Managing Human Error in Structural Engineering

"Be not ashamed of mistakes and thus make them crimes" — Confucius's ancient maxim suggests that avoiding future error is the higher form of justice.

DAVID P. BROSNAN

In a growing number of industries, managers are recognizing that what goes wrong is often a broadly predictable product of organizational information and personal judgment. In particular, the aviation profession invests heavily in the study of human behavior in high-pressure, technically complex environments. The findings of its systematic collection and analysis of data have led to remarkable improvements in control systems, information quality, personnel management, and most of all, public safety. The revolutionary thinking and methods that have emerged from that work have been adopted by engineers who control nuclear power plants, the captains of oceangoing vessels, firefighters and doctors and nurses in hospital operating rooms.

Human error explains many events other than airplane crashes. The nuclear reactor accidents at both Three Mile Island and Chernobyl stemmed from flawed human interaction with machines and with other people. A major flood in downtown Chicago in 1992 that caused a billion dollars of property damage was attributed to piles driven mistakenly through a tunnel. The explosion of a pesticide plant in Bhopal, India, was blamed on operational errors of the staff. Studies of American health care estimate that as many as 98,000 persons die every year because of mistaken diagnoses, incorrect medication and other types of medical errors.

Structural engineering can benefit from the application of human factors principles so that error in engineering design and construction work can be anticipated and managed in the interest of public safety. Knowing that most aircraft accidents happen because of flawed decision making, bad communications and poor teamwork has brought about a deeper appreciation of the limits of human understanding and human performance. The human beings who design and build structures possess all of the same limitations and shortcomings of those who fly aircraft. Like aviators, structural engineers owe the public their best efforts to control errors in their work.

From a human factors point of view, many sectors of the structural engineering profession have embraced extreme and mistaken positions about the role of people in structural

TABLE 1.
The Sources of Structural Failure According to the Beliefs of an "Expert Witness"

Causes of Failure	Characteristics
Negligence	Improper analysis or design; standards disregarded
Incompetence	Misunderstood or misapplied engineering principles or characteristics of systems & materials
Ignorance, Oversight	Design documents & safe construction practices not followed
Greed	Short-cuts for profit; intentionally ignoring codes & safety
Disorganization	Unclear lines of authority & poorly defined roles & responsibilities of parties
Miscommunication	Fragmented or bypassed lines of communications among parties
Misuse, Abuse, Neglect	Improper occupancy or maintenance of facility

From Ref. 3

accidents and failures. In professional literature one finds a fair amount of moral posturing.[1] For wider audiences, writings (like those of Henry Petroski) explain accidents and structural failures as the price society sometimes has to pay for technological progress.[2] Efforts to intimidate practitioners into good behavior have obscured the difference between error and ethical impropriety. The frequency of finger-pointing litigation in the construction business, and the public indifference to some types of danger like highway accidents, do not help. Table 1 shows the opinion of a structural engineer who provides expert testimony in court cases about the sources of accidents and failures.[3] Sanctimony has even crept into the pronouncements of important institutions. The National Academy of Engineering (NAE), for example, lavishes praise on its "moral exemplars" who called attention to mistakes at the risk of their reputations. But the Great Man Theory implicit in those retrospectives offers little guidance to most engineering practitioners. One of the NAE's most celebrated case studies, the Citicorp Tower in New York, has in fact raised even larger questions about day-to-day decision making in structural engineering.[4] Everyone makes mistakes; absent a deliberate act, structural failures should not be classified as moral failures. All investigations of structural failures need not degenerate into a rogue's march in which the "guilty" are publicly stripped of their dignity. From a human factors perspective, the more important questions to ask are:

- Why did a qualified individual happen to make this mistake?
- How can it be avoided in the future?

The correctness of engineering calculations represents only one part of the large scope of potential human error in construction work. To effectively control error, engineers also need to recognize the conditions that lead individuals and groups to take unintentional risks, embrace false priorities and promote flawed thinking. But it does not end with the engineer or the engineering firm. The rules governing technical decisions, the project environments in which structural engineers work, the clarity and usability of their reference materials, and the interfaces between engineers and computational tools also promote engineering error in significant and serious ways.

