Construction Disasters: Design Failures, Causes, and Prevention

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In reprinting articles from *Engineering News-Record* for this book, material was occasionally omitted to avoid repetition or improve continuity. In those cases, the omitted material was replaced with ellipses (. . .).

Sometimes, relevant information such as the final death toll or cost of a disaster was made available only after the article was originally published. Sometimes, errors were noted in articles after publication. Such corrections and new facts are enclosed in brackets: [ ].

In order to present a realistic picture of the development of construction engineering over the past half-century or more, the articles reprinted here have been left in their historical contexts. McGraw-Hill policy is not to discriminate on the basis of gender. However, since the engineering profession as a whole has traditionally been dominated by men, the work of male engineers is necessarily the primary or exclusive focus of this book. No sexual bias is implied or intended.

Preface

Why *Engineering News-Record* Reports Failures

ENR policy is to report both failures and successes. We report both for the same reason: to give readers the information they need in their own businesses, so that they can avoid the failures and emulate the successes.

Every week ENR editors and correspondents report on the ingenuity of the construction industry—design innovations, clever approaches to building, new developments in materials and equipment, new ways to manage companies, coups in bidding and winning contracts. These are all success stories.

Some weeks we also have to report the failures of people and companies and the things they plan, design, make, or build: financial failures such as bankruptcy, personal failures such as crime and corruption, planning failures such as a downtown renovation that doesn't work, disasters that are caused by natural phenomena like earthquakes and floods. There are also structural failures such as dam collapses and system failures such as hotel fire-safety assignments that fall apart in a fire.

ENR pays a great deal of attention to accidents that kill and injure people—people who build as well as people who use and live or work in or near structures that fail. The importance of this attention is threefold: First, it is the responsibility of the building trades to constantly improve and refine design, as well as construction materials and methods, so as to prevent unnecessary failures and minimize damage from those that cannot be averted. Second, fatalities and injuries often receive much publicity in the general press, which adds to the pressure. Third, the expenses and legal consequences of fatalities and injuries can create serious problems for ENR readers.

In addition, ENR reports many failures that do not harm people physically—potholes, cracks in facades, leaking roofs, tunnel machine entrapments, popping windows, and so forth. We also try to dig out expert opinions or professional judgments on why these things happen. Readers frequently let us know that they expect and want us to do this. In fact, readers constantly contribute to and supplement our reporting, and many letters from readers are included in this book.

Engineering News-Record could run only upbeat stories, and success stories are usually easier to get than the truth behind the failures. But that policy would not serve readers' best interests. Our readers need to know what is really going on, and we try our best to tell them.

In this book, more than two dozen of the worst disasters of the past half century are reported in detail, using words (and often pictures) that originally appeared in the pages of ENR. The reports are often sobering. But brought together in this way, they also reveal the progress the building industry has made during those years and point to the progress it is continuing to make.

The Editors

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1 Introduction

A poorly constructed apartment house collapses in a mild earthquake in Manila, and 400 people die. An offshore drilling platform capsizes and more than 100 are lost. A little dam in Connecticut washes away and a neighborhood is inundated.

Such happenings numb the minds of the general public: so many killed here, so many maimed there, so many millions of dollars of property destroyed. For most engineers, architects, and contractors, however, the numbers are not mere statistics. The numbers leap off the pages appended to the lives of real people—not only the immediate victims, but the people who conceived, designed, and built the structures that failed.

Structural failures are remarkably uncommon, considering the number of structures standing today, and the number added every year. Nevertheless, the number of minor failures is large enough so that insurance companies report about one architectural or engineering firm out of every three is involved in a claim for financial damages *every year.* The number of highly visible, major disasters in which heavy property damage results or lives are lost is large enough so that there is hardly an engineer, architect, or contractor alive who does not personally know of a colleague who has been touched by tragedy.

This book gives details of many of the major construction disasters of the past half century. All of these disasters have led or are leading to changes in the way buildings are designed and built. Over the span of 50 years, it is remarkable how much we have learned—and how much knowledge we have applied—about fire, wind, earthquake, and the physical properties of construction materials.

Nevertheless, many patterns continue to be repeated. Our structures continue to fall prey to natural and man-made disasters. Partly this is due to unforeseen problems that have arisen as we have stretched technology to bridge wider rivers, cope with higher building costs, or build on marginal sites. Among such problems discovered in the past 50 years: wind-induced resonant vibrations that destroyed the Tacoma Narrows Bridge, lamillar tearing in welded steel joints, and reservoir-induced earthquakes behind ever-larger dams.

