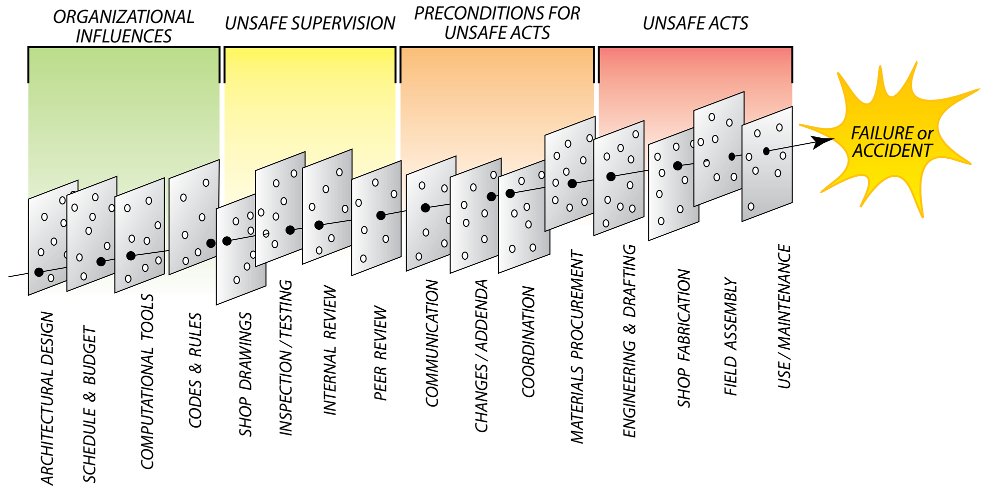
Human Error and Structural Engineering

By David P. Brosnan, P.E.

Structural engineers assume great responsibility for the safety of the public. As a profession, we owe society our best efforts to control errors that may occur in the course of our work. Our engineering education places its primary emphasis on the performance of materials under stress. In fact, some engineering and construction failures have happened because of the performance of people under stress.

We are not the first to recognize this. Over the last 50 years, the aviation industry has made great strides in understanding human behavior in a technically complex environment and has achieved marked improvements in public safety. It has been shown that relatively few aircraft accidents occur because of mechanical failures. Most happen because of flawed decision-making, bad communications, and poor teamwork or leadership. Similar findings have been determined for the accidents and mistakes made in hospitals and nuclear power plants. Structural engineering can also benefit from a human factors perspective.

For a long time, our profession has swung between two responses to structural failure. In engineering literature, we find sanctimonious attacks on the deficient professional practices of "bad" engineers. For public consumption, we use the writings of Professor Henry Petroski to explain the historic necessity of structural failure as a price of technological progress. These contradictory reactions have caused a widespread misunderstanding of the difference between ethics and error. The fact is that we all make mistakes; not all structural failures are moral failures. Engineering calculations represent only one part of the landscape of error. We should also be aware of the conditions that lead individuals and groups down the path of unintentional risk-taking, flawed thinking, and false priorities. Equally important are the rules that govern our technical decisions, the reference materials we use, our interface with computational tools, and the office and project environments in which we work.



Swiss Cheese Model for Error Propagation in Structural Engineering.

How Individuals Make Errors

Persons at all levels of authority and all ranges of experience are capable of flawed thinking and bad judgment. In aviation, great value has been placed on proper decision-making in high-pressure situations. Military aviation units conduct formal meetings of "human factors boards" as a regular part of their safety regimens. In civil aviation, prospective pilots are required to know the types of flawed thinking that lead to accidents. These are known as the five hazardous attitudes.

Most of the pilot error that is blamed for aircraft accidents involves risk-taking that stems from one or more of these attitudes, as opposed to a lack of knowledge or technical mistakes. Certainly we can recognize that such attitudes are not peculiar to aviation and have many parallels in structural engineering work.

In addition to the shortcomings of human personality and thought, we must add the limits of human perception and human performance. Human beings make errors in repetitive tasks at a far higher rate than machines or computers do. We get tired after long hours of work. We can be deceived. We can be distracted. We want to give our superiors good news. Ironically, while human error may be the most important cause of failure, human judgment may be our best safeguard against structural failures.

The Five Hazardous Attitudes

1) Anti-Authority	*The rules don't apply to me or to my special situation.*
2) Impulsiveness	*Hurry up! Let's get it over with!*
3) Macho	*Let me show you how the big boys work.*
4) Invulnerability	*Only bad, stupid, or unlucky people make errors.*
5) Resignation	*It doesn't matter what I do.*

How Groups of People Make Errors

It might seem that a larger number of people would be able to see through the mental fog that limits the judgment of an individual; more eyes will see more mistakes. But it does not necessarily hold true; while individuals can make small mistakes, groups can make whoppers. Some of history's worst blunders have been made by groups of highly intelligent, principled, and moral people who sincerely believed that they were doing the right things. The usual problem is not a lack of ethics, but a lack of perspective. Often groups are made up of individuals with very similar education, training, experience, and beliefs. Despite obvious personality and age differences, most people sitting together in the conference room of an engineering firm would be likely to agree with one another about technical issues. Such "groupthink" tends not to challenge, but to reinforce, its mistaken preconceptions.

