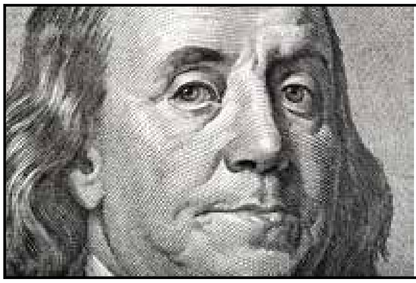
structural
FAILURES



An investment in knowledge pays the best interest.
– Benjamin Franklin

Unrecognized Knowledge

Recurring Structural Failures

By Julie Mark Cohen, Ph.D., P.E., SECB

Julie Mark Cohen is a Consulting Structural and Forensic Engineer and Independent Science and Technology Studies Scholar. Part of her research is sponsored (4/1/2017 to 3/31/2019) by a grant entitled "A Study of Knowledge Flow and Recurring, Costly Infrastructure Failures" by NSF's Science, Technology, and Society program. Using her research results, she will be writing a book entitled Unintentional Structural Failures by Design. (*jmcohen@jmcohenpe.com*)

Forensic practice in structural engineering typically entails seeking technical causes of failures. Occasionally, discussions of technical causes are disseminated through publications or conference presentations. However, the underlying or root causes of failures are seldom disseminated, because they are rarely sought. Seeking root causes are frequently not the objective in litigation. Root causes are found in the "discipline of design" (Roe et al., 1967), specifically in design decision-making, which relies on technical knowledge and judgment between value and utility. Structural engineering design decisions follow from civil (structural) engineering university education, tradition and culture in practice, licensure, peer review, and continuing education.

One example of unrecognized knowledge and a subsequent failure occurred in the early 2000s with high-strength, hard steel threaded rods of ASTM A722 Gr 150 material that were galvanized for use as waler bolts in a marine environment. The rods fractured soon after installation. The author presented highlights from a sealed legal matter (with fictionalized participants and location) in STRUCTURE, February 2015. The technical cause for the failure was hydrogen embrittlement and stress corrosion caused by the galvanizing. The root cause was the lack of recognition of available, pertinent knowledge. In 1974, ASTM A143, the Standard Practice for Safeguarding Against Embrittlement of Hot-Dip Galvanized Structural Steel Products and Procedure for Detecting Embrittlement, was revised to include: "In practice hydrogen embrittlement of galvanized steel is usually of concern only if the steel exceeds approximately 150 ksi (1100 MPa) in ultimate tensile strength, or if it has been severely cold worked prior to pickling." In 1975, ASTM A722, the Standard Specification for High-Strength Steel Bars for Prestressed Concrete, was adopted. This is an example of available and pertinent knowledge unrecognized by structural engineers making design decisions.

A second example pertains to the minimization of locations of seismic-resistant steel framing. This can result in disproportionately large framing members that possess "size effects" within welded beam-column connections, thus leading to a technical cause of fracture. The root cause is that "lumping" of resistance does not follow systems theory regarding an optimal distribution of resistance which should be uniform throughout the system. The majority of fractured welds that occurred before and during the 1994 Northridge earthquake, and were discovered after the earthquake (FEMA, 2000), possessed size effects. These connections resulted from a judgment that value (most probably labor cost savings) took precedence over utility. Structural steel "design" textbooks, from the 1970s and later, supported this judgment because they showed structural plans with minimal locations of lateral load-resistance. However, they failed to inform readers that connections with larger shapes had not been fabricated and tested in laboratories.

From over thirty years of research, the author has identified and substantiated eight categories in which relevant, pertinent knowledge from related engineering fields has not been used and failures have ensued, either shortly after structures were placed in service or after several years in service. These areas include:

1) Striving through design decisions for structural performance objectives by minimizing, not optimizing;
2) Not using systems design characteristics, such as stability, symmetry, redundancy, load path, continuity, coupling (soil-foundation-structure interaction);
3) Not heeding warnings and recommendations in ASTM standards and steel industry documents against galvanizing high-strength, hard steel with Fu ≥ 150 ksi.
4) Not accommodating deformation incompatibilities resulting from thermal and non-thermal effects;
5) Assuming that concrete is impermeable;
6) Not acknowledging behaviors (stress risers) that follow from size effects, boundary conditions, etc.;
7) Not designing structures in moist environments to adequately shed water; and,
8) Not designing structures to be inspected, maintained, repaired, and replaced.

This article introduces the first two of the eight areas, *design* and *systems thinking*.

Structural Forensic Investigations

In their investigations, forensic structural engineers often perform independent calculations for which they rely on the same consensus documents (i.e., codes, standards, and specifications) that were used to design the failed structures. These documents contribute to the knowledge bases for technical opinions presented to attorneys and help an expert working for an attorney to assess an engineer's performance relative to the "standard of care." That is, the knowledge with which the forensic engineers are familiar forms the knowledge basis for a trier of fact (i.e., judge or jury) to determine whether a practitioner met the standard of care. Is this good enough for the future of the structural engineering profession and society?

