TEACHING BRIDGE DESIGN IN THE GRAND TRADITION OF MODERN ENGINEERING

Paul Gauvreau
University of Toronto

The current approach to structural engineering education in North America produces graduates who are reasonably adept at calculating stresses in structures and dimensioning structural components to ensure safety and serviceability. Given a structural concept that has been developed by others, therefore, recent graduates can calculate its response to a given loading, and determine whether or not structural components are safe and serviceable. Their education has given them practically no preparation, however, to deal with the creative aspects of design. They are thus generally incapable of taking a blank piece of paper and producing a workable preliminary structural concept that satisfies given functional requirements. From this perspective, it can thus be said that our universities turn out graduates who enter practice unable to design.

Because universities have not taught the creative aspects of structural engineering for at least thirty years, engineers have had no alternative but to obtain their design training on the job. Because engineering is a practical activity, it is reasonable to expect that the workplace can be an effective setting for teaching some aspects of the practice of design. To be done properly, however, on-the-job design training requires a significant investment of time and effort by employers. Given current economic realities in the engineering business, training is usually one of the first costs to be cut by firms in an effort to maintain short-term profitability. This situation has severely limited the effectiveness of the workplace as a provider of design training.

Although most engineers invariably end up acquiring some measure of competence in design, the process by which this happens is haphazard at best. There is thus cause for concern regarding the quality of the design training engineers receive and, by implication, the quality of the structures they design. Design training is too important an undertaking to be left entirely to the vagaries of the workplace. The university has a responsibility, therefore, to become an active and important provider of design training. This article examines ways by which the undergraduate engineering curriculum can be transformed into an effective means of teaching students to become competent and creative design engineers.

The Current State of Bridge Design Practice

The proposed transformation of the design curriculum must consider not only how to give recent graduates the ability to put design concepts onto a blank piece of paper, but also how to improve the quality of the design concepts that they create. In order to accomplish this objective, it is important to have a proper understanding of the quality of the design concepts produced by the current practice of bridge design.

At first glance, the practice of bridge design appears to deliver high quality designs. Modern bridges deliver a high standard of safety and serviceability, which is generally far superior to the reliability provided by the products of other areas of engineering. The computer software industry, for example, routinely expects consumers to accept significant design deficiencies (bugs) without question or legal recourse. Bridge designers, in contrast, are ethically and legally bound to produce reliable structures literally on the first try, every time, since doing otherwise could easily involve loss of human life and significant financial loss.

Safety and serviceability, however, are not the only requirements that bridges must satisfy. Society demands that the cost to build and operate bridges be within limits consistent with the responsible management of public funds, and expects that the aesthetic impact of bridges will be, at very least, not negative. The economic and aesthetic record of bridges built during the past quarter century is at best mediocre. This is largely due to inertia that has prevailed over the past thirty years in the field of bridge technology. The relation between economy, aesthetics, and technology will be examined in greater detail in this subsection.

Trends in Bridge Technology

Engineers who ended their careers in the mid-1970s would have little difficulty in recognizing and using the structural systems, components, and details currently used in bridge design and construction, since bridge technology has not undergone significant development since then. Structural engineering research during the past thirty years has been predominantly concerned with refinements in analytical methods to calculate demand and capacity in conventional structural systems and components. Although this has led to incremental improvements in design standards and has given design engineers access to powerful analytical tools, it has not advanced the fundamental technology used to design and build bridges.

The lack of progress in bridge technology that has prevailed over the past quarter century is illustrated in the following figure. The photograph on the left, taken prior to 1975, shows a precast concrete segment before its assembly into a bridge superstructure. The photograph on the right shows a similar precast concrete segment from a bridge built in 2000. It is evident from the figure