Careful study of such disasters has helped keep the number of recurrences

Figure 1-1 The South Canadian River Bridge on U.S. 75 near Calvin, Oklahoma, fell on May 21, 1976. Drivers of two semitrailer trucks were killed. The expansion joints at each pier apparently locked, so that all expansion and contraction accumulated at one joint. When the span "walked" off the pier at that point, it dragged other spans with it. *(United Press International.)*

remarkably low. Unfortunately, another class of problems has been less amenable to study and solution. Simply put, these are the disasters caused by the unforgiving nature of many modern construction materials and methods. Today's public, a public quite used to the wonders of technology, feels betrayed, hurt, and angry when something goes wrong—especially if the "something" interferes with the use of a highly visible object like a skyscraper or a bridge.

This public attitude has been growing slowly over the past century. James B. Eads, for example, had to go to great lengths to assure the public of the safety of his proposed great bridge at St. Louis. At the bridge's inauguration in 1874, he said, "the peculiar construction of [the bridge's superstructure] is such that any piece in it can be easily taken out and examined, and replaced or renewed, without interrupting the traffic of the bridge. . . . In completing the western span two of the lower tubes of the inside ribs near the middle of the span were injured during erection, and were actually uncoupled and taken out without any difficulty whatsoever, after the span was completed, and two new ones put in their place in a few hours."

In October 1969, a tugboat knocked away a section of the lower chord of one of the arches. There was no progressive collapse, thanks to Eads's overdesign. The gap was jacked and new structural members were inserted. In those days the construction of a great bridge was as immense and as visible an undertaking as a space shot is today. At a time when few buildings had more than 4 or 5 floors, Eads, Roebling, and their contemporaries could build structures that would take people 150 feet or higher above a river. Bridge towers—the height of a modern 20-story building—dominate early photos and prints of post-Civil War America.

Today's construction sites are rarely policed with the care of a space shot, however. Thus daring concrete structures can sometimes fall prey to a hidden flaw: poorly placed reinforcing rods. Composites find ways to corrode from within unless perfectly waterproofed. Facades and roofs fail with distressing regularity.

The public has come to expect and demand daring design, rather than to be suspicious of it. Computers have made many once-difficult calculations easy, allowing designers to reduce the thickness and strength of structural members but narrowing the margin for error in actual construction.

How many people are aware that different codes and different design practices may allow the designer to calculate needed strengths in different ways? More to the point, how many potential clients understand that a concrete beam designed under code assumptions of "ultimate strength" can cut the need for steel reinforcing by anywhere from 5 to 20 percent compared to the same beam

Figure 1-2 This overloaded loft building on Duane Street in New York City collapsed late in 1944. The facade was mass-produced cast iron, made to look like stone, which was popular in New York before the turn of the century. *(ENR File.)*

designed under "working-stress" assumptions—but that conditions may demand working-stress assumptions even if the "code authority" allows ultimate-strength design?

Likewise, how many clients understand the possibilities for error when modifying a structure that is already being occupied and used? There is hardly a report about any major disaster that does not note a myriad of minor deficiencies in design, construction, or modification of the structure involved. It is a tribute to the code writers that such deficiencies do not usually erase the margin for safety that is designed into structures that comply with codes in the first place.

Under the pressure of economics, however, those margins have been steadily reduced. How far can we go, and continue to build and use structures with old organizational forms?

"The use of such terms as 'ultimate design' for a method which is not in fact ultimate design at all, the magic of load factors, and a misleading complexity of complicated formulae do not in any way justify the extremely low safety factors. Use of computers for solutions with programs developed by some analyst who has never seen concrete only speeds up the application to further failures," said C. D. Williams, president of Southeastern Architects and Engineers, in a 1971 letter to *Engineering News-Record.*

Even when a design is adequate and capable of being built safely by average construction crews, unforeseen delays can always spell trouble. If the concrete trucks are late arriving at a continuous pour, are the workers down at the face of the last lift, shoveling out keys and trenches? Is the clever, prefabricated formwork designed so that such emergency work is even *possible?*

There are tens of thousands of parts, tens of thousands of design calculations, in even a small structure today. Those parts must be made to work together, those calculations must be constantly updated, as the work on the structure proceeds from architectural concept through engineering to detailing of working drawings (by specialists in such matters as rebar placement and steel joints) to the construction site and fabrication shop. And no matter how carefully the plans are detailed, there is hardly any structure that can be built exactly as designed. Who can imagine all the possible places in a structure where ductwork, wiring, plumbing and structural members might interfere with one another—until some hapless construction worker perched 40 feet up tries to fit some piece into a space that "isn't there"?

