TO ENGINEER IS HUMAN

The Role of Failure in Successful Design

With a new afterword by the author

"Serious, amusing, probing, sometimes frightening and always literate."
—*Los Angeles Times*

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DESIGN AS REVISION

There is a familiar image of the writer staring at a blank sheet of paper in his typewriter beside a wastebasket overflowing with crumpled false starts at his story. This image is true figuratively if not literally, and it represents the frustrations of the creative process in engineering as well as in art. The archetypal writer may be thought to be trying to put together a new arrangement of words to achieve a certain end—trying to put a pineapple together, as Wallace Stevens said. The writer wants the words to take the reader from here to there in a way that is both original and familiar so that the reader may be able to picture in his own mind the scenes and the action of the story or the examples and arguments of the essay. The crumpled pages in the wastebasket and on the floor represent attempts that either did not work or worked in a way unsatisfying to the writer's artistic or commercial sense. Sometimes the discarded attempts represent single sentences, sometimes whole chapters or even whole books.

Why the writer discards this and keeps that can often be attributed to his explicit or implicit judgment of what works and what does not. Judging what works is always trickier than what does not, and very often the writer fools himself into thinking this or that is brilliant because he does not subject it to objective criticism. Thus manuscripts full of flaws can be thought by their authors to be masterpieces. The obviously flawed manuscripts are usually caught by the editor and sent back to the author, often with reasons why they do not succeed. Manuscripts that come to be published are judged by critics and the general reader. Sometimes critic and reader agree in their judgment of a book; sometimes they do not. Positive judgments tend to be effusive and full of references to and comparisons with other successful books; negative judgments tend to be full of examples demonstrating why the book does not work. Critics often point out inconsistencies or infelicities of plot, unconvincing or undeveloped characters, and in general give counter-examples to the thesis of author, editor, and publisher that this book works. In short, the critic points out how the book *fails.*

The point was made quite explicitly in a recent review of *The Man Who Could See Through Time,* a play by Terri Wagener in which a physics professor and a young sculptor debate science and art. Reviewing the play in *The New York Times,* Frank Rich wrote:

> The best two-character plays look so effortless that we tend to forget how much craft goes into them. . . . To see a two-character play that fails, however, is to appreciate just how difficult the form really is.

And so it is with engineering structures. The great suspension bridges look so simple in line and principle, yet the history of failures of the genre has demonstrated that their design takes a touch of genius. And geniuses like Washington Roebling and Othmar Ammann can arguably be said to have learned more what not to do from the great failures of their forgotten predecessors than today's designers can be expected to learn about how to design the next suspended masterpiece from either the Brooklyn or the Verrazano Narrows Bridge.

Some writers, even if they do not try to publish them, do not crumple up their false starts or their failed drafts. They save every scrap of paper as if they recognize that they will never reach perfection and will eventually have to choose the least imperfect from among all of their tries. These documents of the creative process are invaluable when they represent the successive drafts of a successful book or any work of a successful writer. What other authors tend to learn from the manuscripts and drafts of the masters that cannot be learned from the final published version of a work is that creating a book can be seen as a succession of choices and real or imagined improvements. An opening sentence or even a word may evolve to its final form only after going through dozens of rejected alternatives. Sometimes the final version is closer to the first than any of the intervening versions, and sometimes a word will be crossed out only to have a ladder of synonyms, near synonyms, remote synonyms, and even antonyms leading like Jack's beanstalk through the clouds of imagined riches, ultimately to have the author fall back on the very word with which he began. These creative iterations suggest that the author's choice of even a single word is more easily understood in terms of rejection than acceptance, in terms of failure rather than success, in terms of *no* rather than *yes.* The fair manuscript gives little if any hint as to why exactly the author put down what he did in his first draft. But the word changed, the sentence deleted, and other alterations that may be traced through successive drafts show clearly that the author did not believe what he had originally written had been right. It failed in some way to contribute to the end that the author was working toward. This is not to say that something unchanged from first to last was deemed perfect by the author; it simply indicates that, rightly or wrongly, he detected no unacceptable fault with it or could see no alternative. The unchanged part of his book's structure might teach the student nothing about its composition, however.

Some of the acknowledged masters of the written word were seemingly never completely satisfied with their work. James Joyce was apparently notorious for making voluminous changes even as his major works *Ulysses* and *Finnegans Wake* were being set in type by the printer. And what was set in type was revised by Joyce in the proofs. In 1984, after volumes of criticism were published based on the original 1922 version of *Ulysses*, a new edition appeared, reportedly correcting over five thousand errors that crept into the first edition. The book was claimed by one critic to be so changed by the restoration of a few dropped lines that a whole new interpretation of the novel was in order.

Other recognized masters often express the thought that they *abandon* a work rather than complete it. What they mean is that they come to realize that for all their drafts and revisions, a manuscript will never be perfect, and they must simply decide when they have caught all its major flaws and when it is as close to perfect as they can make it without working beyond reasonable limits. Even the twenty-odd years Joyce spent on *Finnegans Wake* was apparently not enough for him to believe he gave a perfect manuscript to the printer, and all authors acknowledge implicitly that revisions to manuscripts reach a point of diminishing returns.