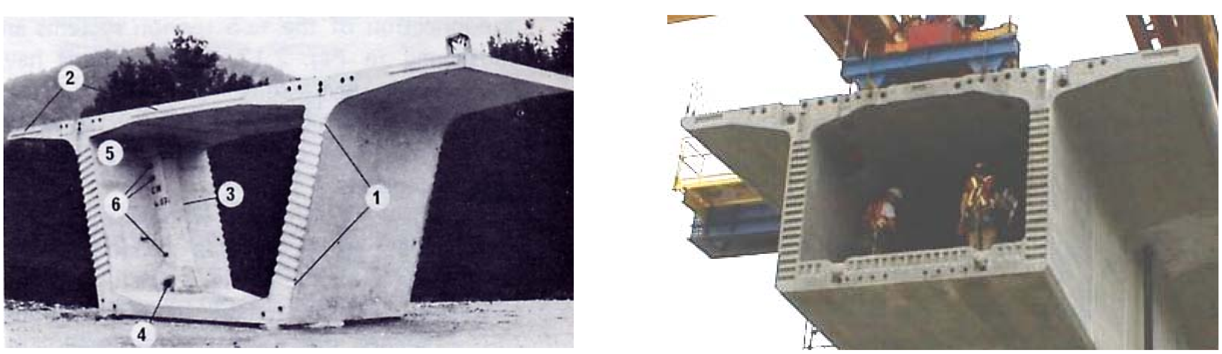

Figure 1 Precast segmental box girder sections. Left: pre-1975 (PTI 1978). Right: 2000

that there is essentially no difference between the two segments with regard to primary structural characteristics, including the overall arrangement of the cross-section, the arrangement of post-tensioning ducts, and the layout of shear keys in the webs and slabs. Although not visible in the figure, the post-tensioning systems used in both bridges are practically identical (post-tensioning technology has not changed significantly since the mid-1960s), as are the techniques used for installing reinforcing steel into formwork (which have remained essentially unchanged since the early decades of the twentieth century).

These observations are consistent with quantitative measures of progress in bridge technology. Over the past thirty years, for example, the consumption of primary materials used in bridge construction (concrete, structural steel, reinforcing steel, and prestressing steel) has remained essentially constant. It is difficult to find a similar situation in other major technology-based sectors of the economy. In microelectronics, for example, where technological progress is constantly expected and consistently delivered, the computational power of microprocessors has increased by a factor of more than 18 000 between 1971 and 2000 (Intel 2003). If microelectronics had advanced at the same rate as bridge technology over the same period, the personal computer revolution, and all of its related technological growth, would never have taken place. Although it is perhaps too much to expect bridge technology to evolve at the same rate as other technologies, the fact that there has been no significant progress in bridge technology in the past quarter century appears to be inconsistent with what can be reasonably expected from a technology-based sector of the economy.

Technology and Economy

Bridge designers pride themselves on delivering economical bridges. Generally speaking, recently constructed bridges are indeed economical, but only within a very limited definition of the concept of economy. In current bridge design practice, economy is considered to be the outcome of a process that begins by identifying a set of design concepts that satisfy all applicable provisions regarding safety and serviceability, and then selecting from this set of solutions the one that is least expensive. In current bridge design practice, minimum requirements for safety and serviceability of structures are prescribed by design standards (also referred to as "design codes"). The process defined above is therefore equivalent to selecting the least expensive concept from the set of concepts that are in accordance with applicable design standards.

To a large extent, current design standards establish minimum requirements for safety and serviceability by defining technology that is acceptable. Standards contain highly detailed and prescriptive requirements for designs using conventional materials, structural systems, and details, yet give practically no information covering the use of new materials or the use of conventional materials in new ways. Although standards generally do not explicitly prohibit new technologies, the absence of specific requirements at a level of detail comparable to that provided for traditional materials and systems represents an effective barrier inhibiting the use of new technology.

Current design standards are thus a snapshot of technology that is at best current, and often considerably older than current. If design standards are the only means of defining the set of concepts that are safe and serviceable, then only concepts based on current or older technology will be included. By following this approach, designers are prevented from considering the entire set of safe and serviceable solutions and are restricted to a subset thereof, consisting only of those solutions that are also deemed to be acceptable by current design standards, i.e, solutions based on conventional technology. Because technology is effectively frozen in time by design specifications, the opportunities for technology to function as an engine for creating economic value are severely limited.