The solution offered by most of the experts is "better inspection." ENR put it this way in the issue of March 2, 1967:

In the long, complicated chain of events that produce a building— from the owner's first decision to build, through checking shop drawings and finally issuance of a certificate of occupancy—inspection is still the weakest link.

Figure 1-3 Many Americans consider the partial meltdown of the Three Mile Island nuclear power plant as the greatest man-made disaster of all times. Repairs to the damaged core (under the containment dome at right center in this photograph) will take at least 5 years and cost more than $1 billion. But no immediate loss of life occurred, and the accident forced electric utilities to train employees better. *(AEG.)*

Almost every week ENR reports news of one kind of failure or another, and these are, of course, the small minority of failures we hear about. Sloppy field work nullifies elaborately calculated designs too often to allow any complacency about inspection. . . .

The 1966 caisson trouble at the John Hancock Center in Chicago dramatized deficiencies in inspection. This $95-million structure was designed and its construction scheduled by the most sophisticated techniques of the industry. Its architect-engineer and contractor are among the most prominent in the U.S. Yet in one caisson foundation, designed for the tremendous load of a 100-story column, a 14-ft, earth-filled void was discovered in the 8-ft-dia concrete shaft. Its top shifted under the trivial weight of a 12-ton column section. An investigation revealed serious defects in other caissons, and the ensuing repairs and delay could cost millions of dollars— probably for lack of a pair of watchful eyes.

It would be too much to say that good inspection can be creative, but at its best, it can do more than merely insure conformance with the plans and specifications. A well-qualified inspector can catch errors in shop drawings or even design. But even in its checking function, good inspection provides insurance that more than pays for its relatively low cost.

EVOLUTION OR REVOLUTION

Basically the problem of inspection requires a reallocation of construction industry resources, and this, of course, means more money. Both types of inspection available today—by private consultants and public agencies—suffer from lack of money. Municipal and county building departments can't afford the salaries required to attract top-notch talent, and even if they could, the vast volume of construction would still overwhelm them. And the widespread refusal of owners to pay the price required for consultants' private inspection often precludes this form of inspection.

Most proposals for reform stay within the traditional structure of the industry, seeking merely to improve existing practices. They would, in effect, siphon the needed funds into inspection by legislation—state licensing of inspectors, or mandatory inspection by design engineers. Construction's perennial gadfly. New York City consulting engineer Jacob Feld, however, thinks the industry needs stronger medicine. According to Feld, the U.S. construction industry should adopt a system that has proved successful in three European countries: comprehensive structural insurance, similar to fire insurance, with a technical control bureau reviewing and inspecting all phases of construction.

INSPECTOR ELEVATOR

The recommendations of the Advisory Commission on Inter-governmental Relations, a 26-member group comprising representatives from federal, state, and municipal governments should gratify states' rights advocates: The ACIR urges a program of state licensing of inspectors, state inspector training programs, and state-set minimum requirements for building inspector staffs in all local government jurisdictions.

These proposals make sense. By raising inspector qualifications to quasiprofessional status, the states could raise the caliber and salaries of inspectors whose median salary appears to be about $7,000 [in 1983, about $20,000 for people] with up to 20 years experience. Minimum state staffing requirements for local governments would supplement quality with quantity. Since the minimum staffing requirement could place a financial burden on small towns, ACIR suggests several ways to handle the problem—such as joining with several other towns for building code administration.

A more appealing approach in one important respect, is that of cities like Phoenix, which has attempted to place the financial responsibility for inspection on building owners, where it belongs. The Phoenix building code requires a registered engineer or architect to "certify that to the best of my knowledge, the structural requirements of the approved plans for which inspection is required . . . have been complied with." The mandatory inspection should insure the engineer's getting a decent inspection. . . .

