

STRUCTURAL FAILURES AND ENGINEERING ETHICS

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ABSTRACT: Major engineering failures act as a catalyst for change in standards of practice and therefore create the opportunity for establishing better ethical practices for the profession. When examining ethics in engineering practice, it is useful to make the distinction between ethics in engineering and ethics of engineering. Ethics in engineering deals with the ethics of actions of individual engineers. Ethics of engineering deals with ethical issues that involve the role of engineers in industry, the ethics of the organizations in which they work and of professional engineering societies, and the ethical responsibilities of the profession. This paper presents case studies of two major structural disasters—the 1907 Quebec Bridge collapse and the 1981 Kansas City, Mo. Hyatt Regency walkway failure. The effect of each failure on engineering ethics is examined from the viewpoint of both ethics in engineering and of ethics of engineering. In response to failures, engineers need to change professional procedures and practices so that they reinforce, rather than place obstacles in the way of, moral action.

INTRODUCTION

Failures as Opportunity for Learning

Failures play an important role in the evolution of engineering (Petroski 1982). The first objective of engineering is to avoid failure. However, when a major collapse occurs, it can be studied to learn to avoid critical conditions that led to that type of failure. Just the fact that a failure occurs does not automatically mean that anything will be learned from it. Learning from failure requires both introspection, in the form of a failure analysis, and communication, the critical element in prevention of related failures. A failure analysis must be performed so the cause of the failure is understood. After this investigation, the results must be communicated to the appropriate people, namely those who will avoid future failures by applying the knowledge gained from the failure analysis.

Failures can be linked to the advance of technology in cases where an innovative design goes beyond the boundaries of existing knowledge. Pushing the edges of technology too hard to make something longer, taller, or bigger than has ever been done before can lead to failure when something about the working of the new, but untested, design is not as anticipated. Understanding technical failures is a means of expanding and correcting the range of proven designs. However, there are many reasons for failure other than lack of technology. Although the technical knowledge exists, the individual who should be applying it in a particular case may be ignorant of crucial information. The complexity of the project plays a role. Procedures may allow or encourage communication breakdowns. Resources that are financial, ethical, or managerial may be inadequate. Sources of failure thus not only lie in the technical realm but are also rooted in institutional, organizational, and industrial practices.

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Ethical Effect of Failures

It is useful to make a distinction between ethics in engineering and ethics of engineering (DeGeorge, unpublished 1989). Ethics in engineering addresses the ethics of actions of individual engineers. Ethics of engineering deals with ethical issues that involve the role of engineers in industry, the ethics of the organizations in which they work as well as of professional engineering societies, and the ethical responsibilities of the profession. Reactions to major failures can affect both types of engineering ethics.

The traditional approach to ethics focuses on the moral actions of the individual (ethics in engineering). This focus neglects the social fabric within which the individual acts (ethics of engineering). An examination of that fabric is necessary to determine what social forms are conducive to an individual's accepting moral responsibility and fulfilling moral obligations (DeGeorge 1986). Analysis of an engineering failure examines the technical causes and the decisions of specific engineers that engendered those structural failures. The analysis is incomplete without an examination of the standards of professional practice within which those engineers acted. It is only from this broader study that an understanding can be gained of how the system may be restructured to prevent recurrence of similar cases.

Major engineering failures act as a catalyst for change in standards of practice and therefore create the opportunity for establishing better ethical practices for the profession. This paper presents case studies of two major structural disasters, the 1907 Quebec Bridge collapse (Roddis 1991) and the 1981 Kansas City (Mo.) Hyatt Regency walkway failure (Roddis 1987). Each case study (1) Summarizes the events leading up to the collapse; (2) presents the technical failure sources and the decisions of the engineers involved, which lead to those weaknesses; and (3) considers the reaction of the engineering profession and the institutional changes that were instigated as a direct or indirect consequence of the failure. The effect of each failure on engineering ethics is examined from both the viewpoint of ethics in engineering and of ethics of engineering.

QUEBEC BRIDGE

The 1907 Quebec Bridge collapse provides a fruitful opportunity for a case study in engineering ethics that provides a view of how some aspects of current standards of practice in structural engineering arose in response to this disaster. The Quebec Bridge, forming a major link in the Canadian railway system, was designed to be the longest cantilever bridge in the world. The bridge, crossing the St. Lawrence River about 14 km (9 mi) north of Quebec, had a main span of 548.6 m (1,800 ft), composed of a pair of 171.5 m (562.5 ft) cantilever arms supporting a 205.7-m (675-ft) suspended span ("The Fall" 1907). The suspended span was to be constructed by cantilevering the north and south halves out over the crossing, joining the span in the middle, and finally freeing the ends of the suspended span for rotation. This construction sequence had been successfully used in 1889 on the 521.2-m (1,710-ft) spans of the Firth of Forth Railway Bridge in Scotland. Fig. 1 shows the bridge in 1907 with the south anchor and cantilever arms completed. The temporary construction tower shown at the end of the cantilever arm is for support of the suspended span panels during erection. On the afternoon of August 28, 1907, while the fourth panel of the southern portion of the suspended span was being erected, the entire 17-million-kg (19,000-ton) south superstructure collapsed, killing 82 workers. Fig. 2 shows the superstructure in ruins. The collapse occurred in about 15 s, but there