> "Structural engineering is too important to society for the profession not to strive to eliminate recurring, costly structural failures whose root causes are in unrecognized, pertinent knowledge."

Unintentionally overlooking available and pertinent knowledge may be intellectual blindness, but it is not necessarily negligence. However, negligence may be found in the lack of recognition of one's ignorance and not seeking advice on how to ameliorate the situation. What do structural engineers not know, why do they not know it, and how can they learn it?

Understanding of Design

Design, *3-D design*, and *design decision-making* are terms that mean different things to architects and structural engineers. Also, *systems design* and *systems design thinking* are another set of terms that mean different things to electric power systems engineers, nuclear power engineers, and mechanical engineers as compared to structural engineers. These differences would not necessarily be a problem, except that the author has found a direct correlation between structural failures and relevant wisdom of those outside structural engineering that has repeatedly gone unrecognized by structural engineers.

In the mid-1800s, as buildings increased in complexity, architects relinquished their responsibilities for structural framing, passing them to civil engineers who specialized in structural engineering. Peters (1991) noted both architects and structural engineers engage in what he called "technological thought, which incorporates two diametrically opposed views of the world." Architects primarily use associative thinking in contrast to structural engineers who use hierarchically ordered, vertically logical thinking. "Design, which is the activity pursued through technological thought, utilizes lateral (associative) thinking, which is almost exclusively synthetical to purpose rather than analytical. It synthesizes or creates as a primary activity rather than dissects," stated Peters.

Regarding engineering practice and education, Holgate (1983) stated, "…engineering is nothing more than the achievement of clearly specified technological objectives for the lowest possible cost in cash. This view has been reinforced for engineering students by the fact that, with a few notable exceptions, textbooks entitled 'Design of Structures' are predominantly concerned with the techniques of conceptual analysis. This contrasts strongly with the attention to mechanical engineering, where much thought has been given to the mental processes involved in design and to the development of the activity."

On design philosophy, Holgate stated, in the architectural field, "many books are available, written by architects *for* architects, on the selection of structural form and the understanding of structural behavior, two fields which have traditionally received little attention in engineering texts." He continued, "Discussion of the merits and demerits of particular designs, which is quite common in the architectural world, is definitely discouraged…"

Reinforcement of Holgate's comments is seen in the 1951 *New York State Construction Code* in the enabling act (Szendy, 1951). Two of the five "objectives of and specific standards" are relevant: (1) "To formulate such standards and requirements, so far as may be practicable, in terms of performance objectives, so as to make adequate performance for the use intended the test of acceptability," and (2) "To permit to the fullest extent feasible, use of modern technical methods, devices and improvements which tend to reduce the cost of construction without substantially affecting reasonable requirements for the health, safety and security of the occupants or users of buildings."

Understanding of Systems

Looking back to the Cold War after WWII, it might be thought that, given the increase in funded engineering research, research documents about materials and systems would have been readily available and disseminated to structural engineers. Several documents useful to structural engineering practice were developed by federal agencies, such as early 1960s research by the U.S. Army on the galvanizing of maraging steels. Most of these documents were marked "unclassified," but just sat on bookshelves. Regarding the lack of dissemination of federally-sponsored research, Alic (2008) stated, "The post-[WWII] shift in U.S. technology and science policies has been somewhat misunderstood. It was not only a shift *toward* support for research but a shift *away* from support for [knowledge] diffusion." He presented an agriculture- and military-focused discussion, but his points apply equally to subject matter of relevance to structural engineers.

Systems design can be understood by considering Systems Thinking (undated), which includes this definition: "a holistic approach to analysis that focuses on the way that a system's constituent parts interrelate and how systems work over time and within the context of larger systems. The systems thinking approach contrasts with traditional analysis, which studies systems by breaking them down into their separate elements…"

Smith (1969), a professor of electrical engineering, defined a 1960s system as "a combination of diverse but interacting elements integrated to achieve an overall objective. The elements may be human beings, devices, plants, organizations, or means for processing information, energy, and objects." He continued, "The increasing complexity of man-made systems and the increasing availability of principles and technique for predicting system behavior have resulted in a new activity called 'systems engineering.' Systems engineering is not *a branch* of engineering; systems problems occur in every branch of engineering, and a given system may involve elements from many different branches. It is *not a principal function* of engineering; some engineers develop systems, others design or operate them. However, the systems engineer performs a unique function in a complex engineering project and success in performing this function requires a special type of training and a special set of characteristics." [Smith seemed to have been unaware of the Systems Design Engineering program at the University of Waterloo that was started in 1964.]

In the late 1960s, several catastrophic structural failures occurred, including the May 16, 1968, disproportionate partial building collapse of a 22-story precast concrete residential building in East London, England. This failure was caused by a natural gas explosion in a corner apartment on the 18th floor. In 1970, the *Building Regulations* in the United Kingdom were amended so that this type of accident would not trigger a disproportionate collapse. Specifically, provisions were included for short-duration, extreme pressure loads applied to a small portion of buildings. In 1970, similar requirements were adopted by New York City (NYC, 1970). Structural "members shall provide adequate protection against progressive collapse under abnormal load, where progressive collapse is interpreted as structural failure" over given vertical and horizontal extents of buildings. Both codes repeatedly used "wall panels" and "walls" in their requirements. It is thought that these were references to precast concrete construction. Although both codes were concerned about continuity and load path, they did not explicitly mention 3-D design or systems thinking.

