ENGINEERING PROCESS FAILURE—HYATT WALKWAY COLLAPSE

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ABSTRACT: Was the collapse of the Hyatt hotel atrium walkway a senseless tragedy or a steppingstone in the betterment of the engineering and scientific endeavor? The collapse claimed 114 lives, leading to a great public and professional outcry and having a dramatic impact on the careers and lives of many fine professionals. The architecture and engineering (A&E) community in the United States began a soul-searching debate on issues as diverse as how project workflow is managed to professional responsibility and ethics. Fundamental errors were identified in the project interaction within the A&E group as well as the construction industry. This review provides a presentation of the demand-capacity ratio within elements primary to the failure and presents results of detailed inelastic analysis of the box girder-to-hanger rod connection. The collapse occurred simply because of the doubling of the load on the connection resulting from an ill-considered change of an ill-defined structural detail. How this error was produced, and how any minor additional effort might have substantially improved the connection capacity, is addressed herein.

INTRODUCTION

That the progress of engineering is associated with setbacks caused by failures is an assertion well documented throughout the history of human endeavor. In recent history, mechanical, transportation, and finally aerospace engineers have provided numerous proofs to this theorem. The problems introduced by powerful machinery developed in the steam age, and by the high pressure, high temperature boilers needed to propel them, challenged mechanical engineers. Innumerous workers lost their lives, and thousands of disabilities were caused in the period of refinement of the technology of pressure vessels and propelling and transmission systems. Eventually, an entirely new engineering discipline was developed to deal with the protective guarding of workers against moving and rotating machinery systems. The steam turbine, a key element of a majority of electrical power plants, required metallurgist and mechanical engineers to work in a joint effort to address the combination of high stresses and high temperature. However, even today, with all the spectacular advances in thermodynamics, finite-element analysis, fatigue and fracture mechanics, and metallurgy, a turbine failure is still the main threat to modern power plant operation.

Transportation vehicle production evolved in the last two centuries from craftsmanship to a technological challenge involving virtually every engineering discipline taught in a modern university curriculum. In the nineteenth century, the locomotive ‘‘shrank the world’’ by connecting the most remote areas within Eurasia, the Americas, and the Indian subcontinent. The steamer narrowed the vast water gaps between continents. It is seldom remembered that boiler explosions and fires were the key enemies of those vessels. In the twentieth century, the process continued, accelerated by the combustion and electrical engine. The automobile and airplane became the standard means of transportation. Each step in the process was paved with failures, often claiming a significant cost in human lives.

The automobile provided flexibility and versatility, which led to entrusting the complex and powerful machinery into the hands of hundreds of millions of often ill-prepared individuals. The battlefield of today’s highways can only be compared with the most ferocious wars fought by humanity. The scientific and engineering community strives to respond to the challenge of providing faster, cheaper, easier, and less expensive to operate equipment with the ever-growing demand for improved user and public safety. The sophistication of the power-train in today’s automobile exceeds that of a recent airplane. Many of the materials used to build a modern car are the result of recent defense research and development carried out by national laboratories. The crush protection system of the automobile evolved from a rigid bumper to a complex energy absorption mechanism aided by seat belts and air cushions. No sooner is each of these marvelous safety improvements introduced, though, than the engineer and scientist are challenged by a new safety question. Each of the new technological and safety steps is paved with stories of dramatic failures, providing sensational news to public-excitement-driven journalism. Examples are the abdominal injuries caused by early seat belts, the front-seat child suffocation caused by air cushions, and the reliability in response of the ABS braking systems that nearly eliminated skidding at emergency braking. And just as mechanical failures began declining, a new class of failures became a priority: failures in protection of the environment.

