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History and Failure

Henry Petroski

Engineering is a profession focused on the future, looking back mainly to calibrate progress; engineers are typically drafting plans for the next generation of artifacts, seeking to achieve what has not been done before. On one hand, we are ever conceiving larger, faster, more powerful structures and systems; on the other, we are ever devising smaller, lighter, more economical machines and devices. Every new thing has meaning in comparison with that which it supersedes—bettering the past, as it were, and usually the recent past.

If past engineering achievements have any relevance, it would thus appear to be principally as standards against which the latest designs are judged. From this point of view, only the most recent of technological history is really relevant for modern engineering, and then only insofar as it presents data to be extrapolated or a challenge to be overcome. Any extended history of engineering would appear to be mostly irrelevant technically. The history of engineering as a succession of achievements, of incremental progress, might motivate young engineers and give them pride in their profession, but it is not commonly expected to add directly to their technical prowess.

This is a shortsighted view. The history of engineering, when embedded in a social and cultural context, does in fact have considerable potential for demonstrating the true nature of engineering as practiced in the real world, but only if it is presented in a way that makes it engineering as well as history. For no matter how profoundly engineers know that their problems have more than a technical dimension, the solutions ultimately will suffer if engineers do not stand on solid technical ground. Thus one of the most promising uses of history in engineering education is to add to a fundamental understanding not of how obsolete artifacts worked but of the timeless aspects of the engineering process itself, while at the same time providing an appreciation for the past and process of civilization and engineering's role in it.

The history of engineering, as of civilization, is clearly one of both successes and failures, and the failures may be the more useful component of the mix. Although examples of good engineering practice can certainly serve as paradigms of good judgment, great people do not become so merely by reading biographies of great men and women.

And great new engineering achievements do not come to be merely by inference from an extrapolation of successful precedents. Indeed, the history of civil engineering is littered with the wreckage of famous bridges that were designed in a tradition of success: the Tay Bridge in 1879, the first Quebec Bridge in 1907, the Tacoma Narrows Bridge in 1940.

In an open discussion of the relevance of history held in 1975 before the Institution of Structural Engineers, R. J. M. Sutherland expressed the opinion, which was echoed frequently, that major engineering disasters "are much more likely to be avoided if future designers, individually, develop a habit of looking back and questioning how each concept grew." Unfortunately, this is seldom done. Ironically, signal successes in engineering have tended to arise not out of a steady and incremental accumulation of successful experience but rather in reaction to the failures of the past—from the minor annoyances accompanying existing artifacts to the shock of realization that the state of the art was seriously wanting. Thus, the collapse of the Tay led directly to the Firth of Forth Bridge, which celebrated its centennial in 1990; the collapse of the first Quebec Bridge led to the redesigned second, now a symbol of Canada; and the colossal collapse of the Tacoma Narrows taught bridge engineers overnight an appreciation for aerodynamics that has led to such new suspension-bridge designs as the Severn and Humber. An efficacious history of engineering should incorporate a treatment of engineering failures not only for their value in adding a measure of humility to the innate hubris of engineers but also for the essential features of the engineering method that they can so effectively reveal.

Sketches in the Sand

One very interesting study of engineering failures was conducted by P. G. Sibly and A. C. Walker some years ago. They found that major bridge disasters have occurred with surprising regularity over the past two centuries. If our engineering science and experience are cumulative, how can such cyclic behavior be explained? The explanation lies in the nature of engineering design, which begins in a most primitive and nonrational way. Engineers literally dream up designs, and usually in graphic form. It is only when an engineer has the equivalent of a sketch or drawing that the engineering sciences can be called upon to analyze the practicality of a design, or that other engineers can be consulted for their experience. The process is often convoluted, of course, and an engineer's sketch can be informed, con-

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plauds are certainly not news, the lessons learned and caveats embedded in his stories of human error and technical failure sound modern because the same sorts of embarrassing mistakes and oversights have continued to plague engineering through the ages. Human error, being part of human nature, cannot be expected ever to cease, but we might be able to reduce it, at least in engineering, by looking to the distant rather than to the more recent past. Being rooted in human error, classical case studies of engineering failures are never obsolete. Furthermore, being generally removed from modern controversy and debate, older case studies can more easily reveal aspects of the engineering method with incontrovertible clarity.