Lessons to Learn

Since the late 1960s, each failure has been treated as an independent event with its own technical explanation, some resulting in code changes (i.e., Pearson and Delatte, 2005), none altering the manner in which structural design textbooks were being written. Forensic investigators have primarily sought out quantifiable errors and omissions. Some investigators have attempted to identify patterns of failures by categorizing them according to structural member type, type of structure, year of design, volume, and dimensions, along with material type, geographic location, and more. These efforts have been carried out by insurers for their proprietary purposes of risk management and underwriting. As a result of focusing on technical causes of failures, root causes have generally gone unnoticed, thus not offering information to develop "feedback loops" to correct deficiencies and inadequacies in structural engineering education and practice.

Structural engineers use or go beyond the minimum requirements published in jurisdiction-adopted codes with their referenced standards, which is necessary, but not necessarily sufficient. The use of these consensus documents implies an expectation of reliable, predictable structural performance intended by the governing codes. These codes include an expectation of structural degradation but not structural collapse, such as for an earthquake that exceeds the design parameters based on a stated probability of exceedance in a specified number of years. However, these documents have not included much, if any, wisdom and experience of engineers in related fields.

Recent Structural Engineering Practice

After the Northridge earthquake, the author (1994) pointed out, "Many structures damaged in the earthquake pulled apart in the same manner in which they were designed – that is, as a collection of two-dimensional vertical and horizontal planes of framing. This lack of breadth and depth leads to structural framing schemes – not 3-D systems – with inadequate reliability for safety, both globally and locally. Therefore, it is not possible to fully consider the soil-foundation-structure interaction in order to develop adequate building-specific performance criteria for anticipated levels of ground shaking." A number of photographs are in the reconnaissance literature, including the structural collapse of the California State University's Northridge precast concrete parking structure.

For many decades, building codes have misused the word *system*, thus misleading its users. For example, in the *Uniform Building Code* (UBC, 1967), the "type of arrangement of resisting elements" was described in terms of system, with terms such as *building framing systems*, *box system, dual bracing system*, and so on. In contrast, "a ductile moment resisting space frame" is not referred to as a *system*. The present author (Cohen) noted that an "arrangement" is not a 3-D system. In another example, the latest *International Building Code* (IBC, 2015), the referenced standard for seismic-resistant framing types is ASCE/SEI 7-10. In the more recent ASCE/SEI 7-16 (2016), *structural system*, the basic lateral and vertical *seismic-force-resisting system*, and a *combination of systems* are not defined. The Commentary included the phrase, "…a geometrically complex arrangement of seismic-force-resisting systems…" Cohen also noted that each building has *one* 3-D structural framing system which includes seismic-resisting subassemblages, which, according to Smith (1969) and others, should be an integration of "diverse but interacting elements."

An explanation may be found in a statement by ISE (2018): "Since WW2 the focus of engineering education has been around analytical technique. Over the last 20 years more thinking about conceptual design has been included in engineering teaching, but in civil and structural engineering it is still mainly taught as just another module, alongside soil mechanics and steel design. Design should be half the equation, analysis the other half. Creativity tells you what to analyse [*sic*], then analysis follows. Without teaching conceptual design from the outset, students can't have a full understanding of why they're learning analysis."

This "half the equation" focus can be seen in today's hierarchy of engineering involvement in a typical building project. That is, it would seem that structural engineers have drifted away from participating in conceptual design and even schematic design. By the time they are invited to enter the project during design development, they have already lost opportunities to design 3-D framing using systems thinking. There is no proof that this approach to structural design offers predictable, reliable performance and reduces the risk of structural failure.

Conclusions

Structural engineering is too important to society for the profession not to strive to eliminate recurring, costly structural failures whose root causes are in unrecognized, pertinent knowledge.

The author's research has resulted in several recommendations for structural engineers "to increase the competence… of the engineering profession" (ASCE 1976 and NCSEA 2011), including but not limited to the following:

1) Participate in discussions with education policymakers at ASCE (the "lead society" for CE at ABET) and NCSEA to increase the number and improve the content of required undergraduate engineering courses for those interested in structural engineering.
2) Improve practice policy by participating in conceptual and schematic design, and conducting project-specific research to procure available, pertinent knowledge for design.
3) Educate owners, lenders, and government agencies on the importance of peer review by structural engineers and those in project-specific related engineering fields.
4) Request continuing education courses that contribute to structural engineers' knowledge base at the graduate level in structural engineering, structural design, structural analysis, materials science, systems thinking/design, etc.
5) Prepare articles on structural failures that have resulted from substantiated underlying lack of knowledge from related engineering fields; disseminate to the structural engineering community, preferably in professional magazines.▪

The online version of this article contains detailed references. Please visit **www.STRUCTUREmag.org**.

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