Basic Concepts of Error Management

The goal of error management is to classify the different types of errors that occur, and to use appropriate techniques to reduce the occur-

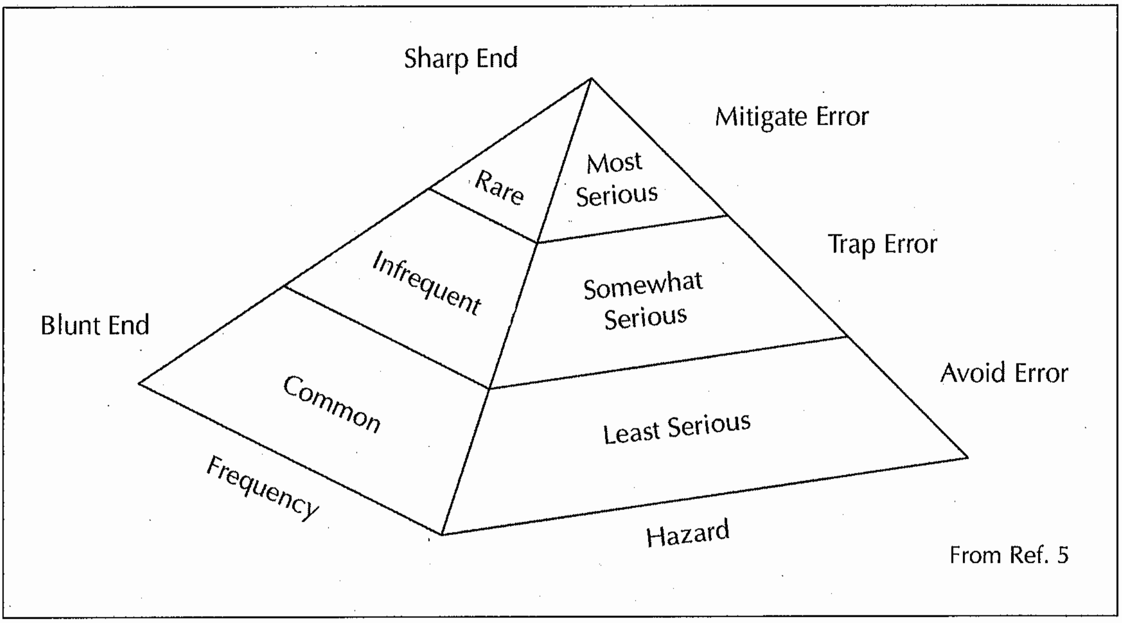

FIGURE 1. The pyramid model of error distribution.

rence and consequence of those errors. The pyramid model of error management, as illustrated in Figure 1, correlates the seriousness and the frequency of errors.[5] In this model, the most potentially dangerous errors are the least likely, and the most common errors are the least serious. In structural engineering, the most common errors should be addressed through education and training. More serious but less frequent errors would be caught with error trapping techniques such as peer review. The most dangerous errors — those that slip through the quality control procedures and appear at the sharp end of the pyramid — must be mitigated. Mitigation methods for structures generally require the establishment of four qualitative properties: proper configuration, continuity, ductility and redundancy. These properties, when present in a structure, assure that local failures do not progress into larger catastrophes.[6]

To make the pyramid model effective, reliable information about all sorts of engineering and construction errors must be available. At this time, sufficient data really do not exist to determine whether error among structural engineers is presently distributed according to the pyramid model. One study shows that 78 percent of structural failures have been traced to some form of human error.[7] (The rate of human error in the airline industry was almost identical before error management techniques were instituted.) Another study indicates that over 50 percent of structural failures involve some form of water.[8] Putting this limited information together, it appears that nearly four in ten structural failures can probably be attributed to errors of detailing rather than errors of computation. This interpretation tends to confirm the commonly held view of practitioners that an exclusively quantitative approach to engineering does not always suffice and must be informed by qualitative considerations. Still, the statistics presently at hand do imply that fruitful results can be achieved if error management is focused on the specific kinds of errors most responsible for failures.

The management methods of aviation offer some insight into what really may cause errors to occur. Investigators who study the errors made by military pilots have compiled a supervisory checklist of the factors believed to be related to them.[9] This checklist is set forth in Table 2. To a structural engineer, it will look manifestly different from the list of personal shortcomings suggested by the professional courtroom witness in Table 1. The work of

TABLE 2.
Human Factors Crucial to Accident Prevention Among Military Pilots

Causes of Accident	Characteristics
Sensory/Perceptual Factors	Degree of situational awareness
Medical/Physiological Factors	Health & fitness for the task
Knowledge/Skill Factors	Training & proficiency
Personality & Safety Attitude	Understanding & controlling risky behavior
Judgment-Risk Decision Factors	Knowing acceptable criteria for decision making
Communications/Coordination	Procedures, workload & information
Design/System Factors	Human-machine interaction
Supervisory Factors	Leadership & work environment

From Ref. 9

practicing engineers, by such reasoning, should be viewed as part of an interactive system, not as discrete choices between good and evil. The factors known to produce accidents further suggest that errors may be predictable when unfavorable circumstances compound one another. For example, a mildly ill engineer working on a tight deadline with ambiguous reference material would certainly be more likely to produce a mistake.