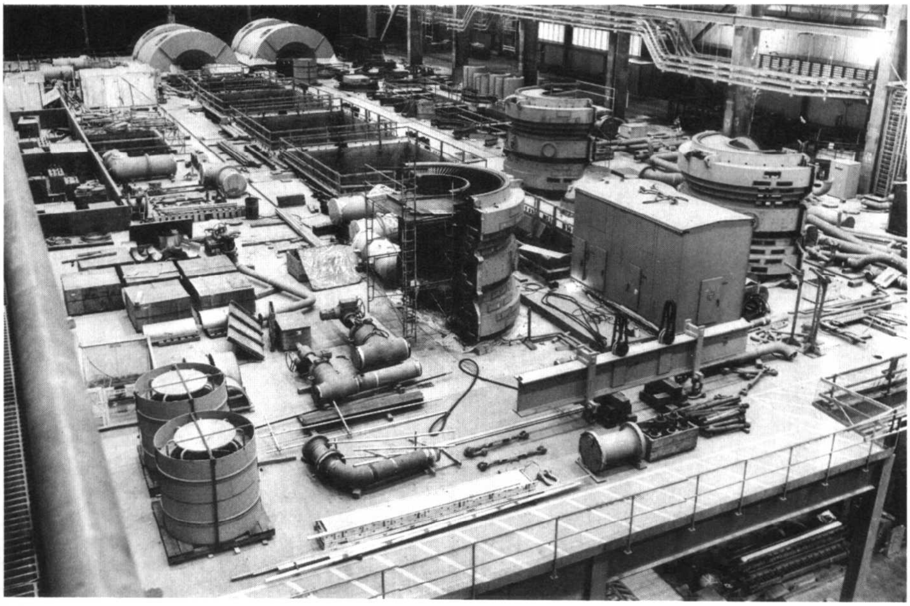

Figure 1-4 Sometimes a financial disaster—mismanagement—can hurt an industry far more than any loss of life ever could. These pipes, valves, and turbines are awaiting installation in a Washington Public Power Supply System nuclear plant that may never generate any electricity. The cost of the system's canceled plants could rise to a staggering $15 billion. *(Washington Public Power Supply System.)*

STARTING FRESH

But efforts to improve inspection quality through conventional means are mere palliatives, according to Feld, who has probably investigated more failures than anyone in the world. For some years he has tried, unsuccessfully, to interest U.S. insurance companies in offering owners the kind of comprehensive structural insurance available in France, Belgium, and Holland. In those countries, technical control bureaus financed by the insurance companies review and approve the structural design, soil testing, choice of materials, field practices and other key phases of construction. On the basis of the technical bureau's certificate of approval, insurance companies underwrite a policy insuring the owner against partial or total structural collapse for a period extending 10 years following a project's completion. This coverage includes formwork or steel erection collapses resulting from faulty construction practice as well as structural collapses resulting from poor design. Inspection fees in Belgium average about 0.9% of total cost; insurance premiums are less.

The great advantage of technical control appears to be the way it focuses responsibility. The love of money is the root of all evil, according to St. Paul, but the fear of losing it is the root of good inspection, according to Feld. Technical control bureaus represent insurance companies that must pay off in cold cash for any failure—from total collapse to minor cracking. As a natural consequence, says Feld, the inspector's greater responsibility inspires keener vision.

The French and Belgian technical control bureaus were created in response to serious construction accidents during the late 1920s. The technical control bureau appeared as a practical way of avoiding the red tape of governmental supervisory agencies, while enforcing public safety. As a private organization, the technical control bureau can proceed with an efficiency often lacking in a governmental agency.

Technical control has many other advantages, according to Feld. By the same principle that enables subcontractors with many jobs to make more efficient use of skilled workmen, technical control bureaus can make more efficient use of engineering personnel by centralizing a trained pool of technical talent.

Despite some complaints that it delays project completion, the French technical control bureau (SOCOTEC) is still growing and expanding its services. It takes on some 12,000 projects a year, representing one-third of France's total construction volume. The majority of its 11,500 employees are engineers. Now operating from 90 French branch offices, SOCOTEC is opening branch offices in Spain, and its staff skills are expanding from basic construction services—such as inspecting concrete, soils, and foundations—into such mechanical services as heating and airconditioning.

Why couldn't the consulting engineer perform this same service? Because no owner, unless he has learned from sad experience, is willing to pay the price, says Feld, and he is skeptical of mandatory inspection provisions. Public agencies generally limit inspection fees to reimbursement of "productive" inspection payroll cost plus overhead limited to 100%. They should allow for 200% added to the productive payroll, or 2½ times actual payroll costs. Properly done field supervision by a resident engineer costs more than design, drafting, and specification writing, according to Feld.