This proposition is corroborated by the U. S. Federal Highway Administration's Highway Construction Price Index (FHWA 2003), which is a measure of the change in the cost to build one square metre of highway (and, by analogy, one square metre of highway bridge). Between 1971 and 2000, this index closely matched the consumer price index, which implies that the unit cost of bridge construction, when adjusted for inflation, has remained effectively constant.

In other technology-based sectors of the economy, a different perspective prevails. Technology is selected less on the basis of what is deemed acceptable by design standards, and more on the basis of what delivers an acceptable balance between cost and all other design requirements. When technology is free to develop in response to the demands of design, the economic results can be impressive. The average price per transistor, adjusted for inflation, has dropped from approximately $0.50 to $0.000001 (a factor of 500 000) between 1971 and 2000 (Intel 2003). These results are a direct result of the technological progress in the microelectronics industry described previously, and thus illustrate how technology can create real economic value when technological progress is demanded and delivered.

Technology and Aesthetics

The flow of forces in structures can be given visual expression by a suitable arrangement and shaping of structural members. Generally speaking, structures that resist load with a constant state of stress tend to express the flow of forces more vividly than structures that resist the same load with stresses that vary within the member. A uniform load applied to a single-span, constant-depth beam, for example, induces stresses that vary throughout the member. The same load applied to a parabolic arch of identical span, however, induces compressive forces in the arch, the horizontal component of which is constant along the span. This observation regarding stresses is consistent with our perception that the arch is more visually expressive than the constant-depth beam.

David P. Billington (1983) has eloquently and conclusively demonstrated that the visualization of the flow of forces in structures that minimize the consumption of materials is a rich medium of artistic expression, which has been used by gifted designers to create bridges of great aesthetic significance. Because this medium of expression is inextricably linked to the response of structures to applied loads, it can really only be used by an artist who has a deep understanding of the interplay between the visible characteristics of a given structure and the pattern of forces and stresses within, and who can use this understanding to create new visual forms. The only group of people who have the knowledge of structural behaviour required for this task are engineers. In recent decades, however, this unique contribution to bridge aesthetics has been marginalized.

The current conventional wisdom on bridge aesthetics considers bridges to be divided into two classes. In the first class, bridges are designed according to the governing principle of "form follows function", which is taken to mean that efficient structural behaviour and low construction cost are sufficient to guarantee visual elegance. The following statements, made by high-level managers of leading design firms, are indicative of this perspective:

Aesthetics are inherent in good bridge design. The classic phase, "form follows function", is a basic principle in bridge engineering. A properly proportioned bridge is attractive. The size and shape of the structure's components provide a definition of its purpose. That's what people appreciate when it comes to bridge aesthetics. Innovative solutions automatically make a structure aesthetically pleasing (Finley 2001).

There must be inherent beauty in cable-stayed bridges because most cable-stayed bridges are beautiful despite our best efforts to make them ugly (Buckland 1990).

Both quotations allude to a beauty that is “inherent” in well designed bridges, i.e., structurally efficient ones. Buckland in particular refers to an essence of elegance that is so strong that it can actually prevail when the designer's creative efforts prove to be ill-founded. It is significant that neither quotation contains any reference to creative effort directed specifically towards the aesthetic aspects of the design. One could certainly conclude from these statements that, by applying the prevailing interpretation of “form follows function”, it is possible to create a work of art without even trying.

The second class of bridges is commonly referred to as “signature bridges”. For this class of bridges, “form follows function” is deemed to be invalid. The desired aesthetic “signature” can only be achieved by going beyond the mere requirements of structural efficiency and economy and, as is often the case, spending a lot of money. If one accepts that aesthetic merit is to be found outside the realm of structural efficiency, then it is no longer necessary or productive to have engineers involved in roles other than purely technical. For this reason, there is often significant involvement of architects in signature bridge projects.

