Learning From Failures

It is imperative that engineers not only learn about the history of failures but also their contexts as well as their repercussions.

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Careful study of failures provides valuable lessons for engineering students and practicing engineers. Is there a need, however, for students and engineers to have a basic understanding of critical, historical failure cases — a failure literacy? What are some common causes of failures? Patterns of repeated failures are particularly worrisome — how can we have three very similar punching shear failures of reinforced concrete structures during construction in a decade? What are the mechanisms for learning and disseminating lessons, and how well have they worked? Lessons that have been learned need to be contrasted with lessons not yet learned. What still needs to be done to promote failure literacy?

A Definition

What is failure literacy, and is there a need for it? Although most dictionaries define literacy as the ability to read and write, it is commonly understood that to be literate is to be educated. Writers are expected to be acquainted with a broad variety of works, and lawyers are expected to know prior cases well enough to have a starting point for researching precedents. However, there does not seem to be a consensus of a compelling need among practicing engineers to know the history of the profession beyond the idea that Hooke's law and Young's modulus are somehow connected to people with those names. Very few civil engineering programs explicitly include engineering history topics.

Nevertheless, it is important to consider history and failure analysis in the context of design. Design can be viewed very simply as a two-step process:

1. Figure out everything that can possibly go wrong.
2. Make sure that everything that can possibly go wrong doesn't happen.

From this standpoint, designers must be failure literate in order to know what can go wrong. Therefore, in the interest of structural failure literacy, there are twelve failure case studies that every structural engineer should know. These studies are briefly discussed in chronological order below.

Quebec, 1907

A cantilever bridge was determined to be the most feasible design to bridge the harsh, icy waters of the St. Lawrence River near

Quebec. The bridge collapsed during construction on August 29, 1907, killing seventy-five workers. Only eleven of the workers on the span were recovered alive, and some bodies were never found. A second attempt to bridge the St. Lawrence River was made. However, it also suffered a partial collapse when the middle span fell into the river. Thirteen workers were lost in the second collapse. The bridge was finally completed in 1917, and it still stands today. Middleton provides a review of the history of the bridge and its two collapses.[1]

The Quebec Bridge was the longest cantilever structure ever to be attempted up until that time. The cantilever arms were initially designed to reach a distance of 171.5 meters (562.5 feet). They were to support a suspended span with a length of 205.7 meters (675 feet). It would stand 45.7 meters (150 feet) above the river. The initial design length clear span was 487.7 meters (1,600 feet).

However, in May 1900, this span was increased to 548.6 meters (1,800 feet) by Theodore Cooper. He stated that this increase would eliminate the uncertainty of constructing piers in such deep water, lessen the effects of ice and shorten the time of construction of the piers. Although there were sound engineering reasons for this change, it was also true that the lengthening of the span would also make Cooper the chief engineer for the longest span cantilever bridge in the world.[1,2]

As the bridge was erected, workers and supervisors found noticeable deflections in some of the chords. When the workers tried to rivet the joints between these chords, the predrilled holes did not line up. In addition, bends (deflections) were observed in some of the most heavily loaded compression members. Over time, some of the member deflections increased.

Deflections were first noticed as early as mid-June 1907, and were reported to Cooper by his on-site inspector, Norman McLure. Compression members had been cambered so that under load the joints would line up and could be riveted together. However, some of the joints failed to close. Both men presumed that the relatively small deflections had occurred due to an unknown pre-existing condition and were not alarmed.[1]

Subsequent inspections turned up more deflecting chords in August. Again, these deflections were reported to Cooper on the same day that they were discovered. Cooper wired a message back, referring to chords 7L and 8L and asking, "How did bend occur in both chords?" The chief engineer of the Phoenix Company replied to Cooper saying that he did not know.[1]

Just prior to the collapse Cooper sent a message to the site to halt work. It was ignored due to the absence of the contractor's chief engineer. At around 3:00 P.M., the Phoenix Company's chief engineer returned to his office. After seeing the message, he arranged for a group meeting as soon as McLure arrived. McLure arrived at roughly 5:15 P.M. and the men discussed the circumstances briefly before deciding to wait until the next morning to decide on a course of action.[1]

Meanwhile, back at the construction site, at about the same time the decision-makers from the Phoenix Company were ending their meeting, the Quebec Bridge collapsed at 5:30 P.M. The thunderous roar of the collapse was heard ten kilometers (six miles) away in Quebec.[1] The entire south half of the bridge, approximately 17,000 tonnes (19,000 tons) of steel, fell into the waters of the St. Lawrence within 15 seconds. Eighty-six workers were present on the bridge at the time. Only eleven workers on the span survived.

Following the collapse, the Governor General of Canada formed a Royal Commission, comprised of three civil engineers, to investigate the cause of the collapse. These engineers were Henry Holgate, of Montréal; John George Gale Kerry, of Campbellford, Ontario; and John Galbraith, of Toronto. Their completed report was a pioneering event in the discipline of forensic engineering, and consisted of over two hundred pages plus twenty-one appendices. As stated by Middleton, "the thoroughness and objectivity of their inquiry and report stand even today as models of their kind."[1]

The immediate cause of failure was found to be the buckling of compression chords A9L and A9R. The official report attributed the collapse to a number of reasons. Listed below are some of the major findings:[3]

- "The collapse of the Quebec Bridge resulted from the failure of the lower chords in the anchor arm near the main pier. The failure of these chords was due to their defective design."
- "We do not consider that the specifications for the work were satisfactory or sufficient, the unit stresses in particular being higher than any established by past practice. The specifications were accepted without protest by all interested."
- "A grave error was made in assuming the dead load for the calculations at too low a value and not afterwards revising this assumption. This error was of sufficient magnitude to have required the condemnation of the bridge, even if the details of the lower chords had been of sufficient strength, because, if the bridge had been completed as designed, the actual stresses would have been considerably greater than those permitted by the specifications. This erroneous assumption was made by Mr. Szlapka and accepted by Mr. Cooper, and tended to hasten the disaster."
- "The loss of life on August 29, 1907, might have been prevented by the exercise of better judgement on the part of those in responsible charge of the work for the Quebec Bridge and Railway Company and for the Phoenix Bridge Company."
- "The failure on the part of the Quebec Bridge and Railway Company to appoint an experienced bridge engineer to the position of chief engineer was a mistake. This resulted in a loose and inefficient supervision of all parts of the work on the part of the Quebec Bridge and Railway Company."
- "The work done by the Phoenix Bridge Company in making the detail drawings and in planning and carrying out the erection, and by the Phoenix Iron Company in fabricating the material was good, and the steel used was of good quality. The serious defects were fundamental errors in design."
- "The professional knowledge of the present day concerning the action of steel columns under load is not sufficient to enable engineers to economically design such structures as the Quebec bridge. A bridge of the adopted span that will unquestionably be safe can be built, but in the present state of professional knowledge a considerably larger amount of metal would have to be used than might be required if our knowledge were more exact."