Civil engineers and architecture have applied the iterative approach to innovation since time immemorial, as documented relatively recently by the short life of early Gothic cathedrals that preceded the mastering of flying buttresses and arches; long span truss bridge collapses before questions of stability were harnessed, e.g., Quebec Bridge; and the collapse of the Tacoma Narrows suspended bridge as a result of insufficient understanding of aerodynamic effects on the structure (Petroski 1995). In construction, introduction of new techniques of shoring and flying formwork and rapid pumping of concrete led to dramatic failures due to premature loading of fresh concrete (Feld and Carper 1997). In Bridgeport, Connecticut, a construction failure took place while the very efficient lift-slab construction technique was being used (Moncarz et al. 1992), nearly eliminating this technique from use. The 1994 Northridge, California, earthquake caused fractures of welded beam-to-column connections in hundreds of steel frame buildings in the Los Angeles area (Moncarz et al. 1999), sending the entire industry back to the research laboratory and the drafting board. All are examples of iterative implementation of design improvements and the resulting failure of advanced technological concepts.

The 1981 Kansas City Hyatt walkway collapse did not happen as a result of innovative design, construction, or material use, but rather as a result of the accumulation of project management errors that together allowed a fatal construction detail flaw to be installed into the support system of the sky-bridges

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crossing the hotel atrium. Questions of what happened, how it could happen, and the lessons learned, are the subject of this and the accompanying contemporary papers (Gillum 2000; Luth 2000; Pfatteicher 2000). This tragic event has previously been discussed in numerous books and papers. Steven S. Ross, summary of journalistic reports and readers' correspondence (Ross 1984) provides good insight on the broad impact the collapse had on the professional community. Dov Kaminetzky's book views the collapse in terms of the errors in design/construction (Kaminetzky 1991). The summary of the Administrative Hearings on the case (Administrative 1984) emphasizes in great detail the lack of rigorous process checks in design and construction document production and approval and flow in the chain of command and responsibility in the system.

