determinate and indeterminate, as well as those that are not properly restrained. To be stable, structures must have enough supports, and they must be properly arranged, to prevent movement. If not, collapse is possible.

Not all of the topics discussed on this list lend themselves easily to demonstration through failure case studies. However, some representative cases are discussed in this chapter, and others appear in other chapters.

Topics in a dynamics course include particle kinetics and kinematics and rigid-body kinetics and kinematics. *Kinematics* is the study of the geometry of motion, whereas *kinetics* analyzes forces that cause motion. Kinetics problems (both particle and rigid-body) may be analyzed using methods of force and acceleration, work and energy, or impulse and momentum. An important application is impact forces acting on structures and machines, using impulse-momentum methods along with coefficients of restitution.

The study of vibrations may or may not be included in a dynamics course. Vibrations are important for mechanical systems, as well as for structures. Excessive vibration is a serviceability issue that is often related to poor performance.

Hyatt Regency Walkway

Every civil engineer should be familiar with the circumstances of the Hyatt Regency walkway collapse. It is a landmark case, both because of the number of people killed and injured and because of the effect on the engineering profession. Although it has been extensively studied, doubts remain as to whether the key lessons have in fact been learned.

Design and Construction

In July 1980, the Hyatt Regency Crown Center in Kansas City, Missouri, opened to the public after four years of design and construction. A 40-story tower, an atrium, and a function block housing all of the hotel's services, combined to form this impressive building. Three walkways spanned the 37-m (120-ft) distance between the tower and the function block. The front of the building is shown in Fig. 2-1.

The walkways were suspended from the atrium's ceiling by six 32-mm (1¼-in.) diameter hanger rods. The second-floor walkway, directly below the fourth-floor walkway, was suspended from the beams of the fourth-floor walkway, and the third- and fourth-floor walkways hung from the

Figure 2-1. The Kansas City Hyatt Regency exterior.
Courtesy National Bureau of Standards/National Institute of Standards and Technology.

ceiling (Feld and Carper 1997, p. 216). The walkways before the collapse are shown in Fig. 2-2.

The erection of this hotel, however, had not been without incident. During construction, the atrium roof collapsed as a result of inadequate provision for movement in the expansion joint and improper installation of a steel-to-concrete connection. Concerned about the building's structural integrity, the owner hired another engineering firm to investigate the collapse and check the roof design. The consulting structural engineering company also rechecked all of the connections and found nothing to cause alarm. Construction resumed, and the hotel opened a little less than two years later (Roddis 1993, p. 1549). The expansion joint that failed was similar to one in the Pittsburgh Convention Center, which is discussed in Chapter 6.

Collapse

On the evening of July 17, 1981, between 1,500 and 2,000 people were on the atrium floor and on the suspended walkways to see a local

Figure 2-2. The Kansas City Hyatt Regency atrium walkways.
Courtesy National Bureau of Standards/National Institute of Standards and Technology.

radio station's dance competition (Feld and Carper 1997, pp. 214–215). At 7:05 P.M., a loud crack echoed throughout the building, and the second- and fourth-floor walkways crashed to the ground, killing 114 people and injuring more than 200 others. It was the worst structural failure in the history of the United States (Levy and Salvadori 1992, p. 224). The scene of the collapse is shown in Fig. 2-3.

Two weeks later, *Newsweek* reported,

> Flags flew at half mast throughout Kansas City last week, and funeral processions wound through the streets. Outside the Hyatt Regency Hotel, where 111 people died in the collapse of two aerial walkways two weeks ago, "No Trespassing" signs barred the curious and the morbid. Inside, a fine dust covered the floor, and a few balloons clung wanly to the ceiling. But the wreckage was gone, trucked to a nearby warehouse, and the sole remaining "sky bridge" had been dismantled. With investigators arriving daily and lawyers lining up to file suits, the city was beginning to come to grips with a tragedy that may not have

Figure 2-3. Scene of the Kansas City Hyatt Regency collapse.
Photo provided by Wiss, Janney, Elstner Associates, Inc. (WJE).

ended yet: 81 victims still lay in hospitals, 8 of them on the critical list. (McGrath and Foote 1981)

Causes of Failure

Upon investigation, the National Bureau of Standards (then the NBS, now the National Institute of Standards and Technology or NIST) discovered that the technical cause of this collapse was quite simple: The hanger rod pulled through the box beam, causing the connection supporting the fourth-floor walkway to fail. If the structural system had been redundant, with alternate load paths, it would have been possible for the other hanger rods to hold the walkways up. However, the other rods could not handle the increased load once the adjacent rod failed. Because of this lack of redundancy, this failure caused the collapse of both walkways. The NBS report was careful about not assigning blame, to preserve cooperation with the various litigating parties (Ross 1984, p. 402).