Cooper insisted on retaining full control of the project, even though he often was not at the construction site. Schreiber recommended that the governmental agency of Railways and Canals hire a consultant on its behalf. This engineer would, in a sense, be double-checking Cooper's work and ultimately have the final authority. After finding out this news, Cooper, the Quebec Bridge Company, and the Phoenix Bridge Company immediately objected. In a letter to Edward Hoare, Cooper wrote, "This puts me in the position of a subordinate, which I cannot accept."[1] Cooper met with Schreiber personally. Following this meeting, Schreiber revised his recommendation to eliminate the need to hire an additional project consultant. The new amended order-in-council to Railways and Canals gave an unclear definition of just how much authority Cooper would have over the project.

No clear chain of command existed. It was assumed that the final authority rested with Cooper. All concerns were directed towards him, even though, due to illness, he was unable to travel to the job site. There was no one present on the job site who was qualified to oversee this type of work or who was in a position to make a timely decision. Whenever the need arose, the authorities on-site would confer with each other before making any decision. In the few occasions where some decision had been reached, there was hesitation in carrying it out. The authors of the Royal Commission Report wrote, "It was clear that on that day the greatest bridge in the world was being built without there being a single man within reach who by experience, knowledge and ability was competent to deal with the crisis."[3]

Tacoma Narrows, 1940

On July 1, 1940, the Tacoma Narrows Bridge, connecting Seattle to Tacoma and to the nearby Puget Sound Navy Shipyard, opened to the public after two years of design and construction. Its 853-meter (2,800-foot) main span connected two 128-meter (420-foot) towers from which cables were draped.[4]

Even though it was the third-longest span bridge in the world, Tacoma Narrows was much narrower, lighter and more flexible than any other bridge of its time. With a 12-meter (39-foot) wide and 2.5-meter (8-foot) deep deck, it accommodated two lanes of traffic quite comfortably while maintaining a sleek appearance. This appearance was so important to the bridge's designer, Leon Moisseiff, that he designed it without the use of stiffening trusses, leaving Tacoma Narrows with one-third the stiffness of the Golden Gate and George Washington bridges. The bridge's light appearance, however, was no illusion. Its dead load was one-tenth of that of any other major suspension bridge. These unique characteristics, coupled with its low dampening ability, caused large vertical oscillations in even the most moderate of winds. This behavior soon earned it the nickname, "Galloping Gertie," and attracted thrill seekers from all over.[5]

While these undulations could be quite unnerving to motorists, no one questioned the structural integrity of the bridge. Moisseiff was a highly qualified and well-respected engineer. Not only had he been the consulting engineer for the Golden Gate, Bronx-Whitestone and San Francisco-Oakland Bay bridges, but he had also developed the methods used to calculate forces acting on suspension bridges.[4]

Even though the Tacoma Narrows Bridge adhered to all of the safety standards and its oscillations were not considered a threat, Professor F. B. Farquharson, of the University of Washington, began researching ways to reduce its motion. By studying how different winds affected a highly accurate model of the Tacoma Narrows Bridge and testing new devices on it, Farquharson was able to propose helpful modifications to the bridge. After proving successful on the model, steel cables were attached from a point on each side span to concrete anchors in the ground. Unfortunately, these cables snapped a few weeks later, proving to be an ineffective solution.[6] Nevertheless, they were reinstalled in a matter of days. In addition to these cables, center stays and inclined cables, which connected the main cables to the stiffening girder, were installed.

Finally, an untuned dynamic damper, similar to the one that had proved quite successful in curtailing the torsional vibrations of the Bronx-Whitestone Bridge, failed immediately after its installation in the Tacoma Narrows Bridge. It was discovered that the leather used in this device was destroyed during the sandblasting of the steel girders before they were painted, rendering it useless.[4] Farquharson also discovered that proper streamlining would almost completely stop the bridge's disturbing movements. The bridge collapsed before this knowledge could be applied.[6]

At 7:30 A.M. on November 7, 1940, Kenneth Arkin, the chairman of the Washington State Toll Bridge Authority, arrived at the Tacoma Narrows Bridge. While the wind was not extraordinary that day, the bridge was undulating noticeably and the stays on the west side of the bridge that had broken loose were flapping in the wind. Just before 10:00 A.M., after measuring the wind speed to be 67.5 kilometers per hour (42 miles per hour), Arkin closed the bridge to all traffic due to its alarming movement — 38 oscillations per minute with an amplitude of 0.9 meters (3 feet).[4] Suddenly, the north center stay broke and the bridge began twisting violently in two parts. The bridge rotated more than 45 degrees, causing the edges of the deck to have vertical movements of 8.5 meters (28 feet) and at times exceed the acceleration of gravity.[6]

Two cars were on the bridge when this wild movement began: one with Leonard Coatsworth, a newspaper reporter, and his cocker spaniel; and the other with Arthur

Hagen and Judy Jacox. All three people crawled to safety.[4] A couple of minutes later, the stiffening girders in the middle of the bridge buckled, initiating the collapse. Then the suspender cables broke and large sections of the main span dropped progressively, from the center outward, into the river below. The weight of the sagging side spans pulled the towers 3.7 meters (12 feet) towards them and the ruined bridge finally came to a rest.[5] The bridge's only fatality was Coatsworth's cocker spaniel. Due to the fact that Farquharson was present that day studying the bridge, its collapse is well documented, photographed and recorded on film.[4]