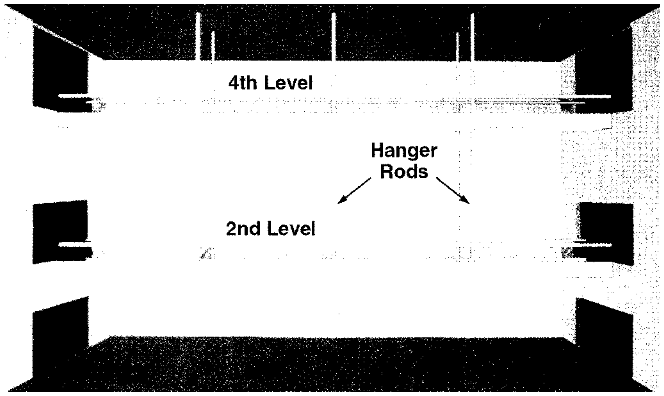


FIG. 1. Two Suspended Walkways Spanning Hotel Atrium

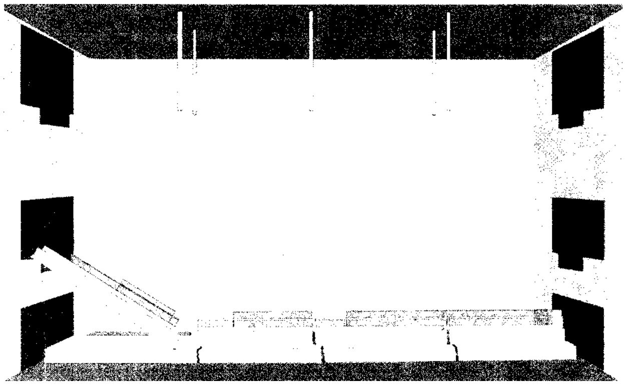


FIG. 2. Hotel Atrium after Collapse of Two Walkways

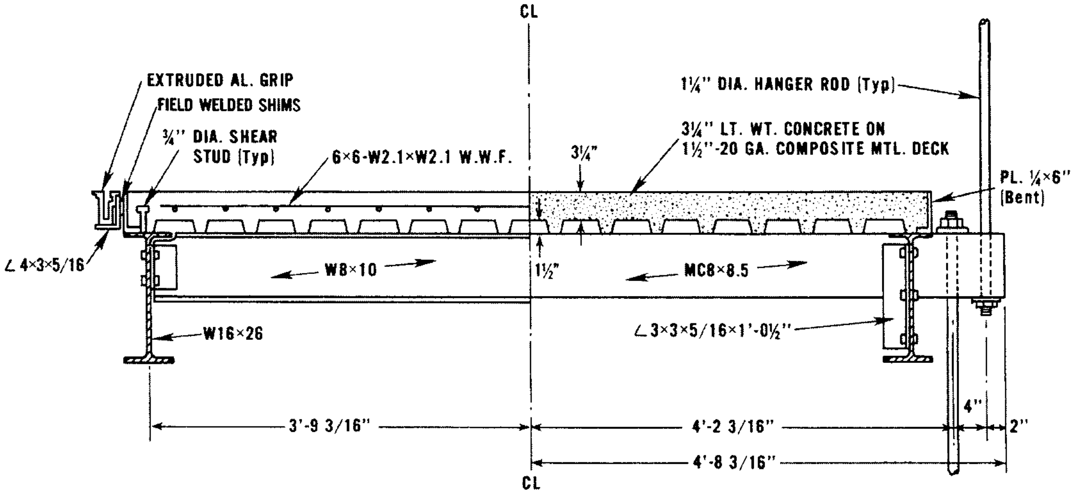
This paper emphasizes the engineering aspects of the failure and, in particular, the critical connection and the loading conditions.

THE STRUCTURE

The era of elegant modern public structures in the late 1970s and 1980s was certainly well appreciated among Hyatt hotel owners and their architects. The 1981 newly opened Kansas City Hyatt Regency Hotel was a prime example. The functional block and the hotel tower were connected by a 26 m (87 ft) wide by 37 m (120 ft) long atrium. Dramatic effect was provided by a multi-story glass curtain wall enclosing one side of the atrium, and by three pedestrian walkways spanning it while suspended from the roof. Two of the three bridges were located above each other at the second and fourth floor; the third was offset and parallel to them at the third floor level. Each bridge was supported at the ends and at equidistant intervals by three pairs of hangers suspended from roof trusses. The two bridges (Fig. 1) located in the same vertical plane shared the roof truss connection. Fig. 2 shows schematically the atrium after their collapse.

Fig. 3 provides a typical transverse section of the walkway deck. The deck was formed of lightweight concrete placed over a corrugated metal deck and was supported by two longitudinal I-beam stringers, W16 × 26, which in turn transferred the weight of the bridge and the superimposed live load to three transverse box beams per bridge. The transverse beams were assembled of two welded flange-to-flange channel sections, MC8 × 8.5. The 32 mm (1 1/4 in.) diameter hangers passed through a hole in the channel flanges and carried the weight transferred by them through a nut and washer installed on the threaded hanger underneath the girder. For the bridges positioned in the same vertical plane (Fig. 1), the lower and upper bridges were suspended by the hanger attachment to the roof truss. Thus, the upper hanger carried the loads of both bridges, whereas the lower hanger carried only the load of the lower bridge. The contact area between the hanger rod washer and weld at the toe of the channels (Fig. 3) was ground down for flatness, thus further reducing the connection between the channel flanges.

The initial drawing of the walkway support showed a continuous rod running from the bottom of and through the lower bridge box beam, through the upper bridge box beam, to the roof truss connection. Under each bridge box beam, a washer and a threaded nut were envisioned for the load transfer between the beam and the hanger rod. As testified by the construction contractor, this detail of continuous threading of the