The thinking about safety prevalent in the aviation profession's training, literature and practice represents a very advanced and enlightened approach to error and its relationship to human factors. While some authors of engineering texts continue to cite Hammurabi's Code as an example of quality control procedures[10,11] and focus on a small number of large disasters, other industries and professional groups have learned from human factors principles to make significant improvements in every day practice. Engineering organizations such as the Institute of Electrical and Electronics Engineers, the Society of Automotive Engineers, the Society of Naval Architects and Marine Engineers and the Industrial Designers Society of America have all promoted the use of human factors techniques. Some business organizations have done likewise. One aircraft manufacturer states:

"Because technology continues to evolve faster than the ability to predict how humans will interact with it, the industry can no longer depend as much on experience and intuition to guide decisions related to human performance."[12]

Individual Error

An essential prerequisite for minimizing error is knowledge of human abilities, behavior and thinking in the work environment. Individuals produce three kinds of errors: knowledge-based error, skill-based error and judgment-based error. As individuals progress through different levels of skill, training and experience, they develop different attitudes toward their work and different beliefs about their own proficiency. Flawed thinking, poor skills and bad judgment are possible at all levels of education and responsibility. Table 3, based on military human factors guidelines for flight officers, shows the dangers inherent at each level of advancement.[13] The most skilled and most knowledgeable people are not always the safest.

Both military and civil aviation training have emphasized the need for sound decision making in high-pressure situations when the stakes are particularly high. In civil aviation, prospective pilots are required to know the types of flawed thinking that lead to accidents.

TABLE 3.
Risky Behavior in Military Pilots at Different Career Stages

Type of Individual	Problem	Traits	Danger
Rookie	Lack of self-confidence	Skills still developing Limited procedural knowledge Easily intimidated	Poor situational awareness Fails to speak up Does not know the rules
"Top Gun"	Overconfident	Works alone Thrives on challenges Pushes the envelope Finishes tasks "at any cost"	Poor perception of risk Poor teamwork False priorities Disregards the rules
Senior Staff	Puts judgement before procedure	"Been there, done that" Intimidates junior staff Overemphasizes experience Pulls rank	Rusty technical skills Fails to recognize own limits Bends the rules
Overstressed	Personal/family or financial issues	Distracted, depressed, hostile, or preoccupied Not focused on task	Poor situational awareness Violates the rules
Poor Performer	Poor basic skills	Never improves Easily overloaded	High rate of technical error Dependency on colleagues Misinterprets the rules

From Ref. 13

These are known as the Five Hazardous Attitudes, shown in Table 4.[14] When pilot error has been cited by investigating authorities as the cause of an aircraft accident, one or more of the hazardous attitudes is invariably blamed. Recognition of such attitudes is emphasized in pilot training because knowledge-based error and skill-based error do not produce as large an accident rate. Military aviation units convene "human factors boards" to examine pilot on-the-job performance and decision making. Engineers may conclude from their own experience that the Five Hazardous Attitudes are not confined to aviation.

But human personality and frame of mind are not the only individual characteristics that contribute to human error. Human beings have limits to their perception and performance. People make errors in repetitive tasks at a far higher rate than machines or computers do. Humans get tired and fatigued. They can be distracted and deceived. One airplane manufacturer's view of pilot error states that "errors typically occur when the crew does not perceive a problem." The manufacturer therefore promotes the use of "visual and tactile cues" in its aircraft instrument panels to "reinforce situational awareness."[12] Even as human error may be the most important cause of accident and failure, sound human judgment may be the best safeguard against it. One researcher's work shows that both medical doctors and airline pilots consistently overestimate the quality of their thinking and work when on duty for long periods of time.[5] The system of working young medical interns for long shifts has recently been attacked as a major source of error in hospitals.[15]

Human nature plays a bigger role in technical decision making than most engineers are

TABLE 4.
The Five Hazardous Attitudes of Civil Aviation

Hazardous Attitude	Mistaken Line of Thinking
Anti-Authority	The rules don't apply to me or to my special situation.
Impulsiveness	Hurry up! Get it over with! Do it now!
Invulnerability	Only incompetent, greedy or ignorant people make mistakes.
Macho	Let me show you the amazing things I can do.
Resignation	It doesn't matter what I do. I don't make a difference.

From Ref. 14

willing to admit. But it should come as no surprise to anyone that when presented with unusually difficult project parameters, most reasonable people will make simplifying assumptions that break them into manageable pieces. When handed a long list of things to do, they will use their judgment to prioritize it. When told to adopt unfamiliar techniques in their work, most will try to avoid them in favor of what they already know and trust. When given conflicting information, they will try to reconcile it. When put under time pressure, most people will try to meet the deadline. All of these common reactions to ordinary situations involve weighing alternatives, making judgments and taking small risks. The more difficulty, tedium, unfamiliarity, conflict and time pressure introduced to the engineer's assignment, the more error one should expect.

This more highly developed way of thinking about the role of individuals in failure and error differs from clinical accounts of structural failure that focus on the mechanics of collapse without closely considering the human influences on the entire process of design and construction. It also casts doubt on the views of expert witnesses and forensic engineers who appear to demonstrate an unjustified degree of certitude when they use words like ignorance, incompetence and greed. However, advanced thinking will not excuse bad results. Rather, the study and management of human error, unlike the belated declarations now prevalent in structural engineering, offer the engineering firm reasonable tools with which to better understand and improve human performance.