The Federal Works Agency (FWA) investigated the collapse of the Tacoma Narrows Bridge and found the following:

- The bridge was well designed and well built. While it could safely resist all static forces, the wind caused the extreme undulations that caused the bridge's failure.
- No one realized that the Tacoma bridge's exceptional flexibility, coupled with its inability to absorb dynamic forces, would make the wild oscillations that destroyed it possible.
- Vertical oscillations were caused by the force of the wind and caused no structural damage.
- The failure of the cable band on the north end, which was connected to the center ties, probably started the twisting motion of the bridge. The twisting motion caused high stresses throughout the bridge, which led to the failure of the suspenders and the collapse of the main span.
- Rigidity against static forces and rigidity against dynamic forces cannot be determined using the same methods.
- Efforts were made to control the amplitude of the bridge's oscillation.
- Subsequent studies and experiments were needed to determine the aerodynamic forces that act on suspension bridges.

In other words, the FWA concluded that because of the Tacoma Narrows Bridge's extreme flexibility, narrowness and lightness, the random force of the wind that day caused the torsional oscillations that destroyed the bridge. The FWA believed that the wind-induced oscillations approached the natural frequencies of the structure, thus causing resonance (the process by which the frequency on an object matches its natural frequency, causing a dramatic increase in amplitude). However, it is now recognized that the failure of the bridge was due to aeroelastic instability and flutter, and not due to either resonance or vortex shedding.[7]

Point Pleasant/Silver Bridge, 1967

The Point Pleasant Bridge across the Ohio River between Point Pleasant, Virginia, and Gallipolis, Ohio, collapsed on Friday, December 15, 1967, after forty years of service. The bridge was crowded with Christmas shopping traffic, and thirty-one vehicles fell with the bridge — forty-four people died, and two of their bodies were never found. This bridge, called the "Silver Bridge" because of its silver paint, was an unusual eyebar suspension bridge with a main suspension span of 213 meters (700 feet) and two approach spans of 116 meters (380 feet) each.

After a long investigation, it was determined that one of the eyebars had fractured due to the combined effects of stress corrosion and corrosion fatigue. Unfortunately, the eyebar design was both non-redundant and difficult to inspect.[5]

The National Transportation Safety Board (NTSB) carried out a thorough investigation to analyze the stresses and to determine the cause of failure. The NTSB concluded that:[8]

> "[T]he initial failure in the bridge structure was a cleavage fracture in the lower limb of the eye of eyebar 330 (north bar, north chain, Ohio side span) at joint C13N, the first eyebar chain joint west of the Ohio tower of the bridge. The cleavage fracture was followed by a ductile fracture in the upper limb of the eye of eyebar 330 at joint C13N, separating eyebar 330 from the chain. Immediately following the separation of eyebar 330 from joint C13N, the sister eyebar 33 slipped from the C13N joint pin, resulting in the separation of the north

chain at that location. The collapse of the bridge began in the Ohio side span, moving eastward toward the West Virginia shore, with the result that within a period of about 1 minute, the [213-meter] 700-foot center span, the two [116-meter] 380-foot side spans, and the towers had collapsed. The Safety Board finds that the cause of the bridge collapse was the cleavage fracture in the lower limb of the eye of eyebar 330 at joint C13N of the north eyebar suspension chain in the Ohio side span. The fracture was caused by the development of a critical size flaw over the forty-year life of the structure as the result of the joint action of stress corrosion and corrosion fatigue."

A detailed discussion of this bridge and its collapse is provided by Lichtenstein.[9]

Of particular concern, from the standpoint of the NTSB, was that "the flaw could not have been detected by any inspection method known in the state of the art today without disassembly of the eyebar joint."[8] This accident spurred research into metal fatigue and into bridge management and inspection methods, particularly non-destructive evaluation.

Ronan Point, 1968

In the early morning hours of May 16, 1968, the occupant of apartment 90 on the 18th floor of the Ronan Point apartment tower in London lit a match for her stove to brew her morning cup of tea. The resulting gas explosion, due to a leak, knocked her unconscious. The pressure of the small gas explosion blew out the walls of her apartment and initiated a partial collapse of the structure that killed four people and injured seventeen.

Ronan Point was the second of nine identical high-rise precast concrete flat plate structures that were erected in London after World War II. In this type of structural system, each floor was supported by the load-bearing walls directly beneath it. Gravity load transfer occurred only through these load-bearing walls. This wall and floor system fitted together in slots. These joints were then bolted together and filled with dry pack mortar to secure the connection.

Pressured by the public, the government formed a panel to investigate the collapse. The panel's report was issued later that year.[10] It was quickly determined that the explosion from the gas leak had initiated the collapse of the building. A substandard brass nut had been used to connect the hose to the stove. The nut had a thinner flange than the standard, and also had an unusual degree of chamfer. A replica of this nut was made and tested to determine how much force was required to break it in tension. It was found that a force of 15.6 kN (3,500 pounds) would break the connection. It was also concluded that the hose connecting the stove to the gas would have failed before the nut at a force of 1.6 kN (360 pounds). The nut was assumed to have been previously fractured by over-tightening during installation, causing it to break, allowing gas to leak into the apartment.[10] Ultimately, the collapse of Ronan Point was due to its lack of structural redundancy. It had no fail-safe mechanisms, and no alternative load paths for the upper floors should a lower level give way. (A complete analysis of this case is provided by Pearson and Delatte.[11])

2000 Commonwealth Avenue, 1971

Four workers died when about two-thirds of a sixteen-story Boston apartment building under construction collapsed on January 25, 1971. The next day's *Boston Globe* newspaper featured dramatic photographs of the remains of the collapsed structure. Nearly 7,300 tonnes (8,000 tons) of debris were removed before the bodies of the workers could be recovered.[12] Fortunately, the collapse occurred slowly enough so that most of the men working on the site were able to escape.

Punching shear was determined to have triggered the collapse. A commission of inquiry was selected by the mayor of Boston and convened a week after the collapse. The Associated General Contractors of Massachusetts, the Boston Society of Architects, the Boston Society of Civil Engineers and the Boston Building and Construction Trades Council had representatives on the commission. Professor William A. Litle of the Massachusetts Institute of Technology helped draft the commission report and later reported on the failure.