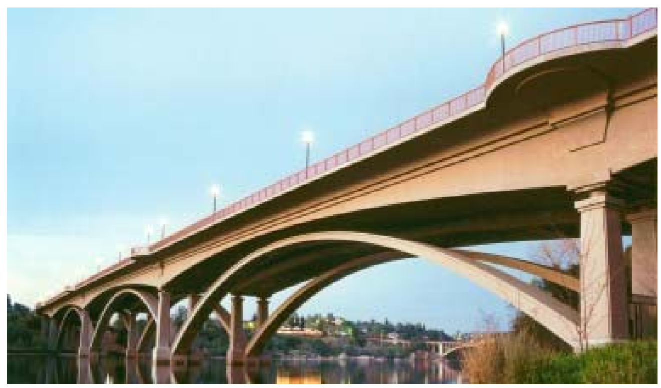

Figure 2 American River Bridge at Folsom, California

It is also becoming common to involve lay people, usually members of communities affected by a proposed “signature” bridge, in the design process. On several projects, the public has actually been allowed to select the primary features of major structural components through a voting process. Such a process, for example, produced a three-span concrete box girder where each span supports an arch rib completely devoid of structural function (Figure 2). In this case, the public wanted arches and they were given arches (Gottemoeller 1998). The completed structure conveys a strong impression that the arch ribs were added as an afterthought to a haunched girder bridge that was already complete, both structurally and visually. Arches are one of the boldest, most expressive structural elements available to bridge designers. It is unfortunate that in this case they were used merely to deceive.

The current situation with regard to bridge aesthetics, therefore, is characterized by increasing disregard for the contribution of engineers to the definition of the aesthetically significant aspects of bridges, in favour of architects and lay people. It is wrong for engineers to be relegated to a purely technical support role based on dogmatic beliefs or political expediency. In so doing, owners deprive themselves of the richness of the engineer’s unique vision, founded in the discipline of structural efficiency and economy.

Current attitudes regarding bridge aesthetics are understandable considering the lack of progress in bridge technology during the past quarter century. The structural systems, components, and details used in bridges are the primary means by which designers express the flow of forces visually. Since these aspects of bridge technology have not changed appreciably over the past twenty five years, it has become increasingly difficult for designers to make new visual statements using this technology. Structural systems that have become familiar through widespread use (e.g. haunched prestressed concrete box girders) have thus lost much of their evocative power. Because the new technologies have not been developed to replace conventional systems, no new opportunities have been created for aesthetic expression through the visualization of the flow of forces. This has contributed to the perception that engineers have nothing of significance to contribute to bridge aesthetics.

The Grand Tradition of Engineering Education

The history of structural engineering shows that there is an important link between what engineering students are taught at university and the quality of designs produced by the practice of engineering. It is useful to examine more closely this relation between education and practice to gain insight into how the current engineering curriculum can best be changed to improve the practice of bridge design in the twenty first century.

One of the most remarkable historical examples of the impact of education on the practice of design engineering can be found in the teaching careers of two Swiss professors, Wilhelm Ritter and Pierre Lardy. Both men taught at the Federal Institute of Technology in Zurich (commonly referred to by its German initials ETH), Ritter from 1882 to 1904 and Lardy from 1948 to 1958. Ritter's students included Robert Maillart and Othmar Ammann; Lardy's included Heinz Isler and Christian Menn. These four students went on to become widely recognized as the twentieth century's greatest designers, respectively, of reinforced concrete bridges, steel bridges, thin-shell concrete roofs, and prestressed concrete bridges.

The work of Maillart, Ammann, Isler, and Menn was guided by a shared perspective on structural design that was strongly rooted in the teachings of Ritter and Lardy (Billington 2003). The link between the achievements of these four designers and what they were taught by Ritter and Lardy is arguably the most compelling example in the history of engineering of the power of education to influence the practice of structural design. The exceptional accomplishments of these four designers would lead some people to believe that the methods of Ritter and Lardy bring little of relevance to the education of "mainstream" designers. The impact of Ritter and Lardy, however, is also visible in the high general standard of structural design that has prevailed in Switzerland throughout the twentieth century and which persists to this day, almost fifty years after Lardy gave his last lecture at the ETH.