The work of the engineer is not unlike that of the writer. How the original design for a new bridge comes to be may involve as great a leap of the imagination as the first draft of a novel. The designer may already have rejected many alternatives, perhaps because he could see immediately upon their conception that they would not work for this or that reason. Thus he could see immediately that his work would fail. What the engineer eventually puts down on paper may even have some obvious flaws, but none that he believes could not be worked out in time. But sometimes even in the act of sketching a design on paper the engineer will see that the approach will not work, and he crumples up the failed bridge much as the writer will crumple up his abortive character sketch.

Some designs survive longer than others on paper. Eventually one evolves as *the* design, and it will be checked part by part for soundness, much as the writer checks his manuscript word by word. When a part is discovered that fails to perform the function it is supposed to, it is replaced with another member from the mind's catalog, much as the writer searches the thesaurus in his own mind to locate a word that will not fail as he imagines the former choice has. Eventually the engineer, like the writer, will reach a version of his design that he believes to be as free of flaws as he thinks he can make it, and the design is submitted to other engineers who serve much as editors in assessing the success or failure of the design.

As few, if any, things in life are perfect, neither is the analogy between books and engineering structures. A book is much more likely to be an individual effort than is a building, bridge, or other engineering structure, though the preparation of a dictionary or an encyclopedia might be said to resemble the design of a modern nuclear power plant in that no individual knows everything about every detail of the project. Furthermore, the failure of a book may be arguable whereas the failure of a building collapsed into a heap of rubble is not. Yet the process of successive revision is as common to both writing and engineering as it is to music composition and science, and it is a fair representation of the creative process in writing and in engineering to see the evolution of a book or a design as involving the successive elimination of faults and error. It is this aspect of the analogy that is most helpful in understanding how the celebrated writers and engineers alike learn more from the errors of their predecessors and contemporaries than they do from all the successes in the world.

While engineers who play it safe and copy designs that have stood the test of time may be well paid (though perhaps not nearly as well paid as the authors of mass market paperbacks who use more formulas in their genre fiction than are available to any engineer), there is no more professional distinction in being such an engineer than there is literary recognition in being such an author. When we speak of creative engineers we are talking about as select a few as there are great writers. And just as the great writers are those who have given us unique and daring experiments that have worked, so it is that the great engineers are those who have given us their daring and unique structural experiments that have stood the test of time.

It is not capricious to compare engineers with artists on the one hand and with scientists on the other. Engineering does share traits with both art and science, for engineering is a human endeavor that is both creative and analytical. Being creative pursuits, the innovative works of engineering test the vocabulary of the critics, whoever they may be, and it is not always clear-cut whether a daring new structure will stand or fall, even in the make-believe world of hypothesis testing. The problem with the new structure lies in the very humanness of its origins and of the world in which it will function. Whether an engineering structure succeeds as a work of art may not be a question of life and death, but whether it will stand or collapse beneath the weight of those attending the dedication ceremonies is indeed a question to be reckoned with.

The very newness of an engineering creation makes the question of its soundness problematical. What appears to work so well on paper may do so only because the designer has not imagined that the structure will be subjected to unanticipated traumas or because he has overlooked a detail that is indeed the structure's weakest link. Certainly no designer who remembers the ill-fated Tacoma Narrows Bridge will design another bridge like it, but a new bridge that is unique aesthetically or analytically may hold surprises even for the designer. To be safe the engineer should try to imagine the structure in every conceivable situation and check each case to be sure that not even the slightest part is liable to break. But to imagine and check *every* conceivable situation might take forever, and the engineer must make judgments as to which situations are the most severe and which are insignificant. The former are analyzed, while the latter are ignored.

But as the literary critic can discover meanings and symbols an author denies having been aware of in a piece of creative writing, so the analytical critic of a new engineering design can find interactions among the parts of a structure that surprise the designer. And just as a literary reevaluation can come years after a book has achieved critical acclaim, so an engineering structure can stand, though precariously, for years before it is reanalyzed, perhaps because it or a structure not unlike it has recently failed. In lucky cases the faulty structure will be caught before it collapses; in many cases it is catastrophe that prompts the postmortem exposé.

The engineering task of designing a bridge shares qualities with the tasks of both poetry and science. Like poetry, the exact bridge one designer conceives to span a given space during a given technological era may never exist in the mind of any other engineer at any other time. Yet, like discoveries in science, if the theoretical and motivational foundations for a bridge are laid, then a bridge will be built, and it will be *the* bridge for that place and time no matter who designs it. No poetic license is allowed in the design of the details of the bridge, for an erratic line on the blueprint or an eccentric number in a calculation can be the downfall of the structure, no matter how much like a sound bridge it looks on paper. And today, if a computer is used, even so small an error as an inadvertent slip of a punctuation mark, decimal point, or sign in an equation can lead to a bridge that fails even if the computer model works.