Originally, the second- and fourth-floor walkways were to be suspended from the same rod (Fig. 2-4a) and held in place by nuts. The preliminary design sketches contained a note specifying a strength of 413 MPa

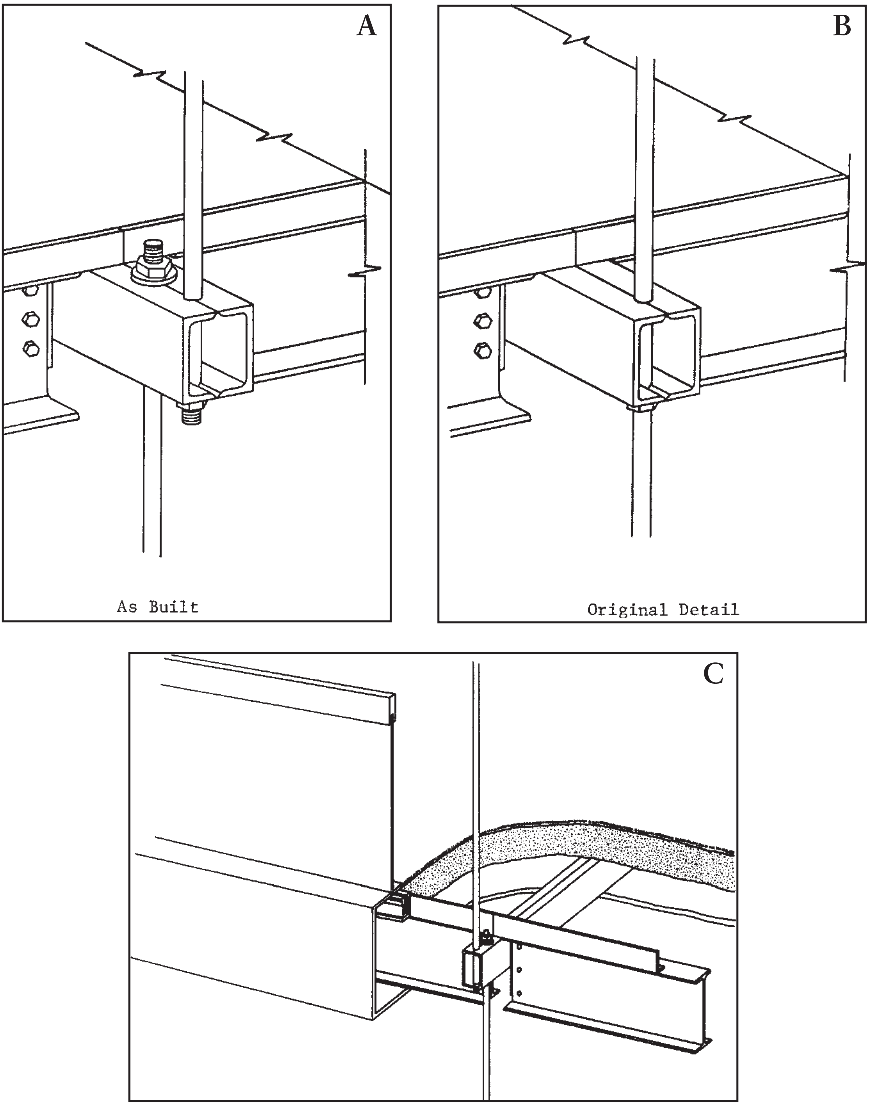

Figure 2-4. Original and as-built hanger details a, b, c.
Courtesy National Bureau of Standards/National Institute of Standards and Technology.

