity with the general theory of beam deformations. This cohort represented a minority of students sampled over three years. More significantly, some students were afraid to even attempt an approximate solution, and no student based his approximate solution on the appropriate principle.

Most students developed an approximate solution to both problems simply by assuming that the point load was at the midspan of the beam. Hence, the maximum deflection was also at the midspan of the beam and could be calculated easily as

$$D = PL^3/48EI$$

Such a solution, however, does not demonstrate insight into the fundamental principles at play in this problem. One such principle is conservation of energy. The external work done by the load, acting through its displacement is equal to the integral of all strain energy over the entire beam. This principle alone, however, is not enough, because the desired displacement is the maximum displacement, which does not occur a the location of the load. Therefore, the principle of virtual work, which is derived from the conservation of energy, is necessary in order to imagine a virtual load acting through the maximum displacement caused by the real load. This virtual load times the real displacement is equivalent to the integral of strain as product of the virtual stresses and the real strains. The principle of virtual work results in the integration of the product of two moment diagrams divided by the flexural section stiffness of the beam, EI. The physical implications of integrating the product of these two moments is two-fold: 1) larger areas of moment diagram result in greater displacements and hence a more flexible beam, and 2) the fact that the real load and displacement in question do not occur in the same location complicates this integration. The purpose of an engineering approximation is to capture as much relevant information as simply economically as possible. The consequence of not capturing enough information is a loss of accuracy. The consequences of engaging in more analytical complexity than necessary are losses of time and transparency, ie. the problem takes longer to solve and the solution is harder to check.

Figure and description not completed
Figure 5. Approximate solutions: (a) typical student approximation, (b) conservative approximation, (c) unconservative approximation.

Figure 5 gives three approximate solutions to this problem

Undergraduates face two major challenges when it comes to mastering engineering fundamentals. The first comes in making the transition from thinking about fundamentals on a clearly defined theoretical level to thinking about fundamentals in a real situation. The only difference is that the engineering required for the real situation involves characterizing the problem on a clearly-defined theoretical level. As a matter of fact, this characterization of the problem—the assumptions one makes, if you will—*is* the engineering. The application of fundamentals once the problem has been clearly characterized, is the math, the science—really the application of tools that an engineer has at her disposal to solve a clearly defined problem. The second comes in finding the motivation to study the fundamentals in a way that leads to mastery. In the United States, this motivation seems to develop strength only once it has become clear to a student how she can use fundamental knowledge to solve a particular problem of interest to her. Ironically, students are expected to learn the fundamentals first, before they have developed a sense of what they will need to know and why they need to know it. Many introductory courses designed to excite young students fail to motivate the material properly because they do not draw explicit connections between the motivating material and the fundamental knowledge.

Fundamental knowledge finds two applications in engineering. Most commonly familiar to students, fundamental knowledge works as a powerful tool for addressing problems whose successful solutions require an individual to reach beyond common sense. Second, but more importantly, the fundamentals are essential for an engineer to define a real problem in such a way as to be solvable via her fundamental scientific and mathematical understanding.

Note that in both cases, application of fundamentals reveals that this knowledge is ultimately a tool in the service of a greater goal—the creation of a structure, a machine, a network, or a process (Billington 1996). In the first instance, the goal is to solve a problem that has been clearly defined. In the second instance, the goal is to define the problem in such a way that it can be solved with the tools at hand. This second instance of framing a particular problem so that it can have a particular solution is not as attractive to academic scientists, because it concerns the particular problem only and shuns any attempt to generalize that does not add to the solution of the problem. Yet this is the heart of engineering, and its true hallmark as an intellectual discipline. An elegant solution to one particular problem, may have little to do with an elegant solution to the next particular problem, or even a different elegant solution to the same problem. In pursuit of such elegance, the engineer will strip away all unneeded and unwanted parameters related to more general cases, until the only parameters remaining are those that significantly impact the design. In this case, the engineer not only chooses what parameters make a significant impact, but she also chooses what actually constitutes a significant impact. The judicious and effective use of fundamental understanding to define the world in radically specific terms for the sake of solving a particular problem might be hard for a scientist or mathematician to understand, since he cannot rid himself of the urge to generalize. He cannot bring himself to abandon the idea that elegance is to be found in expressions, no matter how complex, that lead to general solutions.