Among the stories told by Vitruvius is one about the engineer Diognetus, who had been retained by the Rhodians to design machines as needed to defend the city against siege. One day another engineer, named Callias, came to Rhodes and gave a public lecture, which was accompanied by a model of a revolving crane claimed to be capable of seizing an enemy’s helepolis, or siege machine, and lifting it inside the wall of the city. The Rhodians were so impressed with the demonstration that they transferred Diognetus’s grant to Callias.

In the meantime, according to Vitruvius, a 180-ton helepolis had been designed and constructed by the enemy, and Callias was asked to scale up his model to meet the challenge. He replied that it was impossible to do so, because not all things that work on a small scale are equally feasible on a larger one. Vitruvius, as a good engineer would, illustrates the principle with a familiar example: A hole of about an inch in diameter can readily be bored with a wood auger, but to bore a three-inch hole by a similar device is impractical, and a six-inch one “seems not even conceivable.” (Although we may not have direct experience with augers, all of us must have experienced a similar frustration with screwdrivers. Indeed, this is why slotted screws are made only so large; above a certain size they come with bolt heads.)

Not surprisingly, Callias was summarily dismissed by the Rhodians, who then begged Diognetus to help them capture the approaching siege machine. Vitruvius’s continuation of the story is full of human dimensions, which makes it all the more valuable for putting the engineering in a real-world context. According to Vitruvius, Diognetus agreed to help only if the captured machine would become his property. When this was agreed to, he did not proceed to construct a larger machine but “pierced the wall in the place where the machine was going to approach it, and ordered all to bring forth from both public and private sources all the water, excrement, and filth, and to pour it in front of the wall through pipes projecting through the opening.” This action continued throughout the night, and the next day the giant helepolis became so boggled down in the man-made swamp that it could neither advance nor retreat. The great machine was abandoned, and Diognetus had it set up in a public place in the city and dedicated it to the people of Rhodes. Vitruvius’s conclusion that “in works of defense, not merely machines, but, most of all, wise plans must be prepared,” clearly remains valid today, because the design process is no less dependent on a proper anticipation of the conditions under which a design is possible and will be used. Furthermore, the story of Diognetus and the Rhodians demonstrates very forcefully, if metaphorically, how human-scale obstacles can check the advance of even the most powerful products of high technology.
Obelisks and O-Rings
The reason Callias could not scale up his model to a full-size defense machine was understood in Vitruvius’s day only by analogy. Indeed, the mysterious problem of scale continued to frustrate designers well into the Renaissance, and still does today in cases ranging from supertankers to massive process plants. Large obelisks were known to have broken under their own weight during erection, great cathedrals collapsed during construction, and colossal ships broke up upon being launched. Galileo opened his seminal work on the strength of materials by recounting similar engineering horror stories, which he used to argue that geometry was not the only tool a designer needed. Analytical mechanics has evolved considerably since Galileo’s time, of course, and the stories he related to motivate his work remain more relevant for engineering than his errant analysis of the cantilever beam (although how even a genius like Galileo could fall into analytical error is itself well worth the attention of the modern instructor and student).

For example, early in the first day of dialogues on his new sciences, Galileo related a story of a column that was being stored on two piles of timbers. A mechanic, seeing this and knowing how obelisks and ships could break under their own weight, feared that the column itself might be dangerously close to breaking. He suggested, therefore, that a third support be added under the middle of the column, and everyone consulted agreed that it was a good idea. So it was done, and the safety of the column was thought to be improved. Some months later, however, the column was found to be broken in two, but not in the way the mechanic had feared. What had happened was that the freshly installed support did not settle as readily as the original ones, and the column was unable to support its own weight balanced on the single central support.