The bridges of Robert Maillart have been praised as works of art that are one with the Alps. In flights of innovation the Swiss engineer may be thought to have spanned the intricacy of contour lines on maps over which his mind floated like an eagle, light to the eye but strong to the touch. Like the pensive man in Wallace Stevens' "Connoisseur of Chaos":

> . . . *He sees that eagle float*
> *For which the intricate Alps are a single nest.*

Maillart's use of concrete reinforced with steel put poetry in place of prosaic bulk, whose ease of understanding may have made a more conventional bridge clearly safe but did not distinguish it. Maillart's bridges were not conceived fully justified line by line upon the page, for they work as entities as spare as poems. And as with poems, in the end, they work simply because they work. Upon their completion on paper, Maillart's plans could be analyzed after a fashion, and they could be somewhat revised here and there to redistribute stresses or smooth the lines. Their proof was in the putting the plans into place, however. And when the concrete had set about the steel, then the falsework supporting the bridge a-building (as the platen supports the poem a-typing) was removed, and each bridge withstood its first test as the poem its first reading. As each new bridge endured the seasons of use and re-use, as the poem the readings and re-readings, each bridge became a success. But Maillart also saw in many of his masterpieces extra weight or an unnecessary line that he removed in the next. His practice of self-criticism and revision was not unlike the writer's.

The engineer no less than the poet sees the faults in his creations, and he learns more from his mistakes and those of others than he does from all the masterpieces created by himself and his peers. While Maillart mastered the steel-in-concrete bridge, he did not originate the form. In the closing years of the nineteenth century François Hennebique, whose French construction firm restored Gothic cathedrals among its other activities, carried out research on the use of steel embedded in concrete to resist the cracking that invariably occurs when concrete is tensed rather than compressed, as it is in all-masonry structures. Hennebique's firm gained experience in reinforced concrete structures by completing thousands of projects, but these were not all without flaws. The bridge crossing the Vienne River at Chatellerault, France, in particular, developed a number of cracks. This was the longest Hennebique arch bridge, and its pattern of cracking showed to all who would observe it that there was room for improvement in the design. As David Billington has argued in his award-winning monograph on Robert Maillart's bridges, Maillart, in particular, learned from such experiences, as he learned from the cracking of his own designs, such as his early bridge at Zuoz, Switzerland.

Small cracks in reinforced concrete do not necessarily pose any danger of structural collapse, for the steel will resist any further opening of the cracks. But cracks do signify a failure on the designer's part to understand his design completely when it was only on paper, since the cracks incontrovertibly disprove the implicit hypothesis that stresses high enough to cause cracks to develop would not exist anywhere in the structure. Discovering cracks in a completed structure thus enables the designer to learn the weaknesses of his knowledge and thereby to improve upon future designs, if only to beef them up where the stresses are less precisely predictable. In this way an engineer's designs can evolve from early works that show promise to the mature works that are brilliant and develop no cracks, much as a poet's juvenilia evolve into masterpieces that appear to be seamless.

Engineering, like poetry, is an attempt to approach perfection. And engineers, like poets, are seldom completely satisfied with their creations. They notice, even if no one else does, the word that is not quite *le mot juste* or the hairline crack that blemishes the structure. However, while poets can go back to a particular poem hundreds of times between its first publication and its final version in their collected works, engineers can seldom make major revisions in a completed structure. But an engineer can certainly learn from his mistakes.

Anton Tedesko, designer of such significant concrete shell structures as the sports arena in Hershey, Pennsylvania, and the airport terminal in St. Louis, relates the story of inspecting fine hairline cracks that developed in a hyperbolic paraboloidal shell in Denver that he designed for I. M. Pei. The concrete shell does not possess the stiffening ribs that have been criticized as architectural blemishes on the St. Louis airport shell, but Tedesko believes the hypar shell's cracks, which he suspects most people are not even aware of, could have been avoided and he has inspected them for over two decades, whenever he stops in Denver. It is not that an engineer admires his own or gloats over others' mistakes, it is that he recognizes, unfortunate though they may be, that defects are unplanned experiments that can teach one how to make the next design better. As Tedesko has written in a retrospective article on concrete shell structures that interweaves stories of collapses with stories of triumph: "I have mentioned examples of unfortunate experiences because it is easier to draw lessons from examples of poor performance than from good performance." Art and literary criticism serve the same purpose, and it is not surprising that artists and writers, like engineers, are often their own severest critics.

Engineering students understand early on that there is a great deal to be learned from a mistake. In a recent engineering class at Duke, students participated in the design of an experiment to produce metals through a foaming process aboard the space shuttle to test the feasibility of manufacturing new lightweight structural materials in a weightless environment. One student in the course admitted that "real engineering is a lot harder than we thought," but he also recognized that the class was "learning a lot from failing and screwing up." These students were coming to the realization that T. H. Huxley expressed in his book *On Medical Education:* "There is the greatest practical benefit in making a few mistakes early in life."