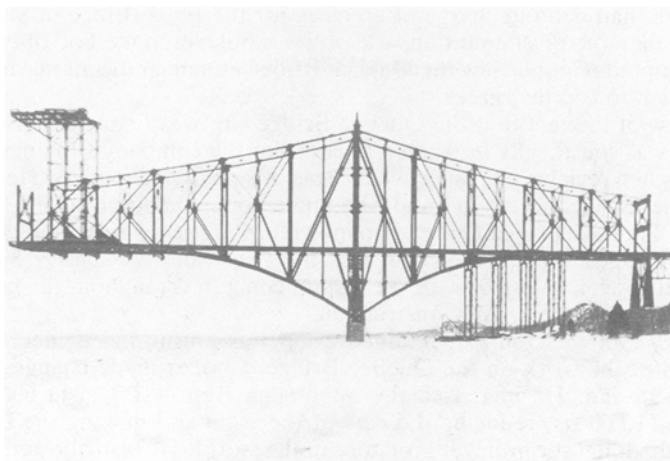


FIG. 1. Quebec Bridge: South Anchor and Cantilever Arms Complete (Photo Courtesy Smithsonian Institution, National Museum of American History)



FIG. 2. Quebec Bridge: Aftermath of Collapse (Photo Courtesy Smithsonian Institution, National Museum of American History)

had been a 10-year prelude setting the conditions that lead to the failure (Tarkov 1986).

Events Leading to Collapse

In 1897, a consulting engineer, Theodore Cooper, expressed interest in becoming a design consultant to the Quebec Bridge Co. Cooper was a highly respected and successful structural engineer with many major bridges to his

credit. He had been in charge of erection for the Eads Bridge in St. Louis in 1873, then the most ambitious use of the cantilevered method of erection yet attempted. Cooper saw the Quebec Bridge as a magnificent masterwork with which to cap his career.

In view of the fact that the Quebec Bridge Co. was financially troubled, Cooper was specifically instructed to consider the company's financial constraints when reviewing prospective contractor's plans and tenders. He clearly had these fiscal concerns in mind when he recommended on June 23, 1899, that the Phoenix Bridge Co. of Phoenixville, Pa., be awarded the contract as their proposed cantilever plan was the "best and cheapest." Severely limited financial resources were a constant concern throughout the progress of design, fabrication, and construction.

In May 1900 the company retained Cooper as consulting engineer for the duration of the work on the Quebec Bridge. Cooper made changes to the Phoenix design. He increased the main span from 487.7 m (1,600 ft) to 548.6 m (1,800 ft), reducing the cost of the piers and making the Quebec Bridge the longest cantilever structure in the world. He also allowed higher unit stresses to be used in design, setting working stresses for both tension and compression members at an extreme value of 165 MPa (24 ksi) well beyond contemporary standard practice. The unprecedented size of the bridge and high unit stresses indicated the need for preliminary tests and research studies. With the exception of some eyebar testing, which Phoenix performed only at the insistence of Cooper ("Theodore Cooper" 1907; Cooper 1906), none were ever conducted.

With knowledge of the revised specifications, it would have been prudent to initiate redesign work so that the extensive calculation and drawing preparation required could be executed in a timely manner. Indeed, Cooper urged Phoenix to do so. However, from 1900 to 1903, while construction of the substructure, anchorages, and approach spans proceeded, no further design work was done on the superstructure. The reason for this lack of action by Phoenix can be attributed to the financial problems of the Quebec Bridge Co. Phoenix simply did not wish to make expenditures that it was not certain could be recovered. It was not until 1903 that Phoenix entered into a contract with the company, after the Canadian government guaranteed a bond issue to pay for the work. Even at this time, dead weights were not recalculated based on the revised specifications and research testing was not undertaken. Cooper's engineering expertise became the sole factor that was relied upon for assuring structural integrity of the bridge.

In his role as consulting engineer, Cooper did not force Phoenix to perform recalculations and required few tests. In fact, he demanded full technical control and blocked an attempt by the chief engineer of the Canadian Department of Railways and Canals to have drawings independently reviewed in 1903. Cooper made his third and last trip to the bridge site in May of 1903, before work began on the superstructure. He regarded on-site visits as unproductive. In 1904 he made it clear to the company that he would not visit the site during erection, submitted a pro forma resignation, but easily allowed himself to be persuaded not to resign. Work on the superstructure began at the end of summer 1904 and initially progressed smoothly. In 1905 Cooper assigned Norman McLure, a recently graduated engineer, as his on-site representative. This resulted in a construction situation where, for a cantilever structure of unprecedented span, no one on site had sufficient engineering authority and experience, leaving all signif-

icant questions to be referred to Cooper in his distant office in New York City.

The first indications of major trouble arose in February 1906 (*Quebec* 1908). Correspondence between Peter Szlapka, the chief design engineer for the Phoenix Bridge Co. and Cooper made clear that the bridge members were designed using Phoenix's original theoretical weights from 1898, which underestimated the actual weight of the structure by about 17%. This caused an increase in calculated stresses of approximately 10%. Cooper approved the higher stresses, a further increase over and above his previously established high allowable values.