Collective Error

Organizations, teams and less formally constituted groups of co-workers contribute to error in different ways than individuals. Organizations provide their members with essential information that may be incorrect, incomplete or out of date. They establish rules and policies that may be confusing or difficult to apply to real situations. Organizations are often responsible for their members' training and are usually responsible for their supervision. They set budgets, schedules and organizational priorities — all of which may limit choices and affect judgment. They purchase tools and equipment that may be awkward or unreliable. They provide a work environment that may be uncomfortable or distracting. Most important, organizations choose the leaders who, good or bad, set a visible example for their subordinates.

One might think that a group of similarly qualified people could put more eyeballs on a technical problem and therefore find more mistakes than an individual. The Wikipedia online information resource, for example, is based on this very idea.[16] But groups can take on their own odd character and frequently become less than the sum of their parts. Groups make mistakes of a much greater magnitude than individuals do. One of the ironies of history is that the worst blunders seem to

TABLE 5.
Evidence of Flawed Organizational Decision Making & Culture

Trait	Characteristics
Illusion of invulnerability	Overly optimistic; encourages risk taking
Collective rationalization	Dismisses practical objections
Unquestioned morality	Dismisses ethical objections
Stereotyped views	Equates disagreement with ignorance
Direct pressure	Challenges dissenters as disloyal
Self-censorship	Participants suppress their own objections
Illusion of unanimity	Equates silence with agreement
Self-appointed thought police	Squelches discussion of unpleasant realities

From Ref. 18

come from groups of intelligent, principled and tough-minded people who honestly believed they were doing the right things for the right reasons.[17] The typical problem is not unethical behavior among the members, but insularity. Groups frequently consist of people having knowledge, skills, experience and beliefs that are very much alike. Such a condition could easily exist in an engineering firm, where all present might be likely to agree with one another about technical issues, if not about politics or music. "Groupthink" insists on its mistaken preconceptions and offers doctrinaire answers to difficult questions, often at the expense of balanced judgment. Table 5 outlines the fallacies and pressures that constitute groupthink.[18]

David Beaty, a British aviator who was one of the first to recognize the role of human factors in accidents, wrote of group dynamics: "We are herd animals, and if we want to keep our position or status, we do what the herd wants."[19] Groups can go to extraordinary lengths to avoid confrontations among their members. The avoidance of confrontation sometimes becomes the all-important, if unspoken, goal of a meeting, leading individuals to acquiesce in decisions with which they would otherwise disagree. A strange phenomenon, known among psychologists as the Abilene Paradox, occurs when the outcome of a group decision is the single course of action which every person in the group privately opposes. In some cases, the members of a group are intimidated by a leader with a very strong personality. But sometimes, also, groups simply adhere to false priorities like "quick meetings" and "no arguments" that improperly override real priorities requiring difficult questions and unpopular positions.[20]

In this light, one might consider differently the efforts of some professional organizations to more fully standardize structural engineering education. Proposed minium professional degree requirements stipulate plenty of classroom instruction but only minimal independent scholarship and research.[21] If everyone has exactly the same educational background, engineers might well come up with identical numerical results but also be too willing to agree with their colleagues, particularly if employers reward them for conformity of thought.

The culture of an organization and the quality of project leadership also can introduce major blind spots and even arrogance with respect to safety and error. Some managers find internal discussion and disagreement about technical issues to be a good thing that stimulates thinking; others consider it a sign of insubordination and disrespect. One can find engineers from all over the world in

TABLE 6.
Classification of Problem-Solving Errors in Technical Work

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

From Ref. 25

professional offices. Their different ethnic origins, religions, traditions and educational systems can sometimes bump into one another. For example, American males are considered most likely among national groups to openly question instructions or assignments.[22] Members of other national groups may be inclined to show (or expect) more deference. Neither situation should be viewed as entirely good or bad. Feedback and obedience are not engineering methods, but the interactions between people can have a real effect on an engineering product. The aviation profession, after studying accidents attributed to poor relations between pilots, now encourages the captains of airliners to take heed of their junior colleagues when they dispute information or directions.

Engineering Error

Engineering errors are often found not in the mathematics, but in the judgments that make the work unrepresentative of the actual system under analysis. Researchers studying error in engineering work discovered that technical proficiency quickly becomes irrelevant when the engineer does not properly choose or model the correct problem to solve. They also found that engineers improperly try to fit old familiar solutions to new and different technical problems; some even fail to consider the basic boundary conditions.[23] Such short cuts become even more dangerous when the old solutions are mistakenly thought to be successful. Some engineers rule out alternative solutions to problems far too quickly and arbitrarily. Such traits are well known to those who study human error, but recently a government-funded researcher suggested that structural engineers could check their engineering work by looking at the drawings of other projects.[24] Many engineers may recall being counseled by their superiors to make their work consistent with previous designs issued to the same client.