The commission retained an engineering firm and a testing laboratory to aid in the investigation. The commission interviewed a number of eyewitnesses, but suspended the interviews after about a dozen because there was no significant disagreement between the accounts.[12] The commission made a number of important findings:[12]

- There were a number of irregularities in the issuance of the building permit. Key drawings were missing. Not a single drawing found in the file carried an architect's or engineer's registration stamp. The structural engineer refused to provide the calculations supporting the structural design to the commission. No principal or employee of the general contractor held a Boston builder's license. (At the time, partial drawings could be used to obtain a building permit, with the understanding that final stamped drawings would have to be supplied before construction could begin.)
- Ownership of the project changed a number of times, with changes also in architects and engineers. These changes added to the overall confusion and contributed to the irregularities cited above.
- The general contractor only had a single employee on site, and most subcontracts were issued directly by the owner to the subcontractors and bypassed the general contractor. At least seven subcontractors were involved.
- The structural concrete subcontract did not require any inspection or cold weather protection of the work, although the designer had specified these measures. There was no evidence of any inspection of the work by an architect or engineer, although the project specifications required this.
- The concrete mix designs were not pre-qualified. Such pre-qualification was a Boston Building Code requirement and stipulated that the performance of the proposed concrete be verified by laboratory testing. Some concrete deliveries did not contain the required air entrainment. Calcium chloride was used as an accelerator for some of the concrete, although it was specifically prohibited by the designer's specifications. The designer's specifications included a water-reducing admixture, which was used in only a small percentage of the concrete supplied. The Boston Building Code requirements for inspection and testing were not met on 65 percent of the days concrete was delivered to the project. Chemical analyses also suggested that some samples had low cement content.
- The triggering mechanism of the collapse was punching shear at the roof slab around column E5, probably preceded by flexural yielding of the roof slab adjacent to the east face of the elevator core. The commission examined the failure from three aspects: 1) Whether failure would have been expected if the construction had conformed to the design documents; 2) Whether the construction procedures and materials conformed to the design documents; and, 3) Whether the design documents met the building code requirements.
- The commission concluded that the failure would not have occurred if the construction had conformed to the design documents, and that the construction procedures and materials were deficient. The most significant deficiencies were a lack of shoring under the roof slab and low-strength concrete. The design documents specified a 28-day strength of 20 MPa (3,000 psi). At the time of the failure, 47 days after casting, the concrete had yet to achieve the 28-day strength.

The mayor's investigating commission made recommendations for improving the city of Boston's Building Codes. However, the commission also reported that if the construction of 2000 Commonwealth Avenue had fully complied with existing codes, then the collapse would not have occurred. The commission was dismayed that the project could have progressed through so many phases without the errors and omissions being found and corrected.

The commission made recommendations to prevent similar collapses in the future. These recommendations included changes in assigning responsibility and in ensuring the competence of the design, construction and inspection of major buildings, as well as additions to organization and staff competence of the Building Department. At the time of the failure, the Building Department had 130 employees, but only two registered professional engineers, and no registered architect.

In addition, changes in building codes to prevent the propagation of a local failure into a general collapse were recommended. This case (and the cases of Bailey's Crossroads and Harbour Cay Condominium, below) illustrate the importance and progressive nature of punching shear failure, which is a critical failure mechanism for concrete structures of this type. Structural safety depends on adequate slab thickness, proper placement of reinforcement, and adequate concrete strength. (A complete analysis of this case is provided by King and Delatte.[13])

Bailey's Crossroads, 1973

On March 2, 1973, the Skyline Plaza in Bailey's Crossroads, Virginia, collapsed while under construction. Like 2000 Commonwealth Avenue, the premature removal of shoring and insufficient concrete strength were suggested as the causes of failure. Low temperatures led to an estimated concrete compressive strength of only 6.6 to 9.9 MPa (960 to 1,440 psi) at the time of the collapse. A National Bureau of Standards (NBS, now the National Institute of Standards and Technology, NIST) investigation team determined that punching shear failure at the twenty-third floor caused a partial collapse that propagated to the ground. Fourteen workers were killed and thirty-four were injured.[14]

The building construction was proceeding at the rapid rate of one floor per week. The design of the slab was not at fault. The slab would probably have had sufficient punching shear strength before the shoring was removed if the cold weather had not retarded the strength gain of the concrete. Although the failure was clearly due to mismanaged construction procedures, the structural engineers and architects were held responsible.[5]

Hartford Civic Center, 1978

No one was killed or injured when the huge space truss roof of the empty Hartford Civic Center Coliseum collapsed under a heavy snowfall at 4:19 A.M. on January 18, 1978. Had the failure occurred just a few hours before, the death toll might have been hundreds or thousands. The dramatic roof, designed with the aid of computers, had shown evidence of distress during construction, but the warnings had not been heeded. The building had been in service for five years when it collapsed.[4]

In order to save money, the engineers proposed an innovative design for the 91.4- by 110-meter (300- by 360-foot) space frame roof 25.3 meters (83 feet) over the arena. The proposed roof consisted of two main layers arranged in 9.14- by 9.14-meter (30- by 30-foot) grids composed of horizontal steel bars 6.4 meters (21 feet) apart. Diagonal members 9.14 meters (30 feet) long connected the nodes of the upper and lower layers, and, in turn, were braced by an intermediate layer of horizontal members. The 9.14-meter (30-foot) members in the top layer were also braced at their midpoints by intermediate diagonal members.[15]

This design departed from standard space frame roof design procedures in five ways:

- The cross-section configuration of the four steel angles making up each truss member did not provide good resistance to buckling. The cross-shaped built-up section has a much smaller radius of gyration than either an I-section or a tube section configuration of the same structural members. As a result, the buckling load for the cross-shaped section is much lower than that of the other configurations.
- The top horizontal members intersected at a different point than the diagonal members rather than at the same point, making the roof especially susceptible to buckling because the diagonal members did not brace the top members against buckling.
- The top layer of this roof did not support the roofing panels; short posts on the

nodes of the top layer did. Not only were these posts meant to eliminate bending stresses on the top layer bars, but their varied heights also allowed water to be carried away to drains.
- Four pylon legs positioned 13.7 meters (45 feet) inside of the edges of the roof supported it instead of boundary columns or walls.[4]
- The space frame was not cambered. Computer analysis predicted a downward deflection of 330 millimeters (13 inches) at the midpoint of the roof and an upward deflection of 150 millimeters (6 inches) at the corners.[16]

Because of these money-saving innovations, the engineers employed state-of-the-art computer analysis to verify the safety of the building.