Feld is joined by Philadelphia structural engineer David Bloom in calling inspection, at best, unprofitable work. Bloom takes inspection work on his projects in self-defense, as insurance that his designs are carried out correctly in the field. Many testing laboratories retained for inspection are "inadequate, or worse," says Bloom. And even though inspection work helps in the continuing education of designers, it is not the highest use of their skills. A reliable technical control bureau could allay conscientious engineers' fears that their designs were not being executed properly.

Even apart from the obvious problem of safety, erection accidents and structural failures are inspiring increasingly complex legal difficulties, especially for architects and engineers. The unification of designer-builder responsibility offered by technical control could lighten designers' risks.

Figure 1-5 A failure of concept is evident in the half-wrecked Pruitt-Igoe public housing project in St. Louis. The impersonal superblocks became an instant slum, part of which has since been torn down. (*A* Globe-Democrat *photograph by J. M. Carrington.*)

Meanwhile, other efforts to improve inspection can continue without fear that they are being wasted in this complex task of strengthening construction's weakest link.

This call for better inspection—more time spent at the job site by better qualified personnel—has in part been heeded. But quality-assurance specialists in other industries know that it is impossible to "inspect in" quality. The whole system—from architect to builder and client—must organize itself to produce a quality product from a design that helps assure quality in the first place. Given the complexity of modern design, inspection sophistication may not have even kept pace in recent years.

But how is the change to come about? Increasingly, the courts have made designers and architects responsible for defects in the finished structure. This has been so, even though the fatal flaws often come about in the construction process and not in the design. Simply put, the architects and designers are more likely to carry heavy insurance policies. And injured employees, barred from suing their own firms because of workers compensation laws, collect the often-inadequate workers compensation insurance, then turn around and sue the

Figure 1-6 Modern construction can be remarkably immune to fire—although loss of life and damage to interior furnishings can be substantial. Here, the basic soundness of framing at 1 New York Plaza is evident after a 1970 blaze. *(Alfred H. Miller Co.)*

deepest pockets they can find. They are usually joined by the very same workers compensation insurance carrier, seeking to recover from the designer's insurance company the pittances paid to the workers.

Designers and architects, in turn, are more likely than ever before to insist upon blind conformance to the construction drawings. Is this a healthy trend? Or should the contractor be a real partner in the process of design and specification? Perhaps there should be greater emphasis on prequalifying bidders for specific jobs, especially where the design calls for construction methods that are uncommon in a given locale.

Then, at least, the builders could be made to fully understand the function of a complex joint—whether it is for expansion or to deflect moisture, whether it is in tension or compression—and not make foolish materials substitutions under the pressure of construction deadlines. Contractors could also be better trained to understand the behavior of structural members under cycling stresses, and how such stresses can induce fatigue in a structure that appears perfectly designed to withstand static loads that can be much greater.

If designers insist on absolute compliance with plans, then the plans themselves must be perfect. Yet the checking of drawings is often carried out by the lowest-level person in the shop—or is not done at all because each person in the design and construction chain assumes someone else will catch any errors.

Luckily, errors in design are often caught by the experts who are usually hired to detail the position of reinforcing rods or the stiffening of wide welded webs.

Perhaps especially critical details—details that will cause major structural damage if not built absolutely perfectly—should be marked with a special, universal symbol. One obvious class of details that could be marked this way is structural members for which there is no backup—members the failure of which will automatically cause collapse.

Clients should have to pay for as-built drawings for any reasonably complex projects, and safety systems such as fire walls and critical trusses and webs should be clearly marked on such drawings. Of course, a legal disclaimer would have to be included warning the client that modification of other things in the structure could also cause failure. But at least the biggest potential trouble spots would be flagged.

Codes must take into account the reduced safety margins being designed into modern structures. Many (if not most) building codes, for example, call for roofs to withstand a "25-year" storm. Buildings are usually meant to withstand the elements for a lot longer than a 25-year useful life. Stated another way, a 25-year storm has a 4 percent risk of occurring in any given year. No client would willingly agree to those odds. But clients and building tenants—and local

Figure 1-7 Formwork failures are among the most common of all construction disasters; formwork design is often left to nonprofessionals. This collapse occurred in Japan in 1978. *(Kyodo.)*