Further observations of engineering and technical employees have helped to classify the kinds of engineering work that generate more errors than others. The technical problems that seem to bring forth mistakes and poor judgment have one or more of the following characteristics:[25]

- Problems involving more than two or three different design variables.
- Problems with strong cues that suggest the wrong solution.
- A wrong solution has "successfully" been used before for a similar problem.
- The choice of an appropriate solution requires a novel approach.

The reactions of engineers to these various types of problem-solving difficulties have been divided into three categories, as shown in Table 6, which describes technical errors in comparison to an ideal of "rational" thinking and action.

Engineers often juggle several projects at a time, and sometimes they pressure themselves into performing several tasks at the same time. Multi-tasking is a known cause of error that reduces situational awareness in all tasks being done simultaneously. The pitfalls of multi-tasking first became known in the publishing industry among proofreaders.[19] Publishers have long understood that proofreaders must make a choice when reading a document. If they look at the text closely for errors of punctuation and grammar, they will have no clue about the plot. If they read to follow the characters and story, then they will miss the mistakes in the text. These findings have implications for the structural engineering peer reviewers who "proofread" construction documents. Quantitative and qualitative checks must be run separately. Those who pore over voluminous calculations looking for quantitative errors will inevitably miss the qualitative mistakes, and vice versa.

Error Propagation

Today, most examinations of engineering error happen after a structural failure or other unsettling discovery. Even peer reviews ordinarily occur after the construction documents are essentially complete. While such reviews can be useful in isolating the errors, they do little to explain why the errors happen, the contributing causes or how they can be prevented. This lack of context has been a difficult problem even in aviation, where pilots or mechanics are often the last people in a long chain of decision making over which they have minimal control. One aircraft manufacturer has lamented that "the only data guaranteed to be collected is [sic] that related to accidents and major incidents... it is difficult to obtain insightful data in an aviation system that focuses on accountability.... We must overcome this 'blame' culture and encourage all members of our operations to be forthcoming."[26]

Without an intentionally malevolent actor, it usually takes a series of errors or omissions to generate an actual failure. The passage of an undetected error through many layers of authority and safeguards is described using the "Swiss Cheese Model" developed by Professor James Reason. In the Swiss cheese model, each slice of cheese represents either a step in a sequential process, or a layer of responsibility. The holes in the slices of cheese represent systemic flaws, individual shortcomings or "blind spots" that offer opportunities for error. In order to achieve the conditions in which failures occur, a direct path must be made through all the slices of cheese between the flaw and the failure.[27]

In building construction, relatively few steps of the process fall under the direct control of a structural engineer. The objective of error management in engineering offices should be to avoid both large holes and clusters of small holes. This rationale accepts the possibility that the structural engineer's slices of cheese will always have some holes (or in other words, that errors will inevitably occur). The Swiss cheese model addresses the ability of errors to continue moving through a system.[28] Figure 2 illustrates the Swiss cheese model for the process of designing and building a structure. Because structural engineers' authority is staggered among various stages of the process, they have the uncommon ability to prevent the mistakes and oversights of others from passing through their own slices of cheese.

Both individual and organizational mistakes contribute to the propagation of error through a multi-layered or sequential process. Most mistakes initiated by individuals are categorized as "active" errors. Active errors occur in decision making, computation and drafting of documents, choices between alternatives, detailing of connections, in-shop fabrication and in-field assembly of structures. Examples of active errors include an incorrectly sized or labeled structural element, an improper application of building code provisions, an improperly welded connection or a form-release agent sprayed on steel reinforcing bars in a concrete wall.

Errors occurring as a result of organizational shortcomings are known as "latent" errors. Latent errors do not require the active participation of an individual. They exist because of poor management, unclear technical standards, conflicting or rapidly changing project criteria, bad human-machine interaction and poor teamwork. Examples of latent errors are an unrealistic deadline for completion of construction documents, flaws in engineering software or an overly optimistic budget for construction work. Latent errors frequently occur early in the sequence of events and,