Work progressed satisfactorily at the site until summer 1907, when the consequences of the high compressive stresses began appearing in the actual structure. Signs of progressive collapse were observed in the form of distortion of compression members throughout August 1907. By August 27, the anchor arm west truss compression chord in the second shoreward panel from the south pier, member A9L, had reached a distortion of 57 mm (2.25 in.) out of its 17.15-m (56.25-ft) length. As Cooper himself stated later ("Theodore Cooper" 1907), any intelligent person should have been able to recognize the gravity of the situation at this point. Unfortunately, those who were sufficiently concerned about the signs of buckling failure, including both McLure, the inspector for the consulting engineer, and Kinloch, the inspector for Hoare, chief engineer of the Quebec Bridge Co., lacked authority to stop work and take action to remedy the problem. On August 28, Hoare dispatched McLure to New York to consult with Cooper. It was at Hoare's direction that work was restarted on the imperiled structure. When Cooper conferred with McLure on August 29 he telegraphed his instruction to Phoenix, not to the bridge site, to "add no more load to bridge till after due consideration of facts." Phoenix did not transmit this information to the construction site. The bridge collapsed that afternoon.

Technical Causes

The technical cause of the Quebec Bridge collapse as established by the Royal Commission of Inquiry (*Quebec* 1908) was the failure of two compression chords. The east and west compression chords (members A9L and A9R) of the anchor arm in the second shoreward panel from the south pier failed virtually simultaneously. The chords, designed to carry a load of 97,900 kN (22,000 kips) were built-up sections with overall dimensions approximately 1.37 m (4.5 ft) deep and 1.68 m (5.5 ft) wide. Four massive vertical plate webs were each made up of four rolled plates, stitch-riveted together to form one built-up plate almost 101.6 mm (4 in.) thick. The middle plates were spaced about 0.31 m (1 ft) apart with the outer plates spaced almost 0.61 m (2 ft) from the inner plates. Lattice angles were riveted across the top and bottom faces of the built-up member in a double-lacing X pattern. The lacing was intended to tie the compression member together into a single element so that the compressive buckling strength could be based on the geometric stiffness of the integrated elements, rather than the vastly smaller buckling strength of the web plates acting individually. The 12.6-kg/m (8.5 lb/ft) angles used for the latticing were inadequate to preclude buckling of the individual column elements on a member with a cross section of 0.504 m² (781 sq in.) weighing 3,959 kg/m (2,658 lb/ft) ("The Quebec" 1907). These compression members failed, either by rupture of their latticing or shearing of their lattice rivets. The design of the latticing for these massive members was based on empirical formulas based on column tests conducted

20 years earlier on columns of far smaller scale. In spite of the capability of Phoenix to test more appropriate specimens, no effort was made during the design to undertake tests to justify this extrapolation of previous practice far beyond its proven range.

Professional Responsibility

The Royal Commission of Inquiry (*Quebec* 1908) assigned responsibility for the failure in unequivocal terms to the consulting engineer, Theodore Cooper, and the chief design engineer, Peter Szlapka. Errors in judgment on the part of these two engineers that contributed to the collapse included a cavalier attitude toward site inspection, use of an usually high allowable stress without sound technical justification, inaccurate dead-weight calculations, and selection of a design concept beyond the technically proven range without any attempt at establishing its feasibility by research and testing.

What led Cooper and Szlapka, two technically skilled and experienced bridge engineers, to commit such serious errors of judgment? From Cooper's statement to the Commission of Inquiry ("Theodore Cooper" 1907), it appears that he became caught between the diametrically opposed personal goals of limiting time and travel commitments due to deterioration of his health and capping his career with supreme technical charge of such a masterwork. Szlapka seems to have been technically competent but he was unable to undertake prudent engineering actions that ran counter to the desire of the business interest of Phoenix to minimize costs. This was particularly apparent when Szlapka allowed Phoenix to claim consistently during construction that compression members that were showing signs of buckling under load had actually been delivered to the site in an initially kinked condition. This fallacy was maintained even in the face of evidence by the site inspectors that the distortions were growing under added stresses.

Reaction of Engineering Profession

The engineering community reacted with grief and shock to news of the great disaster ("The Greatest" 1907). It was immediately recognized that a serious blow had been struck to public confidence in the whole engineering profession. Initial attention focused on determining the cause and suspicion rapidly fell on the probability of "failure of some compression member in the anchor arm of the cantilever" and on member A9L in particular ("The Quebec" 1907). As the contemporary engineering profession saw it, "the question of supreme interest to the engineer is not the primary one of what member failed first, or the legal one of why work was continued regardless of these evidences of distress, but why the chords were distressed at all, why they behaved as they did" ("Editorial" 1907).

A collective lack of knowledge was confessed by the engineering community with regard to the behavior of long steel columns of exceptional size. The focus was thus on a failure involving an advance of technology where the size of the built-up compression members pushed them beyond the boundaries of existing knowledge. Some attention was given to the possibility of undue pressure exerted on the consulting engineer by the bridge's promoters and the bridge building company [a possibility that Cooper denied ("Theodore Cooper" 1907)]. However, the failure analysis primarily focused on actions of individual engineers with relatively little attention given to the professional organization context of those actions.

