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NOTES ON SAFETY QUALITY ASSURANCE AND PERFORMANCE

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EDITOR'S NOTE

Consideration of the environment and environmental systems has generally neglected the notion that we are fast approaching the time when not only will most of the threats to our environment be man-made, but the habitated environment itself will be largely man-made. From this perspective, concepts involving reliability, quality assurance, and human error, not in the vocabulary of environmentalists accustomed to dealing with natural systems will become increasingly important. The following commentary identifies some issues concerning human behavior and human error in the design of structures.

Forty years ago at the beginning of structural safety analyses in the United States, which was launched with Freudenthal's classic paper in 1947 [1], there was great reluctance to abandon the traditional concept of absolute safety. Gradually, however, probabilistic models have been accepted to describe loads and provide a basis for rational decision.

At the time of the 1972 Tall Buildings Conference [2], safety analysis was in an exceptionally fertile period. Two moment analysis had been devised and a way had been found to develop practical design codes. The 1972 papers on structural safety were exceptionally important from an intellectual point of view but were rather academic. Following the conference, a number of major studies were completed including the work of Galambos and Ravindra for LRFD in steel [3] and the work of Ellingwood, Galambos, Cornell, and MacGregor [4] supporting the new American National Standards Institute (ANSI) load factors.

Now, forty years down the road, structural reliability analysis is well established even though we have unsolved problems such as system reliablity and

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poorly solved problems such as seismic analysis. We have also new problems such as serviceability and the treatment of existing buildings but it seems clear that reliability analysis is set on a path of orderly evolution.

Given such a success story, it is unfortunate that we have to add a caveat. Although we have formulated a number of sophisticated models which can be turned over to designers or code groups for "rational decision," we have investigated only a small part of the problem.

We have formulated the random game against nature with physical variables but this is only a side-bet. The big game is the human game, where the variables are human nature and man-made organizations.

To understand the real game we must consider human behavior which we now know to be a primary variable in structural response. We must begin to make realistic assumptions about human beings who are not rational optimizers but rather survivors or "satisficers" looking for solutions that will do the job—trying to succeed, trying to survive.

One of the most interesting studies of human error was made by Melchers and Harrington in Australia when they sent out a very simple design survey to 325 licensed engineers. About one in ten replied [5].

The first question involved a single story rigid frame building (two columns; two rafters; fixed joints) with specified design codes, location, opening patterns, materials, and dimensions. Design moments at the nodes were requested.

A critical design case was the combination of dead + live + wind loads in the roof. Only nine responses seemed to conform to the code without gross errors. For these nine, the estimated design moment at the ridge had a coefficient of variation of 52 percent.

Another nine responses tried to comply with the codes but had gross errors, usually linked to internal pressures. If one combines the nine "correct" solutions with the nine "gross error" solutions, the design bending moment at the ridge varied from -107 to +70 with a coefficient of variation of 1,182 percent. The average was of the wrong sign. Only 10 percent bothered to use the 0.75 load reduction factor in the code for the load combination.

With results like these, we must ask—why do so many buildings stand up?

To realistically evaluate structural safety we must go beyond the statistics of human error and consider the entire design, construction, and utilization process. The scope of the problem can be illustrated through an example related to the Port Authority of New York and New Jersey which recently released a remarkably candid report on the Journal Square failure [6].

The failure involved the collapse of a suspended ceiling over a public thoroughfare after a number of years of service. The ceiling was supported by wire hangers with tabs in the slab. Upon investigation it was found that the drawings indicated a maximum hanger load of sixty pounds. No one seems to have designed the hanger locations and the ceiling contractor seems to have used a pattern for lightweight suspended ceilings. The ceiling was heavy plaster.

Over the years, some hangers broke and maintenance or service people tied them back up—sometimes two wires to a single tab under the slab. During a maintenance operation, part of the ceiling was observed to drop. Eventually, an engineering team took up the problem. The failure occurred during an inspection.

There is a simple naive explanation for this failure—the ceiling support was inadequate. A stronger support system should have been provided.

In reality there was a flow of failures:

1. an inappropriate suspension system was provided for a heavy plaster ceiling which would support maintenance crews;
2. responsibility for the design fell into the cracks between organizations;
3. maintenance people did not report important incidents;
4. the organizational response to a significant partial failure was confused; and
5. the engineering response did not recognize the seriousness and potential consequences of the failure.

Such a failure can be called a *system* failure. Consideration of such failures leads us to the broad question of Quality Assurance.

When we begin to consider the complete construction system, we introduce many new variables, e.g.,

- *People* – How are they motivated? What training should be provided?
- *Organization* – Who are the players? How do we partition responsibilities? How do we ensure communication?
- *Risk* – How should it be assigned?

We begin to question our classical concepts of blame. The common situation where, in the face of construction problems, all players assume defensive positions has been widely questioned by, for example, a committee of the Corps of Engineers. The concept of the "lowest bidder wins" can lead to appalling results.

When the concept of safety is broadened, many allies are found. Industrial psychologists in management circles, for example, can explain a great deal about motivation.

Not long ago, Charles Perrow, a sociologist at Yale University, published a fascinating book called "Normal Accidents" which arose out of his involvement with the investigation of nuclear accidents [7]. Perrow's thesis is that one must assume that "accidents will happen" and that certain systems are inherently prone to catastrophy. Error proneness is measured by two system properties. The first critical property concerns system interactions. Do elements interact in a simple linear (i.e., predictable) way or are there many complex interactions which are unplanned and not considered explicitly? In our vocabulary, are there many secondary effects?

Table 1. Quality Assurance in Construction:
A Preliminary Research Agenda

1. Project Formulation
   - the role of players
   - utilization plans
   - design criteria
   - communications
2. Quality Assurance in Design
   - trends in codes (LSD)
   - choice of systems/error proneness
   - policies re checking
   - policies re independent review
   - division of responsibilities
   - documentation
3. Quality Assurance in Construction
   - policies re material testing
   - inspection strategies
   - how to inspect/key elements
   - communications, feedback
4. Human Errors
   - concentration, haste effects
   - motivation, morale
   - incentives
   - auto-control, ethics
   - education
5. Miscellaneous
   - alternative organization
     - USA vs Europe
     - private vs government
     - military vs civil
   - case studies, forensic engineering
   - legal constraints

A second critical question concerns the coupling in a system. In tightly coupled systems, a change in one element directly affects another, e.g., the position of the steering wheel in a car and the direction of the front wheels. In a loosely coupled system, fuzzy relationships exist between responses.

According to Perrow, a system is error prone if it is tightly coupled and has many complex interactions. His analysis was prophetic with respect to chemical plants which he correctly diagnosed as highly prone to catastrophe before Bhopal.

His analysis also suggests why our structures generally succeed in spite of naive analysis and many errors. There is a very loose coupling between our design calculations and real building response. We have many complex effects which we do not consider but, in general, secondary effects such as the contribution of partitions to stiffness, work in our favor.

This is where the field of structural safety analysis seems to be headed at the moment. The questions asked are being broadened to include all the physical, organizational, legal, and practical considerations which affect the quality of a structure during its lifetime. As a preliminary agenda for related studies in the field of tall buildings, one possible list of areas for consideration is shown in Table 1.

An attempt to develop a useful approach to quality assurance in building design and construction will involve many new questions. At present, for example, the art of design checking is very poorly understood. The selective advantages and disadvantages of alternative project organizations have never been well established.

It is evident that the results of a broad approach to quality assurance can only lead to guidelines for action and perhaps a series of case studies which can be used for educational purposes. Such qualitative analysis is used routinely in medical, legal, and management education and should be an essential feature in engineering education as well.

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