Although roughly fifty years separate the teaching careers of Ritter and Lardy, both men shared many of the same views on what and how to teach. (Billington (2003) provides a more extensive description of and commentary on their methods of teaching.) The key elements of their pedagogical approach can be summarized as follows:

1. *The use of simple, graphical methods of structural analysis*. Both men regarded structural analysis as a tool serving the needs of design, rather than an end in itself. They understood that the additional accuracy of overly complex methods of analysis is often illusory, and generally diverts the designer's attention away from opportunities to use the arrangement of structural members to control forces and stresses. They therefore favoured simple methods of analysis, including graphical methods by which forces in structures are calculated by drawing lines on paper corresponding to the magnitude and direction of the vectors representing the forces. These methods were sufficiently accurate to guarantee safety and economy, allowed designers to visualize the flow of forces throughout a given structure, and provided a direct link between structural behaviour and the visible form of the structure.
2. *Critical study of completed structures*. Both Ritter and Lardy placed considerable emphasis on the description and critical discussion of completed structures, structural systems, and details. These studies went far beyond the mere calculation of stresses, and invariably included critical com-

ments on ease of construction, economy, and the aesthetic quality of the examples they considered.

3. *Inseparability of the aesthetic and technical aspects of design*. When Ritter and Lardy stressed the importance of aesthetics in their studies of completed structures, they made it clear to students that visual elegance was not obtained by cobbling ornamentation or other non-structural devices onto structures that had already been designed. Rather, Ritter and Lardy demonstrated the potential for creating aesthetically significant structures through the visualization of the flow of forces. They reinforced awareness of the intimate link between structural behaviour and the aesthetic impact of structures through the use of graphic statics.
4. *Enthusiasm for new technology.* Ritter and Lardy both taught during periods of important change in structural engineering technology. Ritter's tenure at the ETH coincided not only with major advances in long-span steel bridge technology, but also with the early days of reinforced concrete structures. Lardy's teaching years coincided with the early development of prestressed concrete construction. Although neither Ritter nor Lardy had all of the answers regarding these new materials, both men recognized their importance for the future of engineering and taught their students the fundamental principles underlying the behaviour of structures built using these materials.

Towards a Renewed Design Curriculum

Having described the primary elements of Ritter and Lardy's approach to teaching, we can now examine in greater detail why it had such a strong impact on the practice of design engineering.

Design is a creative activity by which existing ideas are combined and transformed into a new concept that best satisfies specific requirements and constraints. For the design of a highway bridge, for example, the requirements and constraints could include a geometrical description of highway alignment and the terrain to be crossed, subsurface conditions, and technical specifications pertaining to safety and serviceability. Relevant existing ideas could include scientific principles governing the behaviour of structural systems and materials to be considered, as well as specific features of completed bridge projects that satisfy similar project requirements. Implicit in this definition of the design process is the need for a means to evaluate the quality of design concepts, to determine which one "best satisfies" the requirements and constraints that define the design task.

Based on this perspective, therefore, the outcome of the design process depends not only on the creative act of combining and transforming ideas, but also on the quality of the existing ideas themselves and the criteria by which the best possible solution is identified. For example, a body of existing ideas that includes knowledge of high-strength steel is more likely to lead to better design concepts for a long-span bridge than a body of existing ideas that includes only knowledge of unreinforced masonry. Regarding the importance of criteria in determining the quality of solutions, it is evident that if the only criterion by which alternative concepts can be evaluated is minimum construction cost, then it will be practically impossible to arrive at a suitable design if long-term durability is a major project requirement.

The design process thus has three primary aspects: the body of existing ideas used as raw material for the creative process, the creative act itself, and the means by which design concepts can be evaluated. These three aspects must be addressed in the education of design engineers.

The body of existing ideas from which new design concepts are generated will be referred to as *technology.* The technology that is relevant to bridge design can be divided into two subsets. The first covers required scientific background, and includes fundamental physical principles describing the behaviour of structural systems and materials, methods for calculating the response of structures to load and imposed deformation, as well as methods for calculating the load-carrying capacity of structural components. The second subset is a body of knowledge of past bridge design practice, and includes descriptions of finished bridges, structural systems, components, details, methods of construction, and evaluations of the performance of bridges and bridge components in service.