SECTION AT CROSS BEAM

SECTION AT BOX BEAM

FIG. 3. Typical Transverse Section of Walkway

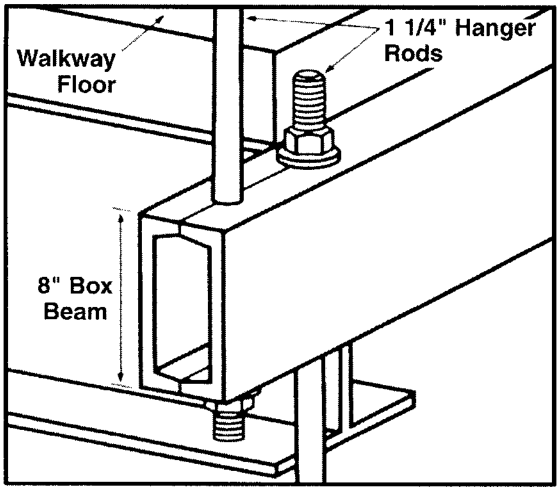
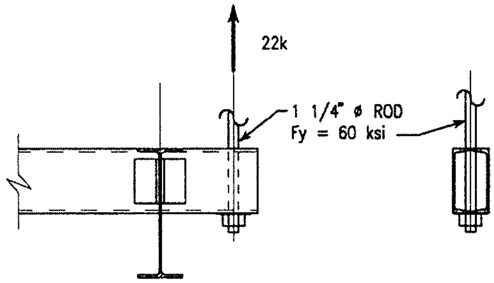
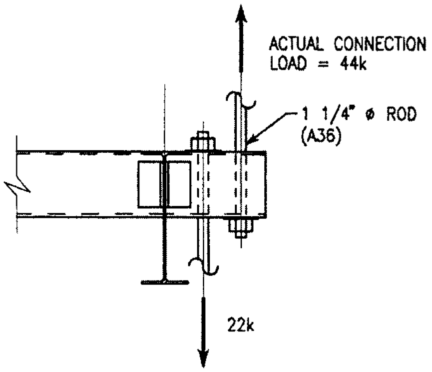


FIG. 4. As-Built Connection



Engineers Sketch



As-Built

FIG. 5. Fatal Connection Evolution

nut through two stories seemed to be highly impractical. Thus, the contractor suggested a change to the drawing whereby each single hanger rod would be replaced by two rods: one going from the lower to the upper bridge, the second going from the upper bridge to the roof truss (Fig. 4). The dramatic impact of this change is shown in Fig. 5. The loads transferred through the contact between the upper bridge box beam and the nut and washer assembly had approximately doubled in the new arrangement. Instead of the force being equal to the tributary load of the upper bridge only, it became the sum of the tributary portion of both the upper and lower bridges.

THE FAILURE

On July 17, 1981, a tea dance was held in the atrium of the hotel. Over 1,000 guests were present on the ground floor of the atrium. Some 56 persons were present on the lower bridge and 7 were on the upper bridge at the time of the collapse. The music was conducive to rhythmic motion. Suddenly, the upper suspension rods pulled through the upper bridge box beam connections and both the walkways came crushing down on top of each other and on top of the public below, 114 people lost their lives and 180 were injured. Rescue and investigative teams rushed to the scene. The basic technical question of how it happened was easy to answer after viewing the conditions of the upper bridge to suspension rod connections: the suspension rod pulled through the connection (Fig. 6), allowing the 60-ton structures to crash to the floor and land on each other, with people trapped in between and underneath. Seemingly undamaged top hanger rods with attached nuts and bolts were hanging from the roof of the atrium. Procedural questions of why it happened would be the subject of numerous speculations, studies, and reports. Credit for the most accurate first-cut answer goes to journalists of the *Kansas City Star* and their consultants. Credit for the most extensive technical study goes to the National Bureau of Standards (NBS) (Marshall et al. 1982).

Failure Analysis Associates, Inc., was retained by the project's architect to perform an independent investigation of the collapse. The team arrived at the site within hours. The analysis started almost immediately. Collection of evidence by thorough measurements and documentation was the first step; numerical analysis followed. The writers, under the leadership of Dr. Roger McCarthy, undertook complex analyses to determine how the failure progressed through the structure and how the individual elements of the bridge-to-suspension hanger rod connection impacted the capacity of the connection.