The pioneering human factors author David Beaty wrote: "We are herd animals, and if we want to keep our position or status, we do what the herd wants." Indeed, groups can go to great lengths to avoid professional confrontations. As a result, individuals may acquiesce in decisions with which they disagree. Sometimes members of a group are intimidated by the leader. But sometimes groups embrace false priorities of office harmony and quick agreement over the real priorities that involve asking difficult questions and taking unpopular positions.

Table 1

Type of Error	Characteristics	Dangers
Bounded Rationality	Oversimplifies complex issues	Disregards information
Imperfect Rationality	Relies only on past experience	Does not apply basic principles
Reluctant Rationality	Jumps to conclusions	Fails to explore all possibilities

Errors Characteristic of Engineers

Studies of error across a number of engineering disciplines reveal that we have a troubling tendency, in the words of one researcher, to "solve the wrong problem." The same researchers also found that engineers sometimes try to fit old familiar solutions to new technical problems, often without reviewing the basic parameters. This becomes even more prevalent when the old solution is regarded to be successful. Another of our human failings is that we too quickly rule out alternative solutions to problems. Such traits are well known to those who study human error, but surprisingly, a government-funded researcher recently suggested that structural engineers should look at other projects' drawings as a way of checking their engineering computations.

Those studying engineering professionals and other technical staff have determined that some types of work yield more errors than others. The kinds of engineering problems that seem to bring forth technical mistakes and poor judgment fall into the following categories:

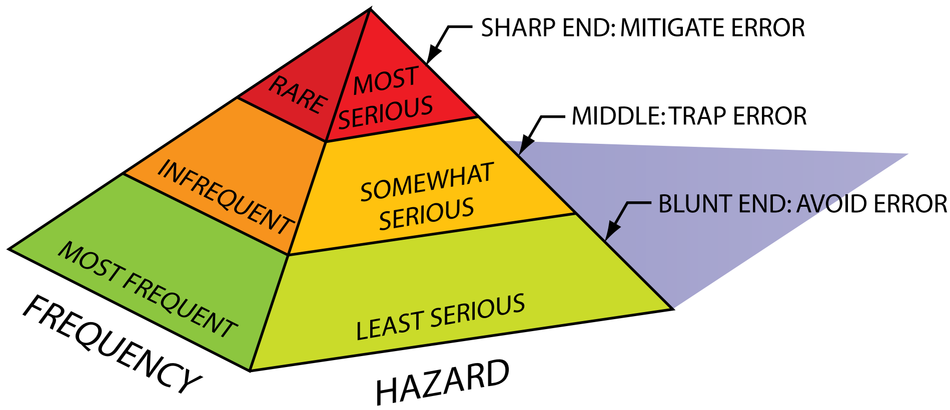
1) There are more than two or three different design variables.
2) Strong cues suggest the wrong solution.
3) A wrong solution has "successfully" been used before for a similar problem.
4) The choice of an appropriate solution requires a novel approach.

A more systematic approach to the kinds of engineering problem-solving errors that we make divides them into three categories (See *Table 1*).

Heretofore most examinations of engineering errors have occurred after a failure or discovery of defects. Between the design and construction phases of building projects, peer review is frequently conducted. It has become mandatory for major structures in some jurisdictions. However, the promoters of peer review usually fail to mention an important human factors consideration about this type of check. It is well known among publishing industry proofreaders and editors that one must make a choice when reading a document. If one scours a novel looking for misspellings and improper punctuation, one will have no clue about the plot. If one reads a book to follow the plot development and characters, one will miss the grammatical mistakes. What it means is that humans do not do well at multi-tasking. Structural engineering peer reviewers who pore over voluminous calculations can get lost in quantitative minutiae when they should be looking for qualitative errors (and vice versa.) "Proofreader's phenomenon" is a human characteristic against which engineers should be on guard when they undertake peer reviews. Qualitative and quantitative reviews are both essential, and require two separate passes through the construction documents.

How Errors Become Failures

It has long been recognized that absent a deliberate act, it usually takes a series of errors or omissions to generate an actual failure. We can explain the propagation of error using the "Swiss Cheese Model" developed by Professor James Reason. In the Swiss Cheese Model, each slice of cheese represents a step in a sequential process. The holes in the slices of cheese represent systemic flaws or individual shortcomings that offer opportunities for error. Most of the time, it is difficult to make a direct path through the holes in every slice



Pyramid Model for Distribution of Error.

of cheese. When the holes fall into alignment, the conditions for failure have been met.