Institutional Changes

The most direct change that was made in response to the collapse was the restructuring of the Quebec Bridge design team (Giroux et al. 1987) when beginning the second attempt to complete the Quebec Bridge. The main lesson was the danger of relying solely on the judgment of one engineer, no matter how distinguished, and the need for a managing body able to place capable individuals in critical positions, with adequate communication guaranteed. For the second attempt, the Canadian government took over the project, providing the sorely needed sound financial foundation. A board of three experienced engineers of various backgrounds was appointed under the supervision of the Department of Railways and Canals. On the two occasions when the board was unable to reach a unanimous decision on an important issue, the department called in two additional engineers. In spite of these precautions, the second Quebec Bridge also suffered a construction disaster. In summer 1916 failure of a casting caused the prefabricated centerspan to fall during jacking operations, killing 11. The second Quebec Bridge, still the longest cantilever bridge in the world, was successfully completed in 1917.

Several months after the collapse of the first Quebec Bridge, students from McGill and Laval universities made an excursion to the ruins. The lesson they gathered from the debris went beyond the purely technical. In 1926 Canadian engineers founded the Ritual of the Calling of an Engineer, a formal commitment to high ethics in engineering. Most engineers graduating in Canada take part in this ceremony, pledging to practice engineering with honor, diligence, and care. The Order of the Engineering is a much more recently founded (1970) U.S. organization. In a similar vein, ASCE adopted its first code of ethics in 1914.

The American Association of State Highway and Transportation Officials (AASHTO) was formed in 1914, and the American Institute for Steel Construction (AISC) was founded in 1921. Although the formation of AASHTO and AISC was not connected to the Quebec Bridge disaster, the existence of these institutions changed the professional environment in ways that would have made the disaster less likely. These institutions provide a mechanism for funding industry research without requiring a single company to shoulder the entire research cost. The institutions also promulgate codes for steel design, fabrication, and construction.

The jointly financed research funded by AISC would have been one way to address concern about compression member behavior. Stability of columns continued to be an area of concern for the engineering profession well after the Quebec disaster. Column design was based on empirically derived formulas fitted to test results. It was not until the 1950s that the Column Research Council (now the Structural Stability Research Council) put column design on a firm theoretical footing by recognizing that the tangent modulus was the proper strength criteria and that residual stress played an important and quantifiable role (Salmon and Johnson 1990).

AISC also has promulgated codes for steel design fabrication and construction since 1923. These codes are organizational schemes in which a number of expert opinions are given weight. Design codes are sometimes criticized as stifling innovation, but when properly used they are a powerful means of disseminating expertise distilled from vast quantities of experience. Existence of a code for bridge design would have been a means to address concern about the unusually high allowable stresses set by a single individual.

Engineering Ethics

Ethics in Engineering

Ethics in engineering addresses the ethics of actions of individual engineers. The actions of Cooper, Szlapka, and Hoare all fail to measure up to high standards. Cooper took pride in being in technical charge of such a great work, but did not resign when he became unable to carry out the necessary responsibilities associated with his position of ultimate technical authority. Szlapka erroneously placed his obligation to his company's financial well-being above his professional duty to ensure integrity of the structure. Hoare held a position for which he did not have the technical competence and thus decided to continue work on a structure whose collapse was imminent. Improving the standards of ethics in engineering must answer the question of how to get individual engineers to act more ethically. The personal ethical pledge of the Ritual of the Calling of an Engineer is an example of changes to ethics in engineering in response to the Quebec failure.

Ethics of Engineering

To look only at the individual reasons for the failure of engineering judgment on the part of Cooper and Szlapka would miss the more broadly applicable organizational lessons to be learned from the Quebec disaster. Restructuring the form of the Quebec Bridge design team and the formation of professional societies such as AISC are examples of changes to ethics of engineering in response to the Quebec failure. The Code of Ethics of ASCE, while largely setting ethical guidelines for engineers acting individually, exemplifies ethics of engineering, defining standards that apply broadly to the engineering profession.

KANSAS CITY HYATT REGENCY WALKWAY

The 1981 Kansas City Hyatt Regency Walkway collapse is a more recent case study in engineering ethics, which sheds light on current standards of practice in the area of structural steel connections. The general layout of the Hyatt Regency Hotel in Kansas City uses an atrium forming a spacious open lobby to join the guest tower on the north with the function block on the south. As shown in Fig. 3, the four-story open lobby was crossed by three open walkways, each 36.6 m (120 ft) long. The second-level walkway was directly under the fourth-level walkway, while the third level was offset by about 4.6 m (15 ft). Each walkway was suspended by six steel rods, 31.75 mm (1.25 in.) in diameter. The rods for the third-level walkway were connected to the roof framing. The second-level rods were attached to the fourth level, which was in turn supported by the roof framing. On Friday evening, July 17, 1981, during a dance contest in the Hyatt Regency lobby, the supports for two of the lobby's suspended walkways gave way. One of these supports is shown circled in Fig. 3. There were 1,500–2,000 people in the lobby on the floor, balconies, and walkways. Witnesses reported a loud crack as the fourth level buckled into three sections and fell along with the second-level walkway. More than 50,000 kg (100,000 lb) of debris, and the spectators on the walkways, fell onto the dancers below (Marshall et al. 1982). One hundred fourteen people were killed and 185 more were injured, many seriously. This was the worst structural failure, in terms of loss of life, that had ever occurred in the United States (Marshall et al. 1982).