A year later construction began. To save time and money, the roof frame was completely assembled on the ground. While it was still on the ground, the inspection agency notified the engineers that it had found excessive deflections at some of the truss joints. Nothing was done.

After the frame was completed, hydraulic jacks located on top of the four pylons slowly lifted it into position. Once the frame was in its final position, but before the roof deck was installed, its deflection was measured and found to be twice that predicted by computer analysis. The engineers were notified. They, however, responded that such discrepancies between the actual and the theoretical should be expected. When the subcontractor began fitting the steel frame supports for fascia panels on the outside of the truss, the subcontractor ran into great difficulties due to the excessive deflections of the frame.[4]

The roof was completed on January 16, 1973.[5] The next year, a citizen expressed concern to the engineers regarding the large downward deflection he noticed in the arena roof, which he believed to be unsafe. The engineers and the contractor once again assured the city that everything was fine.[4]

Petroski discusses this case in terms of the need for engineers to be able to reason out whether or not computer results make sense, through hand calculations and knowledge of structural behavior and performance:[17]

> "Because the computer can make so many calculations so quickly, there is a tendency now to use it to design structures in which every part is of minimum weight and strength, thereby producing the most economical structure. This degree of optimization was not practical to expect when hand calculations were the norm, and designers generally settled for an admittedly overdesigned and thus a somewhat extravagant, if probably extra-safe, structure. However, by making every part as light and as highly stressed as possible, within applicable building code and factor of safety requirements, there is little room for error — in the computer's calculations, in the part manufacturers' products, or in the construction workers' execution of the design. Thus computer-optimized structures may be marginally or least-safe designs, as the Hartford Civil Center roof proved to be."

Since Petroski wrote these words, despite tremendous advances in computing power and software, there is no sign that computer programs will soon be able to envision failure modes that the designer has not foreseen, or check their own work. (A complete analysis of this case is provided by Martin and Delatte.[18])

Willow Island Cooling Tower, 1978

The Willow Island, West Virginia, cooling tower collapsed while under construction on April 27, 1978, killed fifty-one workers in the worst construction disaster in U.S. history. A jumpform system was being used, with the forms secured by bolts in one-day- and three-day-old concrete. The forms were designed to be progressively moved up the tower as it was built.[5,19,20] The temperature had been in the mid-thirties at night. The NBS (now NIST) found that the concrete had not attained enough strength to support the forms. The report concluded that "the most probable cause of the collapse was the imposition of construction loads on the shell before the concrete of lift 28 had gained adequate strength to support these loads."[19]

The towers were being constructed using a patented lift-form technique that had been successfully used for construction of thirty-six cooling towers. The lift form scaffolding was made up of five basic components:

- jumpform beams;
- anchor assemblies;
- jacking frames;
- formwork; and,
- scaffolding platforms.[21]

A four-level high system of scaffolding was used and working platforms were suspended from the inside and outside jacking frames. The top level was where the construction materials were received by the hoisting system, where the steel reinforcement was distributed and where the concrete was delivered. The second level was used only during the formwork adjustment process. Levels three and four of the scaffolding system provided access to the jumpform beams and final surface preparation such as patching and grouting was done from these levels.[19] The scaffolding system was entirely supported by the previously completed portion of the tower. Each day a 1.5-meter (5-foot) lift was completed and the entire scaffolding system moved with the jacking frame to the new elevation.

The daily routine to prepare for concrete placement consisted of four procedures. First, workers loosened the last concrete lift by removing the wedging from the formwork. Next, the forms were adjusted to accommodate the changing diameter of the shell and the jacking of the entire formwork and scaffolding system took place at the next elevation. Then, the lowest jumpform beam was unbolted and moved to its new location at the top. Finally, the formwork was wedged into position.[21]

After lift 10 was completed, the concrete and construction materials were carried to the working platforms by an elaborate hoisting system. Six cathead gantry cranes powered by twin drum hoists delivered the materials.[19] The catheads moved up the lift form scaffolding as the construction advanced. A static line guided all of the materials as they were hoisted to the working platforms. The static line was attached to the slide plate at the interior end of the cathead at one end and secured to an anchor point on the ground at the other end.[21] During construction, due to the changing geometry of the tower, both the catheads and static line had to be adjusted periodically.

While concrete was being placed for lift 29, 170 feet above the ground, lift 28 collapsed, causing fifty-one workers to fall to their deaths. Because all of the formwork around the perimeter of the tower was tied together, it all fell together.

The NBS (now NIST) investigated and concluded that:[19]

- At the time of failure, the concrete bucket was in transit from the base of the tower to cathead gantry No. 4. Eyewitness accounts and measurements indicate that the bucket was approximately 60 feet below the cathead beam. Therefore, it is not believed that the concrete bucket hit the cathead, causing it to fail.
- Cables for catheads No. 4 and No. 5 were broken after the onset of the collapse. Therefore, the breakage of the cables did not initiate the failure.
- Field and lab tests showed that the collapse did not initiate due to a component failure of the hoisting, scaffolding or formwork systems.
- The compressive strength of the concrete near the location of cathead gantry No. 4 was estimated to be 1.5 MPa (220 psi) at the time of the collapse.
- Analysis showed that the resultant stresses at several points along lift 28 equaled or exceeded the shell strength in compression, bending and shear. Failure at any of these points would have propagated, causing the collapse.
- The most probable cause of the collapse was determined to be the imposition of construction loads on the shell before the concrete of lift 28 had gained adequate strength to support these loads.