(60 kip/in.^{2}) for the hanger rods, which was omitted on the final structural drawings. Following the general notes in the absence of a specification on the drawing, the contractor used hanger rods with only 248 MPa (36 kip/in.^{2}) of strength.

This original design, however, was impractical because it called for a nut 20 ft (6.1 m) up the hanger rod and did not use sleeve nuts. The contractor modified this detail to use two hanger rods instead of one (Fig. 2-4b), and the engineer approved the design change without checking it. This design change doubled the stress exerted on the nut under the fourth-floor beam. Now this nut supported the weight of two walkways instead of just one (Roddis 1993, p. 1548). Figure 2-4c shows how the connection was integrated with the rest of the walkway. It was concealed and could not be easily inspected.

Moncarz and Taylor (2000) discussed the structural system in detail and analyzed the demand-to-capacity ratios of the components. Their firm, Failure Analysis Associates, had been retained by the project architect. Each walkway was made of lightweight concrete on metal decking, supported by longitudinal I-beam W 16 × 26 stringers. The designation "W 16 × 26" means an I-shaped wide flange section, 16 in. (406 mm) deep and weighing 26 lb per linear foot (mass 38.7 kg per linear meter). The transverse beams were each made of two MC 8 × 8.5 channels, welded toe to toe to form a box. A channel shape designated as MC 8 × 8.5 is 8 in. (203 mm) deep and weighs 8.5 lb per linear foot (mass 12.7 kg per linear meter). Holes were drilled through the welds to hold the support rods. The bearing area for the hanger rod washer was flattened by grinding, further reducing capacity (Moncarz and Taylor 2000, p. 47). The failed fourth-floor beam is shown in Fig. 2-5, and the hanger rod is shown in Fig. 2-6.

Failure Analysis Associates carried out sophisticated computer modeling (finite element) analysis of the box beam connection. The connection was near failure with dead load only, and an additional live load of 7 people on the upper bridge and 56 on the lower bridge proved to be enough to trigger failure. Plastic deformation of the box beam was estimated at 3–6 mm (0.12–0.24 in.), which was hidden by the finish and fireproofing materials (Moncarz and Taylor 2000, p. 49). The third-floor beam, which did not fail, is shown in Fig. 2-7. This box beam showed substantial permanent deformation.

Analysis of these two details revealed that the original design of the rod hanger connection would have supported 90 kN (20,000 lb), only 60% of the 151 kN (34,000 lb) required by the Kansas City building code. Even if the details had not been modified, the rod hanger connection would have violated building standards. As built, however, the connection only supported 30% of the minimum load, which explains why the walkways collapsed at well below maximum load (Feld and Carper 1997, pp. 218–222). The NBS built and tested a full-scale mock-up to simulate the failure and found that the static effects were much more significant than the dynamic effects (Kaminetzky 1991, p. 219).

Figure 2-5. Failed fourth-floor beam.
Courtesy Lee Lowery, Texas A&M University.

Figure 2-6. Hanger rod.
Courtesy Lee Lowery, Texas A&M University.

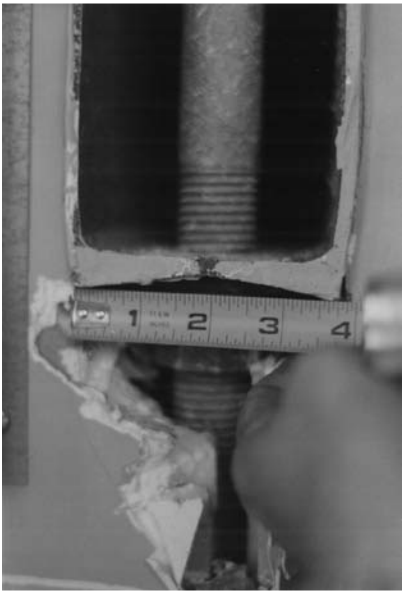

Figure 2-7. Third-floor beam showing deformation.
Courtesy Lee Lowery, Texas A&M University.

Events Leading Up to the Collapse

Luth (2000) details the steps in the design and construction process. He makes the important point that the critical connection was never designed and that the view represented by Fig. 2-4 was never drawn until after the failure. Luth's illustration of the various stages in the history of the connection is shown in Fig. 2-8.