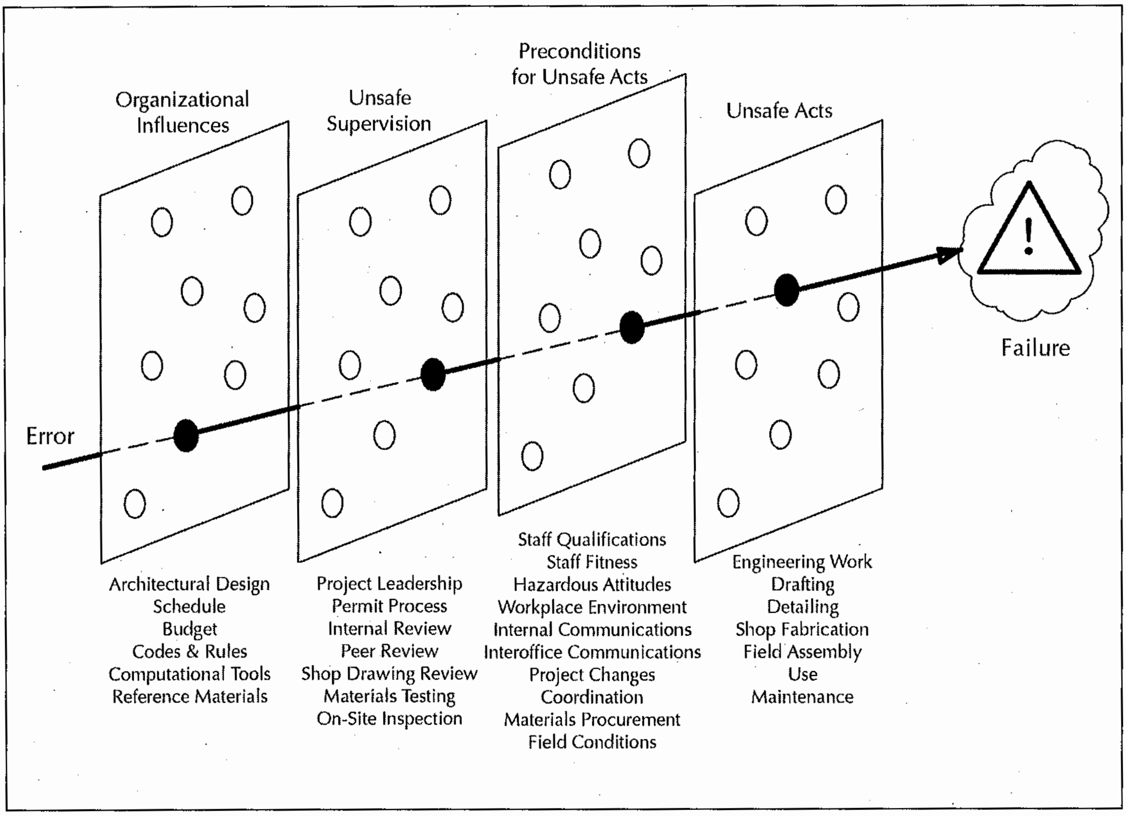

FIGURE 2. The Swiss cheese model of error propagation as applied to structural engineering.

therefore, can exclude the possibility of correction by those most affected, leaving them nothing but bad choices at the end of the sequence. Experience teaches that those who help bring about latent errors usually enjoy immunity from punishment, while those who make active errors more typically pay the price.

In order to recognize and act on both the errors and the propagation of errors through the Swiss cheese model, the Human Factors Analysis and Classification System (HFACS) has been developed by the U.S. Navy.[29] The HFACS considers four categories of performance, as shown in Table 7. Unsafe acts are the most active types of errors, while organizational influences are considered the most latent. HFACS is a tool that helps systematically analyze information about safety problems and generate recommendations. But such a tool requires a body of data. The aviation industry, followed by others, has encouraged its employees to report even minor incidents and "no harm/no foul" mistakes in order to gather such data for analysis.

Recommended Improvements for Successful Error Management

The structural engineering profession should consider the adoption of a more modern and enlightened approach to the management of error. Arbitrary after-the-fact punishment for mistakes cannot be the sole means of regulating human behavior. Evidence from other professions and industries shows that it is neither effective nor justifiable in work that involves uncertainty or complexity. Opinions of an engineer's personal character or ethical grounding should not be tied to one's performance at an engineering task. Quality control procedures for engineering work should address the kinds of faulty information, thinking and workplace conditions that engender human error. The valuable work done for

TABLE 7.
Human Factors Analysis & Classification System Used in Aviation, Medicine & Fire Fighting

Error Classification	Error Type	Examples
Unsafe Acts	Active	Bad execution of skill-based tasks Correct execution of wrong procedure
Preconditions for Unsafe Acts	Active or Latent	Poor situational awareness, illness, fatigue, fixation Poor communication with other team members
Unsafe Supervision	Latent	Inadequate training Inadequate oversight, guidance, pace-setting Failure to measure & track performance
Organizational Influences	Latent	Ambiguous direction or documentation Failure to provide safe methods & procedures Lack of appropriate tools

From Ref. 29

other industries should no longer be ignored in favor of intuitive management techniques, hero worship and primitive reactions to avoidable events. Improvements are clearly needed in four key areas:

- technical documents;
- the engineer-computer interface;
- engineering management; and,
- the collection of data about engineering and construction error.