A consultant investigated the failure on behalf of the general contractor. The consultant's findings disagreed with those of the NBS investigation. The consultant claimed that the most probable cause of failure was the early removal of anchor bolts and cones from the lower portion of lift 27. The consultant believed that if the anchor bolts were left in place and attached to the jumpform beams, the collapse would have never occurred. Their position was that the strength of the concrete was immaterial, since it should not have had any load applied.[21]

The consultant's position is reasonable. As Velivasakis noted:[21]

> "The particular circumstances point to the unfortunate fact that the removal of the critical anchors was done by workers who had very little knowledge of the significance of their actions. No supervising personnel had ever instructed these workers of the importance and critical nature of the anchorages and the proper timing of their removal."

Harbor Cay Condominium, 1981

The collapse of the flat-plate Harbour Cay condominium building in Cocoa Beach, Florida, on March 27, 1981, was caused by a punching shear failure that triggered a progressive collapse, much like what occurred at 2000 Commonwealth Avenue and at Skyline Plaza. Eleven workers were killed and twenty-three were injured. An NBS (now NIST) investigation team that included two individuals who had investigated the Skyline Plaza collapse determined that the slab thickness of 203 millimeters (8 inches) did not meet the ACI code minimum of 279 millimeters (11 inches). Also, the top reinforcing steel was placed too low, reducing the effective slab depth, *d*, from 160 millimeters (6.3 inches) to 135 millimeters (5.3 inches). As a result, the calculated punching shear stresses exceeded capacity.[22]

The investigation revealed a number of critical omissions in the calculations:[5]

- There were no checks for deflection or code minimum thickness provisions.
- There were no punching shear or beam shear checks.
- No code checks for column reinforcement spacing were performed.
- Calculations were based on grade 40 steel, although grade 60 was specified.
- No calculation of effective depth of slab flexural reinforcement was made.

According to Feld and Carper, the structural engineer was a retired National Aeronautics and Space Administration (NASA) engineer who hired another retired NASA engineer to do the calculations.[5] (This situation illustrates the important point that structural engineering is not rocket science. Evidently, it is considerably more difficult.)

Hyatt Regency, 1981

In July of 1980, the Hyatt Regency, in Kansas City, Missouri, opened to the public after four years of design and construction. A forty-story tower, an atrium and a function block (housing all of the hotel's services) combined to form this impressive building. Three walkways suspended from the atrium's ceiling by six 32-millimeter-diameter (1.25-inch) tension rods each spanned the 37-meter (121-foot) distance between the tower and the function block. The second floor walkway, directly below the fourth floor walkway, was suspended from the beams of the fourth floor walkway, while the third and fourth floor walkways hung from the ceiling.[5]

The erection of this hotel, however, had not been without incident. During construction, the atrium roof collapsed as a result of inadequate provision for movement in the expansion joint and as a result of the improper installation of a steel-to-steel concrete connection. Concerned about the building's structural integrity, the owner hired another engineering firm to investigate the collapse and check the roof design. The consulting structural engineering company also rechecked all of the connections and found nothing to cause alarm. Construction resumed and the hotel opened a little less than two years later.[23]

On the evening of July 17, 1981, between 1,500 and 2,000 people were on the atrium floor and the suspended walkways to see a local radio station's dance competition.[5] At 7:05 P.M., a loud crack echoed throughout the building and the second and fourth floor walkways crashed to the ground, killing 114 people and injuring over 200 others. It was the worst structural failure in the history of the United States prior to the September 11, 2001 terrorist attacks.[4]

Upon investigation, the NBS (now NIST) discovered that the cause of this collapse was quite simple: the rod hanger pulled through the box beam, causing the connection supporting the fourth floor walkway to fail. Because of the lack of redundancy, this failure caused the collapse of both of the walkways.

Originally, the second and fourth floor walkways were to be suspended from the same rod and held in place by nuts. The preliminary design sketches contained a note specifying a strength of 413 MPa (60 ksi) for the hanger rods that was omitted on the final structural drawings. Following the general notes in the absence of a specification on the drawing, the contractor used hanger rods with only 248 MPa (36 ksi) of strength. This original design, however, was highly impractical because it called for a nut 6.1 meters (20 feet) up the hanger rod and because it did not use sleeve nuts. The contractor modified this detail to use two hanger rods instead of one and the engineer approved the design change without checking it. This design change doubled the stress exerted on the nut under the fourth floor beam. Because of this change, the nut supported the weight of two walkways instead of just one.[23]

A recent paper by Luth details the steps in the Hyatt Regency's design and construction process.[24] He makes the important point that the critical connection was never designed, and the detail often used to illustrate the case was never drawn until after the failure. Luth's figures and tables illustrating the sequence of events are of particular interest.

Kansas City did not convict the Hyatt Regency engineers of criminal negligence due to lack of evidence. However, the Missouri Board of Architects, Professional Engineers and Land Surveyors convicted the engineer of record and the project engineer of gross negligence, misconduct and unprofessional conduct in the practice of engineering. Both of their Missouri professional engineering licenses were revoked, and the engineer of record lost membership in ASCE. Also, the billions of dollars in damages awarded in civil cases brought by the victims and their families dwarfed the half-million-dollar cost of the building.[23] Jack Gillum, the engineer of record, has published an excellent paper discussing the failure, his actions before and after, and the responsibilities of the engineer of record.[25]

This case was revisited, with considerable new information and analysis, in four papers published in a special issue of the *ASCE Journal of Performance of Constructed Facilities*.[24–27] In addition, all four papers were published and presented in abbreviated versions to the second Forensic Congress.[28]

In his editor's note to the issue in which the four abovementioned papers appeared, the editor of the *ASCE Journal of Performance of Constructed Facilities*, Ken Carper, asked:[29]

> "If we are truly honest, can we assert that much has improved in the way we go about the business of designing and constructing similar buildings today? Has the project delivery system truly become less convoluted, and are roles and responsibilities for all parties now really more clearly defined?"