The engineer's elegant solution to a particular problem is as simple as possible. The simpler and more clear the solution, the more it coincides with common sense, the better. Yet two ironies bedevil our understanding of this simplicity as elegance. First, once attained, the best simple solution belies the amount of work and refinement required to develop it. This deception works most effectively on the young and the inexperienced. If it is so simple, why did it take so long to reach? It took that long precisely because it is that simple! People who have arrived at simple solutions know the weary road that leads to such refinement. After all, we are human beings. We can easily make a complex mess. (11/16/07 give example of Pilkington fins and re-designed fins). How we must work to clean away all but the absolutely essential! Second, the elegant solution may rely more on common sense than on the application of engineering science. What are we to think if we solve a problem more readily by thinking like carpenters or electricians? Are we then no longer engineers? Engineers require the strength to seek humbly after the best solutions to particular problems, regardless of where they may lie.

What is clear is that a simple, correct, solution can only be developed based on fundamental understanding. What is also clear is that such fundamental understanding does not come easily. According to Harvard Education and Psychology professor Howard Gardner:

> …even the best students in our best schools do not understand very much of the curricular content. The "smoking gun" is found among physics students at excellent universities—for example, MIT and Johns Hopkins. These students perform credibly in classroom exercises and end-of-term

> tests. But consider what happens outside class, when they are asked to explain relatively simple phenomena, such as the forces operating on a tossed coin, or the trajectory of a pellet after it has been propelled through a curved tube. Not only do a significant proportion of students (often more than half) fail to give the appropriate explanation; even worse, they tend to give the same kind of answers as peers and younger children who have never studied mechanics. Despite years of schooling, the minds of these college students remain relatively unschooled. (Gardner 2000)

Howard Gardner make a case for the apprenticeship as a means to addressing a student's specific needs, and therefore reaching toward understanding.

> The weaver in a preliterate society just models and adds a few words of explanation; the weaver in a literate society can make use of charts, diagrams, mathematical equations, and books. Unlike the traditional schoolteacher, however, the weaver who teaches for understanding draws upon these epistemic forms when whey arise in the course of a genuine problem, a challenging project, a valuable product. A judicious introduction and integration of apprenticeship methods within a scholastic setting should yield students whose potential for understanding is engaged and enhanced (Gardner, 2004)

Discuss medical training, and training in the other professions. Engineering is different, because it is tied to the lone inventor, the rugged individual, who, armed with technical knowledge, is able to transcend his context and change society. This is the entrepreneur, the risk taker. And yet, many of our best 20th century engineers and architects come out of a tradition by which they were heavily influenced.

> The Third International Mathematics and Science Survey (TIMSS) (Schmidt et al., 1997) criticized curricula that were "a mile wide and an inch deep" and argued that this is much more of a problem in America than in most other countries. Research on expertise suggests that a superficial coverage of many topics in the domain may be a poor way to help students develop the competencies that will prepare them for future learning and work. (How People Learn, p. 42)

Do I understand structure because I understand the fundamentals, or do I understand the fundamentals because I understand structures? I think that the two interact, but I think that a familiarity with structures motivates one to engage the fundamentals with greater resolve than a familiarity with the fundamentals motivates one to engage structures.

Discussion of the importance of drawing as an intellectual discipline

> Drawing is the language of the Engineers, because the geometric way of thinking is a view of the thing itself and is therefore the most natural way;

> while with an analytic method, as elegant as that may also be, the subject hides itself behind unfamiliar symbols. --Carl Culmann

References

Billington, D.P. (1983) *The Tower and the Bridge: The New Art of Structural Engineering*, Princeton University Press, Princeton , New Jersey.

Billington, D.P. (2005) *Civ 262: Structures and the Urban Environment*, Powerpoint Lectures, Department of Civil and Environmental Engineering, Princeton University, Princeton, New Jersey.

Watson, W.J. (1927) Bridge Architecture, New York, New York.