Although it would be possible, strictly speaking, to design bridges without any knowledge of prior practice, this is not done. Knowledge of past practice streamlines the design process by giving designers a basis for the rapid selection of initial concepts as well as the elimination of ideas that are known from past experience to have little potential for success.

The ability to produce feasible design concepts from relevant items of technology will be referred to as *skill*. Skill is thus the capacity to perform the creative activities required in the bridge design process. (In the context of bridge design, "feasible" refers to concepts that, with a reasonable amount of additional development effort, will lead to designs that satisfy the project requirements.) One of the primary challenges in bridge design that requires the application of creative skill is to identify how best to use knowledge of prior practice in the design process. As stated previously, this aspect of technology can streamline the design process, but, in the hands of insufficiently skilled designers, such speed is often achieved at the cost of severely limiting creative freedom. A primary aspect of creative skill in bridge design is thus to know how to look forward by looking backward, i.e., how best to use knowledge of old solutions to develop new ones.

The basis by which designers determine, given a set of feasible concepts, which one is best will be referred to as *values*. It is a misconception that persists among engineers and laymen alike that design decisions follow directly from the "numbers", i.e., the concept with lowest stresses, material quantities, or construction cost is necessarily the best. This is an extremely narrow view, which neglects the fact that, for a given project, there can easily be several alternative concepts all of which have similar stresses, quantities, and cost. A simplistic consideration of the numbers, moreover, is of little help when the relative importance of the various quantitative measures is not obvious. How can engineers decide on the basis of numbers alone, for example, to go beyond the minimum requirements prescribed by design standards to reduce long-term maintenance costs or to reduce seismic vulnerability? Issues that are clearly unsuitable to quantitative treatment, such as aesthetics, also require a different approach. Decisions regarding these issues must be made not on the basis of which alternative has the highest quantitative score, but rather on the basis of which alternative is *best*.

Design training, therefore, is the task of transferring technology, skill, and values to students. The approach taken by Ritter and Lardy is consistent with this perspective.

Both men recognized that the technology component of design training must include not only fundamental scientific principles, but also knowledge of prior design practice. Ritter and Lardy were masters of the scientific foundations of engineering and taught this material with rigour and due regard for the fact that this knowledge must serve design. What distinguishes them from their counterparts teaching today, however, was the importance they placed on the critical study of completed works. Ritter, for example, undertook an extended tour of the U. S. A. in 1893 to learn about the latest developments in American steel bridge construction. Upon his return, he lectured to his students on the structures he had seen and studied in the U. S., covering not only the more general properties of structural systems, but also the arrangement and function of important structural details (Billington 2003). Through the study of real structures, Ritter and Lardy gave their students a body of knowledge they could draw on in design practice, which gave them greater ability and confidence in the creation of initial structural concepts.

In the critical study of completed structures, Ritter and Lardy emphasized new technologies. As stated previously, Ritter lectured to his students on the latest developments in steel bridge technology. He also lectured to his students on reinforced concrete, which during his time at the ETH was a new material that was still not accepted by many engineers. Lardy taught prestressed concrete to his students, likewise a new material in the 1950s. His lectures covered the behaviour and design of prestressed concrete structures in breadth and depth that are still far greater than what would be seen in most North American undergraduate programs today. By taking new materials seriously, Ritter and Lardy gave students a perspective that the development of technology is important to the future of civil engineering. Rather than training their students to design the structures of the past, they trained them to design the structures of the future.

There is no evidence that either Ritter or Lardy taught material explicitly intended to develop creative skills in students. Courses in brainstorming and "lateral thinking", now popular in many institutions, were unheard of in their day. The curricula taught by Ritter and Lardy, however, were rich in opportunities for students to develop creative skills, primarily through the intensive use of visual methods for the analysis and design of structures. Modern research has demonstrated that the very act of drawing stimulates creative thought (see, for example Edwards (1986)). Although this link between drawing and creativity might not have been consciously understood by Ritter and Lardy, there is little doubt that the importance they placed on drawing in the curriculum greatly enhanced the creative abilities of their students.