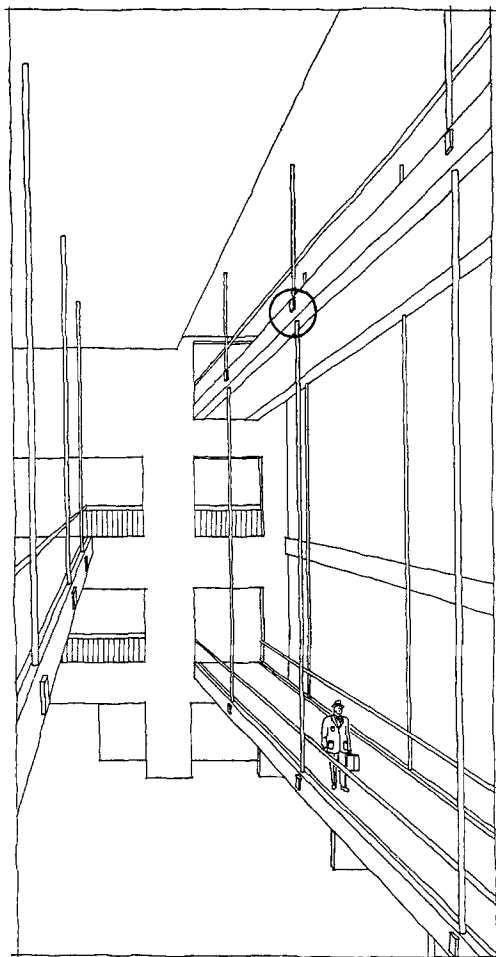


FIG. 3. Kansas City Hyatt Regency Hotel: Schematic of Walkways as Viewed from North Wall of Atrium [Courtesy National Institute of Standards and Technology (Marshall et al. 1982)]

Events Leading to Collapse

The design of the Hyatt Regency Hotel began in early 1976 (Deutsch 1985). The architect heading up the design team was Patty Berkebile Nelson Duncan Monroe Lefebvre, a joint venture of three Kansas City architectural firms: Patty Berkebile Nelson Associates Architects, Inc.; Duncan Architects, Inc.; and Monroe and Lefebvre Architects, Inc. Gillum-Colaco, Inc. became the consulting structural engineer in July 1976. Gillum-Colaco subcontracted all structural engineering services for this project to Jack D. Gillum & Associates, Ltd. Jack D. Gillum, president of Jack D. Gillum & Associates, was the professional engineer and Daniel M. Duncan, an associate of that firm, was the project engineer. The general contractor heading up the construction team was Eldridge & Sons Construction Co. of Kansas City. Havens Steel Co. of Kansas City became the structural steel

fabricator and erector for the atrium steel in December 1978. Production of shop drawings for the atrium steel was subcontracted by Havens to an outside detailing firm. The structural engineer and the steel fabricator and erector were the key participants for the structural steel aspects of the atrium.

The structural engineer prepared preliminary design drawings for the walkways showing design criteria, including design loads. A preliminary engineering sketch prepared by Duncan showed a strength of 413 MPa (60 ksi) for the walkway hanger rods. This material strength was not shown on the final structural drawings for the rods. The rods actually provided had a strength of 248 MPa (36 ksi) as specified in the general notes of the structural drawings and, as a result, the 31.75-m (1.25-in.) diameter hanger rods used on the walkways were insufficient to meet the requirements of the Kansas City building code. Critical members of the walkway support system were thus underdesigned without even considering the issue of connections.

The hanger rods were connected to box sections that were the cross beams of the walkway floor framing. The original configuration of this connection is shown in Fig. 4 on the left as a continuous single-rod connection. These box sections were made of channel sections placed toe to toe. The structural drawings for the walkways show a detail of the box-beam-hanger-rod connection. The rod passed through the centerline of the box beam. The load from the box beam was transferred into the rod by a nut on the rod below the box beam. The rod was shown threaded to accommodate this nut. No loads are shown on this connection detail nor on its accompanying framing plans. Since no loads were given, the detailer interpreted this connection as a special connection designed by the structural engineer and copied the configuration shown on the structural drawing detail to the shop drawings with the addition of a standard nut and washer and a minimum weld to hold the channels in alignment for erection. This connection as detailed used no bearing plates or stiffeners and was inadequate to meet the requirements of the Kansas City building code.

The detail of the box-beam hanger rod connection shown on the structural drawings for the walkways was intended to be typical for all such walkway connections. However, this detail shows the rod terminating below the walkway. This is not the case for the fourth-floor walkway since the rods were intended by both the architect and the engineer to be continued down to the second-floor walkway, although this was not shown on the structural