STRUCTURAL EVALUATION

The failure of the connection between the hanger rod and the box girder is well documented through the physical evidence. The deformed end-connections of the upper bridge box beams clearly indicate hanger pullout. The east side rods (in the foreground of Fig. 1) suspended from the ceiling of the atrium were straight and vertical after the failure, while the west side rods had an inclination. This suggested hanger pullout initiation on the east side of the upper bridge. The central of the three east side connections showed the most symmet-

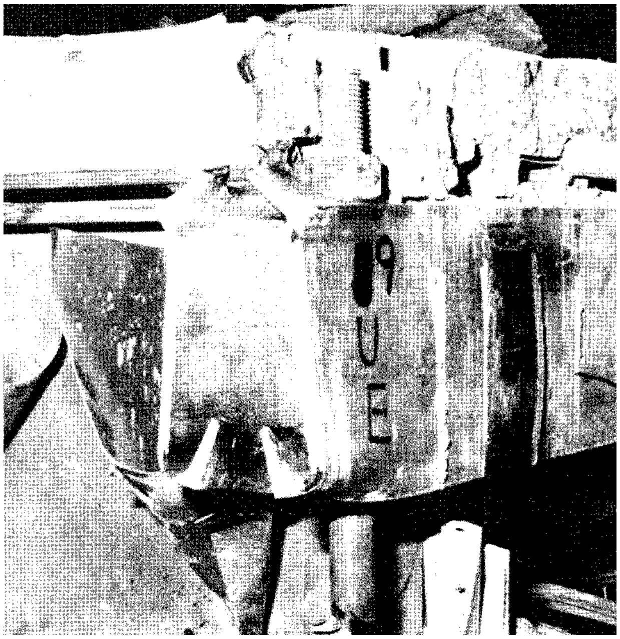


FIG. 6. Box-Beam Connection after Pull-Out of Top Suspension Rod

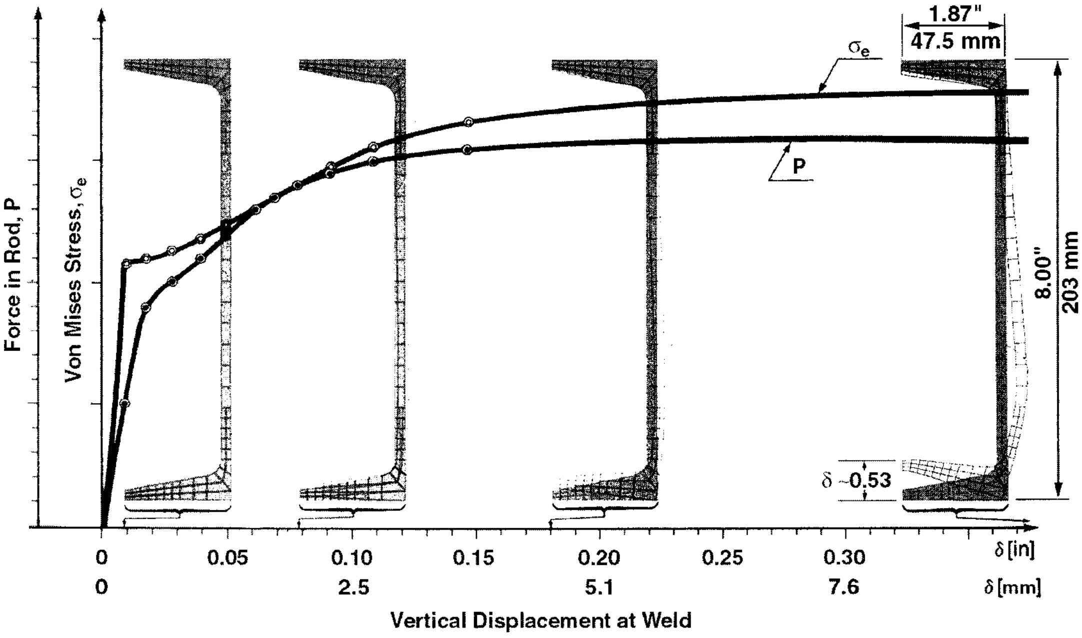


FIG. 7. Summary of FEA of Box Beam Showing Small Displacement at Large Plastic Deformations

rical deformations, suggesting the initiation of the collapse at the central, east connection of the upper bridge.