Structural engineers can accurately think of themselves as consumers of technical information. They have every right to expect high standards of clarity and usability from publishers of building codes and other complex technical manuals and documents. Technical information sources should consider a system of uniform heuristics for their publications, understanding that those products are reference materials and their users hardly ever read them in full. Nothing prevents the color printing processes used in engineering magazines and mass mailings from being used also for the benefit of public safety by giving proper emphasis to important provisions and making information easier to find. Fundamental clarity and usability of engineering standards are not optional. They should not be subordinated to institutional false priorities like the advancement of new design methodologies or units of measurement used infrequently at best.[30]

Organizations that publish public safety regulations should avoid frequent and repeated revisions to technical standards, their methodology, their nomenclature or their governing philosophy. One can make a valid argument that the confusion caused by those changes may represent as great a danger to the public as the original unchanged code provisions. Governing bodies should seek instead to produce regulations that are written for the needs of the actual readership. When major changes are believed to be warranted, technical journals and publications should be used to inform practitioners and invite profession-wide discussion before deciding on their adoption. The experience of working engineers remains one the most essential safeguards for the safety of the public. The technical rules of engineering practice need not be altered so often and so completely that hard-won years of experience can be made worthless.

The profession likewise lacks uniform standards for the engineer/computer interface. This deficiency is becoming a larger problem as software companies now can alter their source code virtually at will over the Internet. In some self-updating software arrangements, actual results obtained from the same user inputs can vary from one month to the next. In other lines of work, such variations are not tolerated. Surgeons have a standard set of instruments with which to operate, and aviators have standardized control panels. Structural engineers should have analysis and design software that provides full and meaningful information in a concise and useful way. Users, and not software vendors, should define the minimum requirements of usability, output format and error avoidance. Wide variations exist among products in the presentation and format of results, and engineering software companies accept no legal responsibility for the quality of their products.[30]

Engineers in management should not confuse an entrepreneurial impulse to take bold risks and make quick decisions with sound engineering practice. Academic course work in engineering management should emphasize the importance of management decisions in preventing accidents. Engineers and their superiors should be aware of the five hazardous attitudes and learn to recognize symptoms of flawed thinking and false priorities. Engineering managers should also learn to control the risky personalities and situations that can produce unsatisfactory results. Teamwork within the engineering office and reasonable workloads on the staff should be emphasized over the desires of management to redeploy personnel among projects. Those who check engineering work must remember that structural systems must always satisfy fundamental principles of engineering. While prior work can be instructive, the only measure of acceptability should not be a comparison to previous designs.

An important success of the human factors approach to commercial aviation safety has been the emergence of the Aviation Safety Reporting System (ASRS). This confidential, voluntary and non-punitive program permits any person at any level of responsibility in the industry to report errors, weaknesses and problems. The ASRS encourages self-reporting of incidents that do not result in accidents or constitute violations of the law. Aviation industry workers have such confidence in the system that they make 50,000 reports, often about themselves, each year. Regularly published summaries are made available to the aviation community. There is presently a database of over 500,000 publicly accessible reports compiled since 1976.[31] In 2005, the International Association of Fire Chiefs instituted the National Fire Fighter Near-Miss Reporting System, modeled on the ASRS and employing principles of HFACS. This system has already generated recommendations for reducing fire fighter fatalities.[32] Given the importance of constructed facilities and the high rate of injury in construction work, the design and construction industry could benefit enormously from a similar non-punitive reporting system.

Conclusion

The human error that brings about most structural failures is far less sinister and far more pervasive than most engineers believe. Engineering firms need more than after-the-fact assignments of blame to human shortcomings; they also need the tools with which to recognize and confront the mistakes that people really make. Improved management of human error in structural engineering should be regarded as a necessary way to assure the sound performance of structural works and the safety of the public. Among practitioners, consideration and implementation of human factors methods also offer the opportunity for discussion of profoundly important issues. Such a profession-wide debate should examine the quality of technical information now in circulation, the effectiveness of organizational management, the interactions between engineers and computers, and the need to collect useful data about error and accidents from a broader spectrum of design and construction sources. Other industries have demonstrated that real progress in reducing error comes from a solid understanding of human limitations, not from attorneys or insurance companies. They have shown that the path to safer engineering practice is wide enough for both technical rigor and professional dignity.

NOTE — *The ideas and concepts of this article were first set forth in abbreviated form in "Human Error and Structural Engineering: A Brief Discussion" in the September 2008 issue of* Structure *magazine. The author gratefully acknowledges the cooperation of* Structure's *editors and publisher in making this longer form article possible.*

DAVID P. BROSNAN *is president of Structural Integrity Engineering Group, Inc., in Medford, Massachusetts. He earned a B.S.C.E. from Tufts University in 1984 and an M.S.C.E. from Northeastern University in 1992. He has practiced structural engineering for 24 years and is a registered professional engineer in Massachusetts. He also serves as an instructor at the Boston Architectural College.*

REFERENCES

1. Hart, G.C., "Licensed Not to Kill: Evaluating Your Moral Obligation," *Structural Engineer,* Vol. 6, No. 8, September 2006.