Mianus River Bridge, 1983

Like the Point Pleasant Bridge, the Mianus River Bridge on the Connecticut Turnpike (I-95) collapsed after decades of service. A 30-meter (100-foot) span collapsed suddenly at 1:28 A.M., dropping four vehicles into the river, killing three people.[30] The bridge's skewed simple spans were suspended on pins and hangers. Ten years prior to the accident the bridge's storm drains had been paved over. This act allowed water, silt and dirt to drop directly onto the hanger assembly and accelerate corrosion. The end caps that were intended to keep the hangers from slipping off the pins were only 7.5 millimeters (0.3 inches) thick.[5,31]

The NTSB report concluded that:[31]

> "[T]he probable cause of the collapse of the Mianus River bridge span was the undetected lateral displacement of the hangers of the pin and hanger suspension

assembly in the southeast corner of the span by corrosion-induced forces due to deficiencies in the State of Connecticut's bridge safety inspection and bridge maintenance program."

Many similar bridges were retrofitted to prevent similar collapses.[5]

L'Ambiance Plaza, 1987

The death of twenty-eight workers in the construction collapse of the L'Ambiance Plaza building in Bridgeport, Connecticut, triggered a massive rescue effort and several investigations. Unfortunately, to this day the true cause of the collapse remains in dispute.

L'Ambiance Plaza was planned to be a sixteen-story building with thirteen apartment levels topping three parking levels. It consisted of two offset rectangular towers, 19.2 by 34.1 meters (63 by 112 feet) each, connected by an elevator. Post-tensioned concrete slabs 178 millimeters (7 inches) thick and steel columns comprised its structural frame. Posttensioning overcomes the tensile weakness of concrete slabs by placing high-strength steel wires along their length or width before the concrete is poured. After the concrete hardens, hydraulic jacks pull and anchor the wires compressing the concrete.[4]

The lift-slab method of construction, patented by Youtz and Slick in 1948, was utilized in the construction of this building. Following this technique, the floor slabs for all sixteen levels were constructed on the ground, one on top of the other, with bond breakers between them. Then, packages of two or three slabs were lifted into temporary position by a hydraulic lifting apparatus and held in place by steel wedges. The lifting apparatus consisted of a hydraulic jack on top of each column, with a pair of lifting rods extending down to lifting collars cast in the slab.

Once the slabs were positioned correctly, they were permanently attached to the steel columns. Two shear walls in each tower were to provide the lateral resistance for the completed building on all but the top two floors. These two floors depended on the rigid joints between the steel columns and the concrete slabs for their stability. At the time of collapse, the building was a little more than halfway completed.

The workmen were tack welding wedges under the ninth, tenth and eleventh floor package to temporarily hold them into position when a loud metallic sound followed by rumbling was heard. Kenneth Shepard, an ironworker who was installing wedges at the time, looked up to see the slab over him "cracking like ice breaking." Suddenly, the slab fell onto the slab below it, which was unable to support this added weight and, in turn, fell. The entire structure collapsed, first the west tower and then the east tower, in 5 seconds, only 2.5 seconds longer than it would have taken an object to free fall from that height. Ten days of frantic rescue operations revealed that twenty-eight construction workers died in the collapse, making it the worst lift-slab construction accident in the United States. Kenneth Shepard was the only one on his crew to survive.[4]

An unusually prompt legal settlement prematurely ended all investigations of the collapse. Consequently, the exact cause of the collapse has never been established. The building had a number of deficiencies, any one of which could have triggered the collapse. The question, however, remains which one of these problems was in fact the triggering mechanism. There are six competing theories as to the trigger:

- Theory 1: NBS (now NIST) — An overloaded steel angle welded to a shearhead arm-channel deformed, causing the jack rod and lifting nut to slip out and the collapse to begin.[32]
- Theory 2: Thornton-Tomasetti Engineers (T-T) — The instability of the wedges holding the twelfth floor and roof package caused the collapse.[33]
- Theory 3: Schupack Suarez Engineers, Inc. (SSE) — The improper design of the post-tensioning tendons caused the collapse.[34]
- Theory 4: Occupational Safety and Health Administration (OSHA) — Questionable weld details and substandard welds caused the collapse.[35]
- Theory 5: Failure Analysis Associates, Inc. (FaAA) — The sensitivity of L'Ambiance

Plaza to lateral displacement caused its collapse through global instability.[36]

- Theory 6: Oswald Rendon-Herrero — Rapid slump of a column footing precipitated the collapse.[37]

Kaminetzky lists, but does not discuss, a seventh theory: "failure resulting from lateral soil pressure acting on the foundation walls."[20]

Fortunately, even though no final determination of the collapse was made, many of the investigators published their theories in the *ASCE Journal of Performance of Constructed Facilities*. (A complete analysis of this case is provided by Martin and Delatte.[38])

The Engineers

In the examination of failure cases, the human element is often overlooked. It is easy to dismiss the engineers involved as lazy, cavalier or lacking in knowledge, and to say that in their position others would not make similar mistakes. However, this is rarely the case. Examining these cases in depth, with emphasis on the repercussions for the engineers involved, makes a sobering exercise.

Theodore Cooper. Theodore Cooper, the engineer of the Quebec Bridge in 1907, is a figure of hubris. He was clearly one of the master bridge builders of the day and had been instrumental in the development of bridge specifications and standards. As a young engineer on site, he had been instrumental in saving Eads's St. Louis Bridge at a critical point during construction.

However, his insistence on maintaining control of the bridge project and on defeating all efforts to check his work left a leadership vacuum at the site. The combination of distance and ill health made effective supervision impractical. The Royal Commission Report placed most of the blame directly on him. He died in 1919. Despite his many contributions to the profession, he is best known for the Quebec Bridge collapse.

Jack Gillum. As the engineer of record for the Hyatt Regency walkways, Jack Gillum lost his license and was disciplined by the ASCE. He has since devoted considerable effort to trying to share what he learned from the experience, including a presentation entitled, "The Engineer of Record and Design Responsibility" at the May 2000 Forensic Congress in San Juan, Puerto Rico. He has shared this tale many times despite the fact that it must be intensely painful for him to do so.

In the conclusion to his paper, Gillum states:[25]

> "There is hardly a day that goes by that I don't think about the Hyatt collapse, the lives that were lost or marred forever, the relatives that lost their loved ones, and the effect it has had on Kansas City, the construction industry, and everyone connected with the project. My hope is that we, as a profession, can and will continue to learn, practice, disseminate, change and adopt procedures and policies that will prevent a tragedy like this from happening again."