Only a few steps of the building construction process can be attributed to a structural engineer. In an engineering office, the objective of error management should be to make the holes in those slices of cheese as small and as widely spaced as possible. Others in the construction process, from owners and architects to contractors and fabricators, also bear some responsibility for conditions that promote the propagation of error. Engineers may be aware of only those other steps immediately before and after our own work. Because we are in the middle, our ability to prevent the latent problems of others from propagating through our own slices gives us immense responsibility.

Models of Error Management

A proper regime of error management divides human error into three categories, illustrated by a pyramid. The most common errors should be the least serious and the most potentially dangerous errors should be the rarest. It's difficult to say whether error among structural engineers is really distributed this way. We know that about 78% of all construction failures have been traced to some form of human error. We also know that over 50% of all structural failures somehow involve water. When combined we find that at least one-third of all failures can probably be explained by errors of detailing rather than errors of computation. Thus an exclusively quantitative approach to engineering does not always produce satisfactory results, and must be tempered by qualitative considerations (See *Table 2*).

One of the most successful developments of the human factors approach to aviation safety has been the Aviation Safety Reporting System. This program permits anyone from ground crews and air traffic controllers to airline pilots and mechanics to report errors, weaknesses in the system, and concerns about procedures. The ASRS is designed to reward self-reporting of problems by prohibiting punishment or retaliation for unintentional errors that do not result in accidents or constitute violations of the law. Summaries are widely circulated. A measure of its success can be found in the 50,000 reports received each year. There is now a database of 500,000 publicly accessible reports. The construction industry could benefit greatly from a similar reporting system.

Table 2: Management of Error

Seriousness of Error	Frequency of Occurence	Management Goal	Management Meathod
Most serious	Rare	Mitigate	Configuration, Continuity, Ductility and Redundancy
Somewhat serious	Infrequent	Trap	Checking, Peer Review
Least serious	Common	Avoid	Education and Training

Conclusion: What Should Be Done to Minimize Engineering Error

The structural engineering profession should openly discuss the adoption of a more enlightened approach to the management of error. Punishment of those who make mistakes after the fact is neither a successful nor justifiable method of quality control in any technically complex endeavor. We should not attempt to judge someone's character on the basis of their performance at an engineering task. Quality control procedures for engineering work should recognize the kinds of faulty information, thinking, and workplace conditions that give rise to human error.

As consumers of technical information, engineers should demand higher standards of clarity and usability from publishers of building codes and other complex technical documents. Uniform heuristics for these publications should be considered. There is no reason that the expensive color printing processes used by technical organizations in their promotional magazines and mass mailings cannot be used also for the benefit of public safety. The clarity and usability of standards should not be subordinated to false priorities like advancing new design methodologies or units of measurement that engineers employ only infrequently.

Organizations that publish public safety regulations should avoid constant tinkering with technical standards, and strive to produce durable and trustworthy codes, written with the actual readership in mind. The experience of working engineers is one of public safety's most essential safeguards. Rules and regulations should not be changed so frequently and completely that years of experience suddenly become worthless.

No uniform standards exist for the computer/engineer interface. If surgeons and aviators have standard sets of instruments and controls, then structural engineers should have analysis and design software that provides complete and meaningful information in a concise and useful way. It is most essential that users, and not software vendors, define the minimum requirements. As all structural engineers know, there is wide variation in the manner of presenting results, and software companies notoriously accept no legal responsibility for the quality of their products.

Teamwork within the engineering office and with other design consultants should be emphasized over the desires of management to move personnel quickly from one project to another. Engineers and managers of engineering work should be aware of the five hazardous attitudes, and learn to recognize symptoms of flawed thinking and false priorities. Engineering managers should recognize the risky personalities and situations that can produce unsatisfactory results. In checking engineering work, it should be remembered that structural systems must satisfy basic engineering principles. Taking lessons from prior work is fine, but comparison to another structure cannot be the only measure of correctness.

This way of thinking about failure and error stands in contrast to the opinions of those expert witnesses and forensic engineers who toss around words like negligence, incompetence, ignorance, and greed. It is also very different from the many histories of structural disaster that emphasize the mechanics of collapse without close examination of the people involved in the design process. The study and management of human error does not seek to excuse bad results, but it does suggest a systematic way for continually acknowledging, adjusting, and improving human performance.

The management of human error in the field of structural engineering should be regarded as more than a way to ensure the sound performance of structural works and the safety of the public. Within our profession, it opens up an opportunity for frank discussion of important issues in a way that allows us to maintain both personal dignity and respect for our colleagues. Perhaps one day such a manner of thinking would allow us to agree with Oscar Wilde's observation that "whenever a man does a thoroughly stupid thing, it is always from the noblest of motives."▪

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