Graphic statics is an example of how drawing was integrated into areas of the curriculum in which drawing would nowadays be considered to be practically irrelevant. Such was the importance of graphical methods of structural analysis for Ritter that, although purely algebraic methods for calculating forces and stresses in structures were well established in his time, he deliberately chose not to include algebraic methods in his seminal work on structural analysis *Anwendungen der graphischen Statik* (Billington 2003). The power of graphical analysis goes beyond stimulating creative thought through drawing. The method of graphic statics calculates the response of a given to a given load literally by drawing a diagram of the forces directly onto a scale drawing of the structure. By giving visual expression to forces in this way, a direct link is created between structural behaviour and the visible arrangement of structural components. This gives designers a powerful means of visualizing the flow of forces in structures in the creation of works of aesthetic significance.

Both Ritter and Lardy recognized that good structures are not the direct outcome of a purely mathematical process of minimizing materials or stresses. They believed that what makes one structure better than another must often be judged using criteria that defy quantitative expression. Much of their teaching involved detailed studies of completed structures, in which they challenged students to think critically, showing the way with comments on the visual characteristics of structures that were often made using emotional language (Billington 2003). These comments were not made gratuitously, but rather were the result of serious reflection based on an understanding of the important relation between structural behaviour and aesthetic significance. Through exposure to critical comments on aspects of design that cannot be quantified, their students gained an appreciation for the fact that calculations are only a means to an end, and that great designs are the result of decisions based on values that go far beyond the mere quantitative aspects of engineering.

Transforming the Curriculum

It could be argued that although the accomplishments of Ritter and Lardy are impressive, their approach to education is rooted in the early and mid 1900s and therefore has limited applicability to the current situation in education and practice. For example, how can their perspective on education help us to train students to become competent designers using new materials such as high-performance concrete and advanced composites, when neither Ritter nor Lardy ever heard of these materials?

We can address this concern with the observation that there is nothing in the elements of Ritter and Lardy's approach to teaching that is tied to a specific technology. What is significant regarding Ritter's embrace of reinforced concrete, for example, is not so much the actual details of what he taught his students regarding this material, but rather the fact that he recognized the importance of teaching his students about how to design structures using what was then an emerging technology. For this reason, the perspective of Ritter and Lardy is not merely of historical interest, but can actually be used as a basis for the transformation of the current engineering curriculum into an effective means of training competent and creative designers.

Given the political will within university administration to transform the engineering curriculum, therefore, there is really no reason why the primary elements of Ritter and Lardy's approach to teaching cannot serve as a basis for this transformation. To ensure success of this venture, however, the following points should be given due consideration:

1. Given the power and ease of use of computer-based methods of analysis, it is worth insisting that there is still a need to teach students simple graphical methods of analysis. These methods