2. Petroski, H., *To Engineer Is Human: The Role of Failure in Successful Design,* New York: Vintage Books, 1992.

3. Ratay, R.T., "Professional Practice of Forensic Structural Engineering," *Structure,* Vol. 14, No. 7, July 2007.

4. Kremer, E., "(Re)Examining the Citicorp Case: Ethical Paragon or Chimera," *Cross Currents,* Vol. 52, No. 3, Fall 2002.

5. Helmreich, R.L., & Shaefer, H.G., "Turning Silk Purses into Sows' Ears: Human Factors in Medicine," address to the Second Rochester Conference on Simulators in Anesthesiology Education, 1996.

6. Structural Engineering Institute, *Minimum Design Loads for Buildings and Other Structures,* ASCE-7-02, Reston, Virginia: American Society of Civil Engineers, 2002.

7. Eldukair, Z.A., & Ayyub, B.M., "Analysis of Recent U.S. Structural and Construction Failures," *Journal of Performance of Constructed Facilities (ASCE),* Vol. 5, No. 1, February 1991.

8. Ransom, W.H., *Building Failures: Diagnosis and Avoidance,* London, E&FN Spon, 1981.

9. Ciavarelli, A., & Sather, T.E., *Human Factors Checklist: An Aircraft Accident Investigation Tool,* Monterey, California: Naval Postgraduate School, 2002.

10. Feld, J., & Carper, K.L., *Construction Failure, 2nd ed.,* New York: John Wiley & Sons, Inc., 1997.

11. Levy, M., & Salvadori, M., *Why Buildings Fall Down,* New York: W.W. Norton & Company, 1992.

12. Graeber, C., "The Role of Human Factors in Improving Aviation Safety," *Boeing Aero Magazine,* No. 8, 1999.

13. Department of the Navy, "Human Factors Review and Interventions" *COMNAVAIRPAC Instruction 5420.2B, Enclosure 5,* [undated].

14. Federal Aviation Administration, *Pilot's Handbook of Aeronautical Knowledge,* FAA-H-8083-25, Washington,D.C., U.S. Dept. of Transportation, 2003.

15. Kohn, L.T., Corrigan, J.M., & Donaldson, M.S., Editors, Institute of Medicine, *To Err Is Human: Building a Safer Health System,* Washington: National Academies Press, 2000.

16. Poe, M., "The Hive" *The Atlantic Monthly,* Vol. 298, No. 2, September 2006.

17. Halberstam, D., *The Best and the Brightest,* New York: Random House, 1972.

18. Janus, I., *Victims of Groupthink,* Boston: Houghton Mifflin, 1972.

19. Beaty, D., *The Human Factor in Aircraft Accidents* New York: Stein and Day, 1969.

20. Harvey, J.B., *The Abilene Paradox and Other Meditations on Management,* Lexington, Mass.: D.C. Heath and Co., 1988.

21. Anonymous, "Basic Education for a Structural Engineer," *Structure,* Vol. 14, No. 4, April 2007.

22. Helmreich, R.L., "The Downside of Having a Brain: Reflections on Human Error and CRM," *Proceedings of the 10th International Symposium on Aviation Psychology, Columbus Ohio, May 3-6, 1999,* Columbus, Ohio: The Ohio State University, 1999.

23. Carroll, J.S., "The Organizational Context for Decision Making in High-Hazard Industries," *Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting,* Santa Monica, Calif.: The Human Factors and Ergonomics Society, 1994.

24. Hanson, J., "Quick Methods: Finding Errors in Structural Analysis and Design Results," *Structure,* Vol. 13, No. 6, June 2006.

25. Morris, N., & Rouse, W., "An Experimental Approach to Validating a Theory of Human Error in Complex Systems," *Proceedings of the Human Factors Society 29th Annual Meeting*, Santa Monica, Calif.: The Human Factors Society, 1985.

26. Higgins, C.R., & Higgins, J.K., "Boeing Position on Nonpunitive Reporting," *Boeing Aero Magazine,* No. 8, 1999.

27. Reason, J., *Human Error,* Cambridge, England: Cambridge University Press, 1990.

28. Fitzpatrick, J., "CRM-The Cathay Way," *Airways,* Vol. 9, No. 8, October 2002.

29. Mussulman, L., & White, D., "The Human Factors Analysis and Classification System (HFACS)," *Approach,* Vol. 49, No. 4, July-August 2004.

30. Brosnan, D.P., "Human Error and Structural Engineering: A Brief Discussion," *Structure*, Vol. 15, No. 9, September 2008.

31. Phimister, J.R., Bier, V.M., & Kunreuther, H.C., "Flirting with Disaster," *Issues in Science and Technology,* Fall 2005.

32. *National Firefighter Near-Miss Reporting System, Lessons Learned, Lessons Shared: Near-Miss Reporting One Year Later,* San Diego: Elsevier Public Safety, 2007.