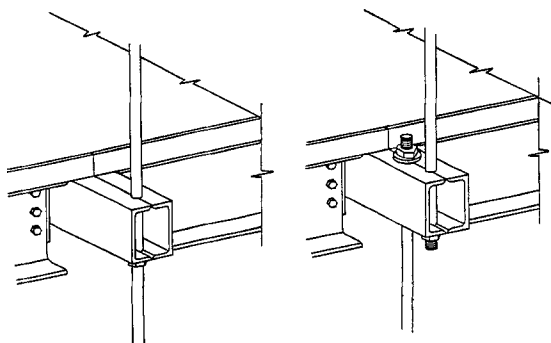


FIG. 4. Kansas City Hyatt Regency Hotel: Comparison of Continuous and Interrupted Hanger-Rod Details [Courtesy National Institute of Standards and Technology (Marshall et al. 1982)]

drawings. In the course of detailing the steel for the atrium, questions arose as to the connection of the rod at the fourth floor and whether the rod must be continuous. After telephone conversations between the structural engineer, the fabricator, and the detailer, a change was made in the fourth-floor hanger rod to box-beam connection from a one-rod to a two-rod arrangement. The revised configuration of this connection is shown in Fig. 4 on the right as an interrupted two-rod connection. This change essentially doubled the load that had to be transferred from the box beam into the upper-hanger rod at the fourth-floor walkway connection. The shop drawings were prepared using this two-rod configuration, and the unassembled components of the connection were shown on the shop drawings. No sketch was included on the shop drawings of the assembled connection in its revised form. The shop drawings were sent to the structural engineer for review and approval. The structural engineer did not review the revised detail for conformity with the design concept nor for compliance with the requirements of the Kansas City building code. The shop drawings were stamped by the structural engineer indicating review only for conformity with the design concept and compliance with the contract documents. The revised two-rod connection was structurally inadequate to support the loads imposed on it.

Two years earlier, in October 1979, more than 250 m² (2,700 sq ft) of the atrium roof collapsed because of the failure of one of the roof connections due to improper installation of a steel-to-concrete connection and lack of expansion capability. Following this collapse, the owner retained another structural engineering firm to investigate the cause and perform a design check of the atrium roof. Investigation work was also done by Jack D. Gillum & Associates and was billed as separate services to the owner. The owner and architect understood that the entire atrium structure was reviewed as part of this effort while the design check actually included only the roof and steel-to-concrete connections, but not the walkways and associated connections. No further changes were made to the walkway connections and construction proceeded. Approximately one year after the opening of the hotel, the walkways collapsed.

Technical Causes

At the time of the collapse, the fourth-floor rods remained attached to the roof. Therefore, attention focused immediately on a possible failure at the fourth-level rod connection. A plausible technical cause—namely, improperly built hanging supports for the walks—was thus quickly hypothesized. The ensuing analysis of the failure by the National Bureau of Standards (NBS) concluded that the most probable cause of failure was indeed insufficient load capacity of the box beam-hanger rod connections (Marshall et al. 1982). The mandate given to NBS was to conduct an impartial and thorough investigation with the objective of finding the technical cause of the failure, but not to determine who was at fault. The outcome was that two factors contributed to the collapse: (a) The original connection design did not satisfy the Kansas City building code; and (b) the design change doubled the load on this inadequate connection. The conclusions of this comprehensive study completed seven months after the collapse include the following points (Marshall et al. 1982):

- The collapse initiated at a fourth-floor box-beam–hanger-rod connection.

- The loads on the walkways at the time of collapse were substantially less than the Kansas City building code specified design loads.
- The as-constructed beam-rod connection did not meet code, nor did the original (continuous rod) detail.
- The change in rod detail essentially doubled the transfer load.
- Neither quality of workmanship nor materials played a significant role in initiation of the collapse.

Professional Responsibility

In contrast to the rapid and conclusive technical investigation, assignment of responsibility for the error was a slow and debatable process. The legal proceedings to identify the responsible parties were long, complicated, and contradictory. The legal process was used for three purposes: (1) To award damages to the injured and the heirs of the dead; (2) to find if criminal law had been violated; and (3) to find if civil law had been violated. The damages awarded to victims and their heirs, in class-action and individual suits and out-of-court settlements, amounted to several times the \$50,000,000 million cost of building the entire structure (Ross 1984). There were various courts with jurisdiction for the case at the local, state, and federal levels. After 20 months of investigation, the U.S. attorney and the Jackson County, Mo., prosecutor found no evidence of criminality associated with the Hyatt failure. The attorney general of Missouri, on the other hand, charged the engineers with negligence in 1983 (Petroski 1982). However, a grand jury in Kansas City did not issue indictments for criminal negligence due to lack of evidence ("Hyatt" 1985).

In 1984, the Missouri Board for Architects, Professional Engineers and Land Surveyors brought civil charges of gross negligence and misconduct against the structural engineering firm and the two engineers who were in charge of the structural design, Daniel M. Duncan, the project engineer, and Jack D. Gillum, the engineer of record. The decision found the firm and both engineers guilty of gross negligence, misconduct, and unprofessional conduct in the practice of engineering (Deutsch 1985). The engineers were subject to suspension or revocation of their Missouri professional engineer registration. Thus in contrast with the seven months needed to determine the technical cause, over four years passed before a legal ruling assigned fault. This ruling is likely to remain the only legal declaration of blame for the Hyatt tragedy ("Hyatt" 1985).

Reaction of Engineering Profession

Investigations into the collapse began immediately ("Hotel" 1981; "Walkway" 1981). Multiple investigations were initiated by the owner, the architectural consortium, the operator, the structural engineer, the contractor, and various law firms representing the victims. The city of Kansas City organized two investigations: a team from NBS commenced the technical investigation; and a team made up of four prominent local engineers and an attorney undertook the task of deriving lessons to prevent future failures. This second team was thus an immediate, conscious attempt at professional introspection to learn from the tragedy.

