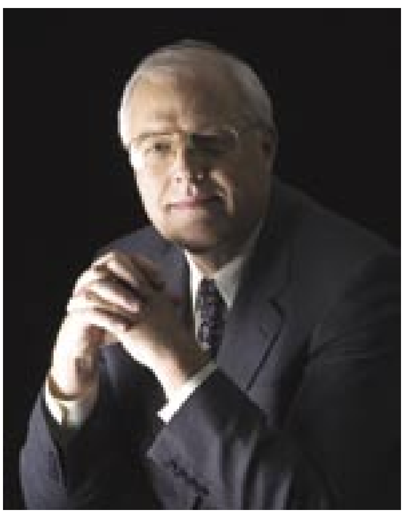
A Culture of Discipline

Structural engineers must approach their work with diligence and a great sense of responsibility to themselves, their firms, and society.

BY LAWRENCE G. GRIFFIS, P.E.



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IN 1886, THE CENTENNIAL EXPOSITION COMMITTEE INVITED FRENCH ARCHITECTS AND ENGINEERS TO SUBMIT BUILDING DESIGNS FOR THE UPCOMING CENTENNIAL EXPOSITION OF 1889, COMMEMORATING THE 100TH ANNIVERSARY OF THE FRENCH REVOLUTION. From approximately 700 proposals received, the project was awarded to a French bridge engineer and metal-worker named Gustave Eiffel, who was well known for his bridge and building designs in Europe and his contribution to the structural skeleton design in the Statue of Liberty some years earlier. Eiffel competed for and won the Centennial Exposition project. He supervised the design and construction while assuming personal financial responsibility for its completion on time (by March 31,1889, a mere 22 months after the start of construction) and within the established budget (6% below the 1.6 million francs he had estimated). The Eiffel Tower is a true marvel of engineering genius by a man who understood and appreciated the beauty of exposed structure as an expression of architecture. The elegant curved form of the tower is a product of the mathematics involved in designing the tower to resist wind forces. Its design and construction displayed a whole host of ingenious innovations for its time:

- A 300-m-tall tower that was the tallest structure in the world from 1889 until 1930, with the construction of the Chrysler Building in New York.
- Over 7,000 tons of wrought iron made up the structure recognized by Eiffel as the only available building material that would provide the necessary combination of strength, moldability, durability and affordability to make its construction a reality.
- Preparation of more than 5,000 blueprints with scale drawings of more than 18,000 pieces traced out to an accuracy of a tenth of a millimeter and then preassembled into 5-m pieces prior to delivery to the site.
- A closely supervised team of constructors never exceeding more than 250 on-site at one time, yet able to complete construction at a record pace of just 22 months with an incredible safety record of but a single fatality throughout the entire construction period.
- The use of multiple foundation types on highly varying soils to achieve a uniform settlement,

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including the first ever watertight metal caissons with injected compressed air for work below the water level.

- The use of specially built steam-powered winches and cranes that were designed to pivot 360° while crawling up the inclined legs of the tower.
- Elevators designed to ascend along the inclined face of the tower legs to heights never before attempted or achieved in prior construction.
- The establishment of the tower as a scientific laboratory with the first ever wind tunnel, making Eiffel the father of practical wind engineering of structures.

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Despite the innovation and beauty of this magnificent structure, the esteemed writers, poets, painters, sculptors and architects of Paris condemned the tower as a "useless and monstrous… barbarous mass overwhelming and humiliating all our monuments…" to which a Eiffel responded:

"For my part I believe the Tower will possess its own beauty. Are we to believe that because one is an engineer, one is not preoccupied by beauty in one's constructions, or that one does not seek to create elegance as well as solidarity and durability? Is it not true that the very conditions which give strength also conform to the hidden rules of harmony?.....I hold that the curvature of the monument's four outer edges, which is as mathematical calculation dictated it should be….will give a great impression of strength and beauty, for it will give to the eyes of the observer the boldness of the design as a whole."

Engineers today can learn from the work of Eiffel and the culture of discipline he exhibited in the design and construction of his tower. The new generation of structural engineers is called upon to design structures that reach taller and span further, that take a myriad of forms and complex shapes, with ever-faster construction schedules and with limited financial resources to design and build them. Yet we are entrusted "to protect the health, safety, property and welfare of the public" in the practice of our profession. The structures we design can carry heavy loads and transmit enormous forces that put ourselves and the public at great risk on a regular basis. We design by codes and standards that are longer and more complex than ever before, and that change with a dizzying pace. Most engineers already work harder, now we must learn to work smarter. I often marvel at the quality of the engineers that major engineering programs are turning out. They are well-schooled in the physics of engineering, but they must be trained to adapt to the business of structural engineering. To achieve success or even survive in this challenging but potentially rewarding profession, we must teach and practice our own culture of discipline.

Let us recognize that the design and construction business in the United States is imperfect at best. Yet it can and does possess a system of checks and balances that our engineers must recognize and be keenly aware of. First, we must recognize that it is wise to build the quality into our design and our construction documents as they evolve. As a safety net, we can initiate formal quality assurance programs into our practice. Let's support a concept of peer reviews, not only within our own firms, but with outside firms as well. Our engineers must be taught to reach out to their fellow designers to discuss design problems, collaborate on design approaches and solutions, and develop the discipline to review their own work as the design progresses.

