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DESIGN AS OBVIATING FAILURE

ABSTRACT

The systematic avoidance of failure is what characterizes rational design. Thus historical case studies of failures are full of important information for successful design, and the designer who is unfamiliar with the history of failures risks repeating old mistakes. Rather than being discussed merely in generalities in this paper, these ideas are explained in the context of the specific structural engineering example of bridges.

INTRODUCTION

The structural engineering problem of designing a bridge may serve not only as a paradigm but also as a metaphor for any problem in design. A *need*, or at least a *want* for a bridge, is first identified, and almost never by the eventual designer. Some individual, group, or community usually perceives the need for a bridge because what a bridge does —carry traffic efficiently, safely, and reliably from point A to point B over whatever obstacles or impediments may lie between the points— is not being provided by existing means or devices.

The need for a bridge defines a design problem that is then posed to those who are accustomed to dealing with such problems —bridge designers. Those who pose the problem recognize, implicitly if not explicitly, that problems in design do not have unique solutions, and there is often a design competition. Those who wish to have a bridge built specify its functions and delineate constraints that define the data specific to each bridge problem: where the bridge must be located, how much traffic it must carry, what clearance it must allow, how it must fit into the existing infrastructure, and so forth. Here is where the designer usually begins to work, and even if social, ergonomic, and environmental contraints are not imposed explicitly in the definition of the design problem, the designer will see them as self-imposed, natural, and desirable aspects of any solution. A truly successful design must not fail to satisfy *all* requirements and constraints, explicit and implicit. The design problem is then fundamentally one of anticipating and obviating failure.

THE DESIGN PROCESS

Given the problem, defined in terms of data about the site, traffic requirements, environment, and other relevant matters, how *does* one design a bridge? According to Fritz Leonhardt, a leading German bridge engineer,

> The data [...] must be fully assimilated and remembered. The bridge must then take its initial shape in the imagination of the designer. For this process to take place, the designer should have first consciously seen and studied many bridges in the course of a long learning process. He should know [...] when a beam bridge, an arch or a suspension bridge will be suitable (Leonhardt, 1984 : 32-33).

It is as if the designer riffles through the catalog his mind has accumulated over years of experience in much the same way early machine designers consulted the textless catalogs of mechanisms described by Ferguson (1977 : 827-836) and airplane designers pored over those of airfoils described by Vincenti (1986 : 717-758).

The bridge designer recognizes that he will have the benefit of experience to draw upon, but that each bridge is also unique in the sense that it will rest on foundations on which no other bridge rests and it will exist in a social, ergonomic, and environmental context that it itself will change. Thus, according to Leonhardt, after sketches of the designer's concept have been drawn and criticized with regard to appropriateness for the site and function, the bridge engineer behaves like an artist with his preliminary studies or drafts:

> The designer should now shut himself away with these first results, meditate over them, thoroughly think over his concept and concentrate on it with closed eyes. Has every requirement been met, will it be well-built, would not this or that be better looking or better for later detailing? (Leonhardt, 1984 : 33).

Only after «several [...] correction phases» do serious calculations begin and

> in the first place with simple and rough approximations to check whether the assumed dimensions will be sufficient [...] Then some runs with modern cumputer programs can be made, using different depths or other variables in order to find the most economical dimensions; these should, however, only be chosen if no other essential requirements, such as aesthetics, length of approaches, grades etc. are affected (Leonhardt, 1984 : 34).

While much organized engineering effort is expended in the analytical calculations of stresses, deflections, and other quantitative measures of performance or performance limits that could be defined as hypothetical «failures» (Vincenti, 1986 : 717-758), the design process is first and foremost clearly a creative and not a deductive one, and in this sense it is not unlike writing or any other creative act (Petroski, 1985).

Clearly it is the qualitative generic choice that constitutes the initial creative and intuitive aspect of bridge design, with calculations and computations following well behind, and this holds true for all design. J. E. Gordon, the thoughtful British aircraft engineer, has written:

> [N]either mathematics nor handbook formulae will «design» a structure for us. We have to do the designing ourselves in the light of such experience and wisdom and intuition as we may possess; when we have done this the calculations will analyze the design for us and tell us, at least approximately, what stresses and deflections to expect (Gordon, 1981 : 375).

And the deficiencies *were* promptly corrected, for they were recognized as indicating potential failure modes not properly obviated in the first place by the bridge builders.

Iron Bridge was an enormous innovative success for the most part because it mimicked the perfected stone arch bridge, and cast iron was as good a material as stone in compression. As iron evolved as a bridge building material in its own right, however, there were countless failures of designs that tried to exploit the *tensile* strength of the metal. And this problem persists to this day, as new alloys, new fabrication techniques, and new structural designs are used in an attempt to exploit a new material's perceived new advantages. But, as is often the case, overly optimistic designers tend to overlook any (unfamiliar) shortcomings of a new material, process, or design and therefore tend to minimize or overlook entirely new or unfamiliar failure modes (FISHER, 1984).

THE CASE OF SUSPENSION BRIDGES

Bridge design also advances by accepting obviously ever more ambitious challenges. Two centuries ago the spans of bridges were measured, nay dreamed of, in hundreds of feet. Today bridges span a mile between suspension towers and two miles on drawing boards and more in the minds of engineers. These symbols of modern technological process were not achieved without cost, however, for the history of suspension bridges is littered with the debris of those that collapsed. Many of these failures are by and large not general knowledge to those who are not structural engineers or historians of technology. The one notable exception is that of the Tacoma Narrows Bridge, which engineers could do little but film as it twisted itself apart in the wind in 1940. Indeed, the bridge engineers of that era, while conscientiously practicing the state of the art, made the unforgiveable design error of not knowing the history of failures of the structural genre with which they were working.