The reaction of the engineering community, as with the public at large, was horror and regret at the loss of life and extensive injuries. As with the Quebec Bridge collapse, initial attention focused on determining the technical cause and interest was directed at the rod-beam connection and its design history. Comments were made on the impracticality of the original

design with a nut occurring 6.1 m (20 ft) up a continuous rod (Stevens 1981) and on the lack of use of sleeve nuts. Discussion also pointed out the problems caused by the thin webs and the apparent lack of adequate change-of-design procedures (Sawyer and Lewis 1981). When the results of the NBS investigation were announced, prevailing opinion was that government investigations are valuable and justified due to the need for impartiality and public availability of the conclusions.

Following the early focus on the technical cause, discussion of the failure within the engineering community entered a second phase concerned with the broad professional implications of the event. The need for improved performance was recognized, especially in the areas of detailing and connections, fee levels, and building envelope design and construction (the great majority of claims for building jobs involve wind and water penetration of roofs and facades) ("Structural" 1981, "Building" 1982). Broader implications of the failure that were mentioned (Leonards 1983) include the recognition that structural detailing needs more attention in routine design practice and engineering education, and that structural schemes that lack redundancy demand an especially thorough design and careful review.

Institutional Changes

One change that has occurred within the structural engineering profession is an increased awareness of the importance of structural details. This awareness extends beyond the specific type of rod-beam connection and highlights the importance of careful review of all novel connections and the value of redundant load paths.

The failure also has led to a sustained increase in professional dialogue concerning broad professional issues such as legal costs of failure, professional liability, insurance, professional responsibility, project quality assurance, and professionalism in civil engineering. This increased discussion is evident in a variety of engineering forums such as journals, periodicals, and conferences, where these topics have been addressed with a higher frequency in the decade since the Hyatt collapse than they had been in the immediately preceding years. Some of this professional dialogue was organized and encouraged by ASCE in direct response to the Hyatt failure. A roundtable discussion on public safety and professional responsibility was convened and a series of workshops widely distributed the results of the roundtable discussion. These workshops also provided a mechanism to allow Judge James B. Deutsch to explain his decision and its implication to a broad segment of the concerned engineering community. ASCE also made explicit efforts to institutionalize this increased awareness of the consequences and prevention of structural failures. Ed Pfrang, the engineer who had headed the NBS investigation, was hired as the new executive director of ASCE ("Pfrang" 1983). ASCE formed two new committees on forensic engineering and engineering performance investigation and informally surveyed its members for direction on the Society's appropriate role in failure cases (Haines 1983).

To address the need for more study of structural failures and more widespread dissemination of the findings, ASCE encouraged formation of a national Architectural and Engineering Performance Information Center (AEPIC), which was opened in July 1982 at the University of Maryland ("Structural" 1982). Unfortunately, AEPIC has not been viable due to lack of data and funds.

A report was prepared by the Task Committee on Design Responsibility of the Professional Practice Division and published by ASCE to provide

clear recommendations on the responsibility for design of steel structures (Final 1985). This report addressed the perceived problem of lack of clarity of responsibility for the design of steel connections and recommended guidelines. Key provisions include:

- The engineer of record (EOR) should have responsibility and authority for all aspects of the structural design, including the connections. Connections should either be designed or reviewed and approved by the EOR.
- The EOR should have sufficient time and compensation to prepare design drawings and to review and approve shop drawings in order to produce safe structures.
- The design drawings should provide sufficient information for the fabricator to produce correct shop drawings.

In a more wide-reaching effort at providing clear guidelines on standards of practice, ASCE has prepared and published a manual describing a desirable process, from conception through design and construction to operations start-up, for delivery of a quality constructed project (*Quality* 1990).

Engineering Ethics

Ethics in Engineering

To examine the ethics of actions of individuals in the Hyatt case, the legal process investigating the professional behavior of the engineers is most informative (Deutsch 1985). The Missouri Board of Architects, Professional Engineers and Land Surveyors charged the head of the structural engineering firm, Gillum, and the project engineer, Duncan, with incompetence, gross negligence, misconduct, and unprofessional conduct in the practice of engineering. Within this context, incompetence is the lack of ability to perform a given duty, gross negligence is acting with conscious indifference to a professional duty, misconduct is intentional wrong doing, and unprofessional conduct is violating or failing to comply with the provisions of the licensing statute. The ruling found cause for discipline under the licensing statute to suspend or revoke the certificates of registration of the two engineers and the certificate of authority of the firm for gross negligence, misconduct, and unprofessional conduct in the practice of engineering.

No finding of incompetence was made, since the engineers were found to be fully capable of performing their duties in a skillful manner.

Duncan was found to have been grossly negligent in the practice of engineering since, as a competent and qualified professional engineer, he knew or should have known that the design of the rod-beam connection was the responsibility of the engineer of record, yet he never did nor caused to have done any such design. In addition, he failed to perform the professionally and contractually required shop-drawing review. Gillum, as the engineer of record, was responsible for the acts and omissions of Duncan and thus also was found grossly negligent. Gillum was also found to be individually negligent for allowing his stamp to be placed on drawings he had not reviewed nor assured himself that someone else had reviewed.