The story of the fallen column was clearly significant to Galileo, and it remains even today a forceful reminder that a seemingly innocuous or even beneficial design change can actually be the root cause of a failure, albeit in a different mode, that it was intended to obviate. Within recent years, not dissimilar minor engineering design changes have ultimately led to such visible disasters as the collapse of the skywalks in the Kansas City Hyatt Regency Hotel and the explosion of the space shuttle Challenger. Although Renaissance engineers certainly did not have nearly the analytical sophistication even of today’s students (who are expected to master Galileo’s problem as sophomores), that is not to say that classical experiences with conceptual or pre-analytical engineering design do not remain relevant. Indeed, it might be argued that had engineers involved in designing modern skywalks or solid rocket boosters been familiar with Galileo’s story of design changes made on the fallen column, they might not have accepted so uncritically the promised efficacy of multiple support rods or extra O-rings.

Design anecdotes told by Vitruvius or Galileo can have value well beyond merely mastering the texts of these classic authors or the nature of Roman or Renaissance engineering. The stories briefly related here—and there are countless like them in major and minor classics and even in obscure engineering texts and memoirs with no pretensions to being classics—show us the timeless features of engineering. The written record of 19th-century engineering, for example, contains quite explicit discussions of projects (such as the Britannia, Firth of Forth, Niagara Gorge, and Brooklyn Bridges) that tested the analytical capabilities of their time. Perhaps precisely because of this tradition of writing, the engineers of such projects tended to be more open about what motivated, drove and checked their designs than are engineers today, who can mask their reasoning in computer graphics and printouts. Sir Alfred Pugsley has written that he found it easier to “get under the skin of...earlier designers...than to do the same in the case of the more typical design teams of today.”

There are features of engineering design that will forever remain independent of the state of the art and, therefore, are independent of whether we use abacuses, slide rules, or computers to analyze and flesh out the conceptual designs from which all engineering flows. Even as the design process is coming under more and more scrutiny, especially in a computer context, more temporarily distant writing about engineering remains one of the most illuminating sources of insight into the often ineluctable engineering method.
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The foundation engineer Ralph Peck has written widely and articulately on engineering judgment, that attribute generally thought most difficult to teach. In discussing the reliability of dams, Peck observed as late as 1981 that "nine out of ten recent failures occurred not because of inadequacies in the state of the art, but because of oversights that could and should have been avoided." Peck has also pointed out that, when it comes to design errors and failures, "problems are essentially nonquantitative" and, furthermore, that "the solutions are essentially nonquantitative." He has acknowledged that improvements in analysis and testing might certainly be profitable, but it is also likely that "the concentration of effort along these lines may dilute the effort that could be expended in investigating the factors entering into the causes of failure." Among Peck's prescriptions for restoring good judgment to engineering practice is a historical perspective; he has deplored, for example, the fact that engineers taking the examination leading to registration as a structural engineer in Illinois could not properly identify such significant structural achievements as the Eads Bridge across the Mississippi.

The practice of engineering is truly as old as civilization, and indeed civilization as we know it is hard to conceive of without the work of engineers. But whereas many of the classic works of civilization, from poetry to pyramids, have long been taken on their own timeless terms, the methods of engineers are often thought to be continually superseded. Although helicopters may have replaced ramps for erecting obelisks, and computers may have made possible designs beyond the calculational reach of engineers only a generation ago, there are fundamental aspects of the conceptual engineering design process that have changed little (if any) over millennia. In fact, the ready availability and power of the tools of modern technology may even threaten to erode somewhat the more basic conceptual engineering skills. Ironic as it may seem, we might find an antidote to the erosion of fundamental design skills and critical engineering judgment more readily in some of the oldest volumes on engineering than in the most modern textbooks. Such promise argues strongly for a proper infusion of history into engineering curricula.

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