Suspension bridges have always been notoriously flexible, and the flimsy foot bridges we sometimes find in the mountains where our children go to summer camp provide first hand experience. Larger bridges, which began to be common in the early nineteenth century, were susceptible to collapse under the rhythmic marching of soldiers whose cadence matched the natural frequency of the bridge itself. To this day the superstition persists that soldiers must break step when crossing *all* bridges, even massive stone arches, and the Albert Suspension Bridge across the River Thames in London has a notice to that effect posted on its approach.

John Roebling, the great nineteenth-century suspension bridge designer and his son Washington, who oversaw the construction of his father's design for the Brooklyn Bridge, understood the phenomenon of destruction by resonant vibrations. On the construction catwalk of the great bridge he posted the sign (MCCULLOUGH, 1972 : 420):

SAFE FOR ONLY 25 MEN AT ONE TIME. DO NOT WALK CLOSE TOGETHER, NOR RUN, JUMP, OR TROT. BREAK STEP!

But the elder Roebling understood that he could not post rules for the forces of nature and the only way to succeed in building a longer and stiffer suspension bridge was to understand how and why previous bridges had failed. High winds proved especially difficult problems to overcome, and Roebling wrote a paper in 1841 describing several then-famous failures of suspension bridges in the wind. After pages of discussing the vicissitudes of bridge-building, he closed his paper with an apology:

> The above remarks (about problems and accidents with suspension bridges) have not been made with a view of bringing suspension bridges into discredit. To impute such a motive to me would be unjust. No one can be a greater admirer of the system than myself [...] In speaking of the weak points of the system, I have only intended to show how much caution is necessary in planning and executing a suspension bridge in order to insure its safety (ROEBLING, 1941 : 196).

Not only the wind but the nature of the traffic that mid-nineteenth century suspension bridges had to carry made the design of a successful one a formidable task. At mid-century the conventional wisdom of bridge designers was that a suspension bridge five hundred or a thousand feet long could not be made stiff enough to bear the concentrated weight of the ever heavier railroad locomotives that then were being developed. Great British engineers like Robert Stephenson and Isambard Kingdom Brunel devised elaborate means to bridge great distances with stiff (and expensive) girder bridges, but Roebling, by understanding above all what could cause a suspension bridge to fail, was able to devise a means of obviating that mode of failure —and in a more economical design. His double-decked Niagara Bridge was ingeniously stiffened and guyed, and it was opened to railroad and wagon traffic in 1855.

THE EVOLUTION OF SUSPENSION BRIDGES

It is the nature of design to «improve» upon existing designs. In the case of suspension bridges this means not only building ever longer bridges, but also doing so with more economy. As successful bridges, such as those of John Roebling, appeared to become commonplace, there was the predictable inclination, encouraged by the pecuniary interests of those who want bridges built and the aesthetic interests of those who design bridges, to take off some of the excess weight and excess material that not only cost money but also destroy the lines of a bridge. After all, if Roebling's bridges could withstand all the vicissitudes of weather and river and traffic, then did he not think of everything and design against all onslaughts to which a suspension bridge could be subjected? Had he not obviated all failure modes? In fact, since his bridges and others like them had performed so well for so many years, were suspension bridges not *over*designed? Certainly in the twentieth century, when structural design principles were so much more sophisticated than they were in the nineteenth, great bridges did not need as much modern steel as their ancestors.

Thus suspension bridges in the first part of the twentieth century evolved into such sleek designs as the original George Washington Bridge (before its lower deck was added), the Bronx-Whitestone Bridge (before its stiffening trusses were added), and the Tacoma Narrows Bridge (before it collapsed). The aesthetic of suspension bridge design in the 1930s was toward longer spans with very shallow deck structures, and this led ultimately to an unanticipated, but historically not unprecedented, failure mode (Sibly and Walker, 1977 : 191-208).

Whereas the Brooklyn Bridge had a very deep deck to stiffen its roadway against the traffic and elaborate suspender and diagonal cables to stiffen it against the wind, the newer bridges had evolved into structures that had only vestiges of those characteristics. What Roebling had thought long and hard about to obviate failure, his successors forgot —or never even dreamed of. The massive weight of the eight lane George Washington Bridge made the deck so heavy that its inertia alone resisted the wind. The Bronx-Whitestone and its contemporaries, designed maybe only five or ten years later, were already beginning to show signs of excessive flexibility in the wind when they opened in the late 1930s.

The limit was reached when the Tacoma Narrows was completed, with a very narrow deck of only two lanes —because that was all the Puget Sound traffic required— and an extremely shallow deck supported on innovative solid girders. The bridge was certainly strong enough to support its own weight and the traffic upon it, but its designers did not think that its light structure might be twisted so vigorously in the wind. While the designers might have correctly anticipated and designed against all other possible ways in which their bridge might fail, the fact that they did not think of the *one critical* failure mode is all that matters now.

CONCLUSION

There is a tendency to look for models in past successes when faced with new design problems. What has worked in the past is believed to provide guidance for what will work in the future. This approach can be fine if all we want to do is make a near copy of something to function in a nearly identical context (and the nearer the safer). There is usually enough conservativism in the model and in our copy to allow for the imperfect analogy, but such wishful thinking obviously cannot be continued without peril. Furthermore, we seldom want to just copy, either because the situation or our creative nature does not allow it. But when we are faced with the design problem of doing something that goes beyond what has been done before, it is much better to look at past failures than at past successes. For it is only in the failures that we see clearly what it is that we are trying to avoid, and it is only by obviating failure that we can insure success.

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