Duncan was subject to discipline for misconduct in the practice of engineering since he materially misrepresented to the architects that the revised double-rod hanger-beam connection was structurally safe and sound. Gillum, responsible for the acts and omissions of Duncan, was thus also guilty

of misconduct as well as individually guilty of misconduct for failing to review the atrium design when specifically requested to do so and for misrepresenting that such a review had been done.

Duncan was not found guilty of unprofessional conduct. Gillum was found to be guilty of unprofessional conduct in the practice of engineering since he failed and refused to take responsibility for the structural integrity of the project as required by statute.

Ethics of Engineering

To see the role of ethics of the engineering profession in this case, the professional context within which the events leading to the Hyatt failure took place must be examined. The central issue is the responsibility for design of steel-to-steel connections. Briefly, the historical development of design responsibility in this area is as follows (Deutsch 1985). Up to the Second World War, rivets were the predominant means of making connections in steel buildings and engineers designed the entire steel structure, including connections. In the postwar era, steel building technology advanced and various forms of bolted and welded connections became common. Each fabrication shop was able to deliver more economically a certain subset of these technically feasible connections. To allow the owner to benefit from the most economical steel fabrication and erection bid, including connections, the custom of structural engineering changed so that steel fabricators designed some or all of a building's connections. The structural engineer retained control over the choice of which connections were to be designed by the fabricator and which were fully designed on the structural drawings. The structural engineer also retained final say on the connection design through review and approval of the shop drawings.

On this final point, some debate existed in the structural engineering profession at the time of the design of the Hyatt, and indeed continues to exist. There are different points of view within the engineering profession as to the scope of work and responsibility of the structural engineer for connections which are designed on the shop drawings. The argument Gillum and Duncan made was that the structural engineer was not responsible for connections designed on the shop drawings. The administrative judge did not find this to be a convincing argument, stating that such a view was not reasonable and that the engineer of record is responsible for the integrity of the structure as required by the professional engineering licensing statute. Indeed, the judge went so far as to condemn the argument claiming the existence of a professional debate over responsibility for design of connections, stating, "Such 'debate' is no more than an intramural competition between those interested in maintaining ethical professional standards and those who are interested in achieving convenience and financial benefit." Regardless of the judge's opinion, such debate does exist and in reaction to the Hyatt failure many in the profession criticized current practice, stating "the system we have today tends to confuse responsibility rather than pinpoint it" (Dahlem 1982). An experienced detailer expressed the opinion "much of the basic problem will remain because of the system" (Beckley 1982). *Engineering News-Record* ran an article describing the Hyatt ruling under the curious heading "Hyatt Engineers Found 'Guilty' of Negligence" (1985). The quotes around the word *guilty* are indicative of the confusion regarding responsibility within the profession.

Such a system that confuses responsibility makes it more difficult for individual engineers to practice ethically. This is clearly a case where changes

in standards of practice are required, so the ethics of engineering encourages ethical behavior on the part of individuals instead of creating obstructions. It was for precisely these reasons that ASCE produced its report on responsibility for design of steel structures emphasizing the design of steel-to-steel connections (*Final* 1985). To address the broader area of the engineer's role throughout design and construction, the *Quality in the Constructed Project* manual (1990) was produced. These documents outline clear practices that would strengthen the ethics of engineering. Neither has had as much influence on day-to-day engineering practices as is desirable. It is easy to identify the need for a clear focus of professional responsibility for structural integrity. But to achieve realistically high professional standards, compensation must be commensurate with the work expected. Unfortunately, the fee levels dictated by the marketplace show that professional responsibility is not commensurate with monetary rewards. This practice does not look promising for encouraging future high levels of professionalism in the field of structural engineering as practiced in the general building industry.

CONCLUSIONS

Failures play an important role in the evolution of engineering. When a major collapse occurs, it can be studied to learn how to avoid the critical points leading to that type of failure and to make future successes possible. This necessitates extensive intradisciplinary dialog in the aftermath of catastrophic structural failures, making use of multiple communication paths, spreading awareness of the discussion, and sustaining professional introspection and communication over a duration of years.

Catastrophic events directly and indirectly serve as an influence for change in the civil engineering profession. These changes go beyond the technical lessons of the collapses and influence the formation of institutions directed at strengthening both individual and collective ethical structures. The structural engineering profession has been very successful in making changes to standards of practice that depend on adoption by individual engineers or by the engineering profession as a self-determining community. The profession has been less successful at instigating changes that require adoption by those outside the engineering community especially with regard to establishing equitable fee standards.

To attain ethical practice within a profession, an individualistic approach to good morals is not enough. The structures of the profession (practices, procedures, institutions) must be conducive to an individual's accepting moral responsibility and fulfilling moral obligations (DeGeorge 1986). Major failures act as a catalyst for change in standards of practice. Resulting changes in ethics of engineering can be far more effective in preventing future disasters than changes limited to ethics in engineering. In response to failure, engineers need to change professional practice so that those in engineering can act morally by design rather than by accident. To paraphrase a philosopher of professional ethics (DeGeorge 1986), we must have moral engineers if we are to have moral engineering. But that is only half the truth. We must also have professional procedures and practices that reinforce, rather than place obstacles in the way of, moral action.

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