Breaking Down the Causes

There are many different categories of causes for structural failures.

Pushing the Envelope. Several of these cases — Quebec, Tacoma Narrows and Hartford Civic Center — represent attempts to push the boundaries of engineering. Quebec was to be the longest span cantilever bridge in the world. Although the Tacoma Narrows Bridge was not the longest span suspension bridge, it was the most slender, and therefore the most susceptible to aerodynamic excitation. The Hartford Civic Center (called by Henry Petroski the first computer-aided catastrophe) represented an early use of computer structural analysis. Optimization, pushed far enough, can turn into failure.

Not Paying Attention. The structures will speak volumes about their problems if engineers will listen. At the Quebec Bridge and the Hartford Civic Center, excessive structural deformations were apparent well before the collapses. Impending distress is often evident to an observant engineer.

Site Supervision. One of the main safeguards against structural failure is a knowledgeable structural engineer on site. At the Quebec Bridge, Cooper made it clear to the bridge owners that he would not be able to visit the site. At 2000 Commonwealth Avenue, there was evidently no site supervision whatsoever.

The project manager for the Hartford Civic Center considered having an on-site structural engineer an unnecessary expense. The engineers for the Hyatt Regency requested three times that they be permitted to provide full-time representation during construction.[25]

Lack of Redundancy & Robustness. Non-redundant structures are particularly susceptible to progressive or disproportionate collapse. The Quebec Bridge, Ronan Point, Point Pleasant Bridge, Hartford Civic Center, Hyatt Regency Walkways, Mianus River Bridge and L'Ambiance Plaza collapses all started locally and quickly spread through all or most of the structure. Structural engineers must expect the unexpected and design so that local impacts or effects do not lead to disproportionate results.

Maintenance. Several of these collapses occurred after several years of service. The Point Pleasant Bridge and Mianus River Bridge cases illustrate the need for effective maintenance programs. For bridges, it is important that critical elements be accessible for inspection in the field.

Patterns of Repeated Failures

Patterns of repeated failures may be the most disturbing and illustrate the need for failure literacy. Many recent collapses echo earlier cases. It is often thought that the failure of the Tacoma Narrows Bridge was unprecedented, but a suspension bridge in Wheeling, West Virginia, across the Ohio River had failed in a similar manner in 1854.[17]

Quebec Bridge & Hartford Civic Center. The Quebec Bridge and Hartford Civic Center collapses have interesting parallels. In each case, dead loads were underestimated. Both represented advances in structural analysis. Both failed by the buckling of compression members, and in each case the incipient buckling was observed and dismissed long before the collapse.

2000 Commonwealth Avenue, Bailey's Crossroads & Harbor Cay. Investigations following these three collapses concluded that both design and construction errors contributed to the cause of collapse. All three failures could have been avoided if better inspections of materials and construction details were conducted.

The Bailey's Crossroads and Harbor Cay collapses resulted in twenty-five deaths and fifty-eight injuries combined.[14,22] These disasters could have been avoided if the engineers working in Virginia and Florida had learned the lessons of the 2000 Commonwealth Avenue collapse. In the words of the American poet Naomi Judd, "The first time you're a victim. After that you're a volunteer."

Lessons Learned

Many of the technical lessons learned from collapses have been incorporated into building codes. In some cases, large bodies of knowledge have grown from these cases. The Tacoma Narrows Bridge collapse generated considerable interest in both the wind tunnel testing of structures and in the mathematical tools to analyze wind effects on structures.[7] Suspension bridge deck design has since been modified to feature either a stiff truss below deck (for example, the Akashi-Kaikyo Bridge in Japan) or an aerodynamic shape (for example, the Humber Bridge in the United Kingdom). In the case of the Whitestone Bridge, which connects the Bronx and Queens and which is considered a "sister" to the Tacoma Narrows Bridge, both approaches were used after the Tacoma failure. First, stiffening, above deck trusses were constructed. More recently, the trusses have been removed and aerodynamic airfoils installed on either side of the deck.

Much of the research into the maturity method and other tools for monitoring concrete strength gain derives from the NBS (now NIST) investigations of the failures at Willow Island, Bailey's Crossroads and the Harbor Cay Condominium. Structural robustness provisions in U.S. and U.K. building codes trace back to Ronan Point.

Bridge inspection and maintenance research often looks back on the Point Pleasant and Mianus Bridge failures. Non-destructive evaluation tools such as ultrasonics, penetrants and magnetic methods are directed at finding defects in steel structures before they grow to a critical size.

Lessons Not Learned

Although many technical lessons have been absorbed, many of the procedural lessons have not. Increasingly, engineers rely on computers for routine engineering tasks. Yet, as noted in *Technology Review* about a decade ago, computers allow people to make more mistakes faster than any other human invention with the possible exception of handguns and tequila.

Better design tools do not help if they do not fix the design process. The problem with the Hyatt Regency walkway connection was not an improper design — the problem was that it was never designed, period. Engineers need to be skeptical and diligent, and they need to have a healthy understanding of the limits of engineering knowledge. It is not what is not known that gets engineers in trouble; it is what engineers know that turns out not to be true.

Expanding Failure Literacy

There is a need for all engineers, and particularly structural engineers, to be failure literate. This literacy entails knowing about the critical historical failure cases that have shaped the profession, not merely the surface technical details, but the environment, the communications difficulties and the procedural issues. It is somewhat frightening to think that for many engineering undergraduates, the Hyatt Regency walkway collapse is an event from before they were born. It is important for engineering educators to know and understand these stories, and to pass them on. It is particularly important to learn to recognize the patterns of repeated failures, and to break the cycle.

Although engineering is typically regarded as technical work, in reality it is a form of communication. Engineers communicate their vision of a structure and how it should perform through drawings and specifications. Expanding failure literacy includes understanding how errors in communication and management can be as dangerous as technical errors. Failure literacy builds a broad awareness of all of the things that can go wrong on a construction project. Awareness brings care, and hopefully that care and caution will enable the engineer and the project team to avoid future failures.

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