The design process by its very nature is iterative. It advances a step at a time. But inevitably, conditions change as the design evolves, thus requiring a retracing of some prior tasks that are now inaccurate or incomplete. In these situations, the step backward is critical to advancing the design forward. Here is where many engineers fail. Here is where the discipline is tested. Here is where the process can fail us. I have observed that engineers are at their very best when a small group converges in a room to review a particular design or a set of drawings. The electricity in the exchange of ideas is exhilarating, very productive and certainly instructional as well. We can learn a lot from ourselves in this process.

The second opportunity for checking the design is in the shop drawing and detailing phase. As the construction documents are reviewed and interpreted in the preparation of shop drawings, questions can arise that test the design. Engineers have to be taught to be alert to those who interpret our documents as they can spot potential pitfalls and deficiencies in the design. If the report comes back "It doesn't look right," we should pay attention and be open-minded. We must check our shop drawings with the idea that we are looking to avert trouble during fabrication and construction. This is the second critical period of the design and construction process.

The final opportunity to test our design comes during construction. Oftentimes, a contractor, fabricator or erector can spot a detail that doesn't feel right or observe a performance of the structure that seems awry. While these people seldom fully understand or appreciate the engineering principles involved, they often have established a feel for performance and for proportion. Listen well during this period, as it represents that last check in our system.

Engineers too should be on-site as much as their contract allows (or better yet, seek additional services for the privilege of more intensive on-site observation than implied in most standard A/E contracts) to observe the progress and quality of construction. We should learn to realize that the most vulnerable period for a structure can be during the partially complete erection stage.

I am reminded of a construction collapse discussed by Joe Yura, Ph.D., in his marvelous lecture given in honor of his receipt of the 2006 Beedle Award presented by the Structural Stability Research Council (SSRC). The famous Quebec Bridge collapsed in 1907 during its cantilevered erection, because construction deflection warnings at the cantilever end went unheeded as construction progressed. Over 19,000 tons of steel came crashing down into the St. Lawrence River.

It is instructive to note that most construction problems and failures result when not one but all three of these opportunities to discover a problem are missed. Upon later review, it is often found that the signs were there, but no one paid attention.

Some further suggestions to avoid problems in the design and construction process are:

1 **Develop a proactive approach to constantly reviewing your own work as the design progresses.**

2 **Plan the work and then work the plan.** Eiffel was a master at planning and communication within his design and construction team. The results of that skill and effort were apparent in the outcome.

3 **Reach out to your fellow designers to seek help and second opinions and to request a review of your design.** Recognize that the element you design may never be checked and could

get built exactly as you specify.

4 Engineering is a team sport, and the best designs result from collaboration. It is worthy to note that Eiffel collaborated heavily with two of his chief engineers and an architect in evolving the final design for his tower.

5 Know your structural software, its design approach and its limitations. Check your designs with simple approximate methods. Always evaluate the reasonableness of your design.

6 Always draw details to scale. Otherwise, you may be led astray.

7 Where conditions can vary, develop a solution that bounds the potential limits. This often happens for member properties in concrete analysis, uncertainties in mass, stiffness, and damping, or in soil-structure interaction.

> **We must recognize that it is wise to build quality into our design and construction documents as they evolve.**

8 Analyze what you design; design what you build. Said differently, be sure the sizes and properties in your analysis match those on the construction documents and are the same ones that get constructed.

9 Always study the deflected shape of your structure under gravity load alone and under wind and seismic load alone to be sure it is behaving in a logical way. Compare the results of a first-order analysis with that of a second-order analysis and observe the change in behavior. Generally, keep second-order effects to 1.5 or less.

10 Examine the frequency and mode shapes of your structure. They offer the opportunity for a better understanding of behavior.

11 When performing a complex or unusual design, test one approach to the problem by conceiving another one to test the validity of the solution. In the design of his tower, Eiffel was well aware of the indeterminacy of his structure and the uncertainty of not only the wind forces themselves, but also the resulting forces from his analysis. He tested his solution with alternate approaches to the analysis.

12 When reviewing someone else's work, discuss with them at the start what he/she feels are the most troubling or "soft" areas of the design. Start the review there, then proceed to the most unusual or unique aspect of the design. After that, review the most repetitive elements first, for one mistake can lead to multiple repairs or replacements. Check the rest with what time remains.

13 Review the drawings and details for constructability and tolerances.

14 Review shop drawings carefully and timely. Promptly address RFIs and problems at the job site. Visit the job site as often as your contract requires, and seek additional services to get to the site more frequently where the project warrants it.

15 Reach out to fabricators, detailers, erectors and contractors whenever you can to test your designs for cost and constructability.

16 Produce designs that respect the proportion and elegance of structure as architecture.

The practice of structural engineering affords the opportunity to design magnificent structures that can create great beauty and touch the lives of many people. It can provide us with the satisfaction of making our world a better place to live. A structural engineer must approach his/her work with diligence and a great sense of personal responsibility to oneself, to the company they work for and to society as a whole. In the spirit of Eiffel and his tower, I would impress upon young structural engineers the need to develop a culture of discipline. MSC