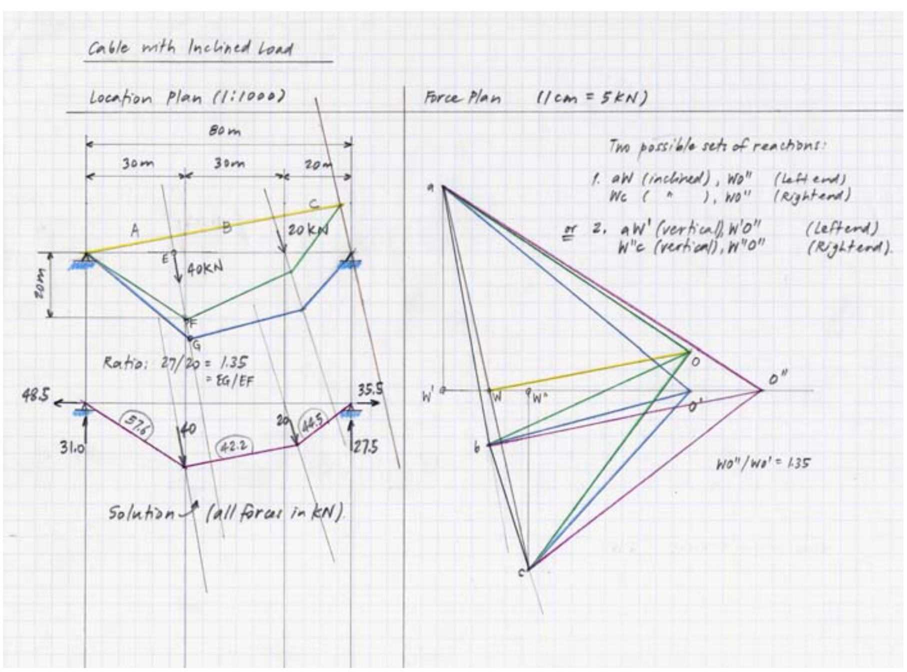

Figure 3 Graphic Statics

are obviously not suitable for all types of structural analysis, but for the static analysis of arches, beams, and cable structures, there still is no better method than graphic statics. Instructors should resist the temptation to have students draw the force diagrams as shown in Figure 3 using computers. The accuracy of forces calculated on the basis of hand-drawn force diagrams is perfectly acceptable for design; there is no need to increase accuracy using computer-based drawings. Drawing by hand allows students to focus on the structure and its response to load, and to think according to their own logic rather than having to conform to the logic of the computer. Finally, it is a fact that a significant portion of the human brain mass is devoted to controlling the hands (Restak 2001). By insisting that students use their hands in complex ways, we encourage them to activate this mental capacity that would otherwise have not been used.

2. Most professors currently teaching structural engineering in North America have had little or no experience as designers in practice. Although some would insist that only experienced designers should teach design, this position is not consistent with the historical precedent set by Ritter and Lardy, neither of whom were designers. These men did, however, maintain significant involvement in practice, focusing on major issues in structural design, not merely providing expert advice on a small specialized problem. Just as importantly, they realized that they had a primary duty to teach. This is also at odds with current realities, in which many professors regard undergraduate teaching as a necessary evil.
3. Teaching students about new technologies will be challenging because there are generally no design standards giving rules for checks of safety and serviceability. Given that the current curriculum is strongly geared towards teaching students to work with current design standards, establishing a focus on new technologies will require a significant change in attitude.
4. The critical study of completed structures must not be viewed as merely a major exercise in structural analysis. There must be critical discussion of why important design decisions were made, and an assessment of whether or not the solutions proposed are truly the best solutions. This is a prime opportunity to discuss, as Ritter and Lardy discussed, the aesthetic aspects of design and their relation to structural behaviour. The structures chosen for study should be sufficiently complex to challenge students and to stimulate new ideas for alternative solutions. In addition, there should be a strong emphasis on state of the art and emerging technologies. There is little point in spending precious class time in critiquing structures built using technology that is fifty years old.
5. Many universities have made attempts recently to make their curriculum more "design-oriented". Unfortunately, these changes have often been made without much understanding of the real nature of design engineering. Instead, students have been given exposure to project management, teamwork, and communication skills, all of which can be useful to engineers in practice, but none of which addresses the need to transfer technology, skill, and values to students. In addition, there is a tendency to develop common design courses suitable for all disciplines of engineering. This approach neglects the fact that many important issues in mechanical or electrical design, such as prototyping, have no relevance at all to structural engineering.

Transforming the engineering curriculum based on the pedagogical approach of Ritter and Lardy will be instrumental in enabling universities to become credible providers of design training. Making this happen, however, will not be easy. The perspective of Ritter and Lardy is at odds with many ingrained notions of how universities should operate as well as what the role of universities should be within the practice of engineering. At some point, though, we must admit to ourselves that the status quo is not working. By renewing the curriculum, we will be able to educate a new generation of designers who will be capable of moving bridge technology forward, and in so doing, we will make a major contribution towards creating real economic value and new opportunities for aesthetic expression.

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