While the key contributor to the failure—the change of the end connection detail as depicted in Fig. 5—was quickly identified, significant effort was expanded to quantify the effect of other existing or potential contribution causes. Initial discussions speculated as to the impact of vibrations caused by the onlookers standing on the bridges and rhythmically moving to the tune of the music. Questions were raised as to the importance of additional concrete used in leveling the floor of the walkway, the size and quality of the box beam flange weld connection, and even the strength of the washers under the nuts.

Based on available video and photographic evidence (Marshall et al. 1982) at the time of collapse, 7 persons were present on the upper bridge and 56 persons on the lower bridge. Based on the tributary area and approximate locations of the people present on the bridge, the top east-south hanger carried the weight of 18 persons (about 13.3 kN, or 3,000 lbs), the east-central hanger carried the weight of 15 persons, and the east-north hanger of 9.5 persons. Thus the live load at the time of collapse was significantly below the design live load of approximately 106.7 kN (24,000 lbs). The average structural weight per top hanger was about 85.4 kN (18,600 lbs); thus, the additional force caused by the weight of the people present on the bridges at the time of collapse was very minor. Yet it must have been this additional minor weight that was "the straw that broke the camel's back." No other explanation exists as to why the walkway survived in place until this, small as it was, loading took place.

The capacity of the end-connection of the box beams was studied experimentally by NBS (Marshall et al. 1982), and through finite-element analysis by the writers of this paper. NBS's testing resulted in an ultimate connection strength of approximately 85.4 kN (18.600 lbs) for the measured dimensions of the bridge connections with an upper 95% confidence limit of 91.6 kN (20,600 lbs). This value is in sharp contrast with the design value of 97.9 kN (22,000 lbs) indicated by the engineer on the revised detail. Therefore, the connection was already at failure with only the dead load.

With such a high level of overstress, a significant plastic deformation of the connection is expected. The reason why that deformation was not observed prior to the collapse is apparent from the summary of the finite-element study by the writers of this paper presented in Fig. 7. At the dead load level the plastic deformation of the channel flanges of 3–6 mm (0.10–0.15 in.) was present. This magnitude of deformation could not be observed without disassembling the connection and measuring the deformation against a straight edge. Observation was impractical, since the steel construction was covered by finish and fireproofing.

Both the experimental and analytical studies showed minimal impact on the ultimate capacity of the connection by the weld size in the as-configured construction detail. The finite-element analysis showed the importance of the channel flange stiffness to the stresses that led to the failure. The obvious indication is that the addition of a plate between the flanges of the channels and the washer could have successfully addressed this problem by stiffening the channel bottom.

Study of the design process, as discussed by Luth (2000), indicates a failure in communication at the transfer of responsibilities for the design of specific elements of the structure from one design/detailing team to the next. The project, while being a fast-track one, experienced several changes of professionals working on its specific elements. This combination of fast-track and design team changes has proven to be detrimental to the project quality.

Conclusions

- The collapse of the Hyatt Regency walkways was the result of a flaw in the design process control. However, the postfailure investigation efforts concentrated on design procedures and not on the process. It can well be argued that no clear industry-wide accepted definition of responsibilities existed at the time the hotel was designed and built. This argument might yet be applied to the next catastrophic failure. However, it is to be hoped that, as with the other major engineering failures mentioned in the introduction of this paper, the Hyatt collapse has also contributed to improvement in public safety and in the quality of built facilities by promoting a more advanced set of rules governing the design/construction process.
- The Hyatt walkway collapse was a direct result of doubling the load on the suspension hanger rod-to-box beam connections through a change in the construction detail.
- The connection prior to the fatal change did not meet the

design load requirements and would have been in violation of existing codes.

- The connection after the change was at the verge of collapse even without the addition of the live load.
- The workmanship had a minor impact on the connection capacity when compared with the strength demand force level.
- Minor changes in the connection assemblage could have greatly improved the capacity of the connection, thus decreasing the potential for failure.

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