At the time of the collapse, Luth was a recent graduate working at the firm that performed the Hyatt Regency's structural design. Luth's figures and tables illustrating the sequence of events are of particular interest. He notes that

> The project design was performed under the "fast track" method of delivery that came into vogue in the latter part of the 1970s. As with many projects delivered by this method, construction preceded design, structural design preceded architectural design, and both the design and construction phases were plagued by a lack of time and quality control. Thrown into the mix were multiple changes in personnel on both the construction and design sides. (Luth 2000, p. 51)

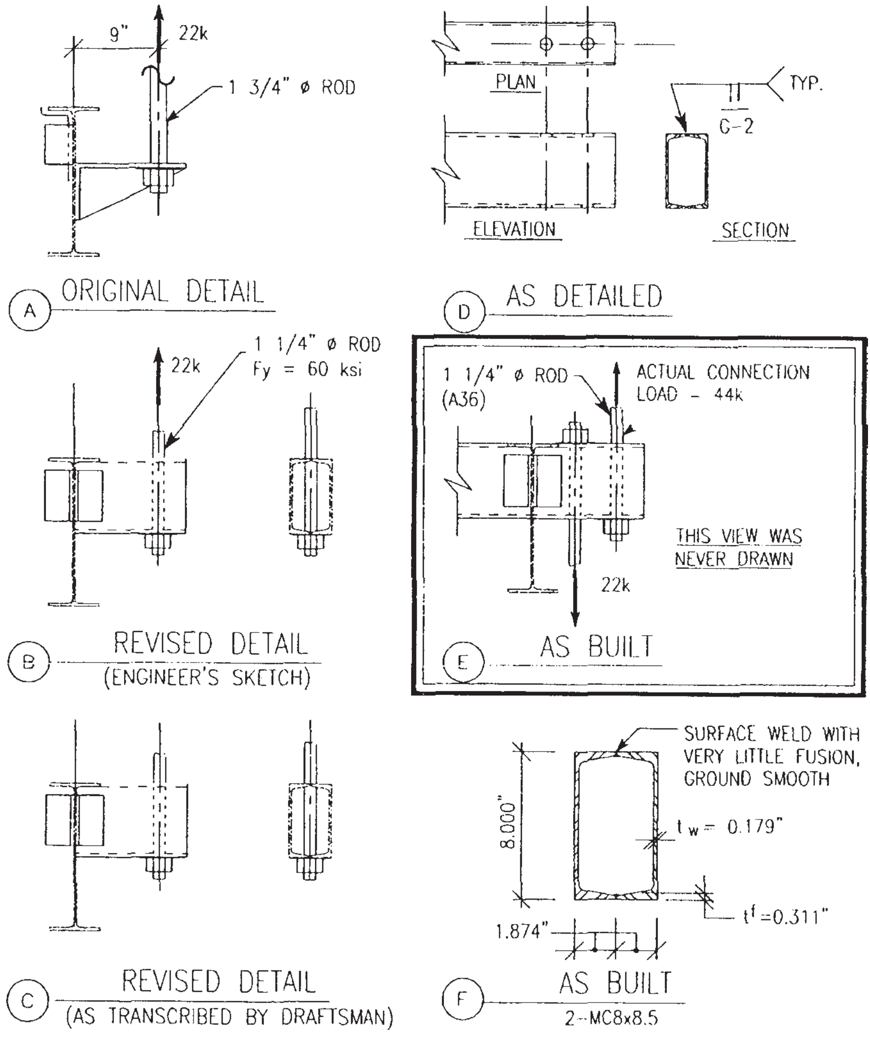

Figure 2-8. The evolution of the failed connection.
Source: Luth (2000).

The following sequence of key events leading up to the collapse is modified from Luth (2000, pp. 51–57):

- Early 1976–August 1978: The project moved from the owner's master planning to the evolution of the design, with major revisions to the sunscreen framing near the walkways. Design was carried out using fast-track methods.

- June 1978: Both the project engineer and the senior design engineer on the project, each of whom had extensive knowledge of the product history, left the firm. A gap in continuity of this magnitude, particularly on a fast-track project, provides many opportunities for details to fall through the cracks.
- Mid-1978: The first walkway detail showed eccentric angles to support the hanger rods, not box beams. At roughly the same time, the architect requested a change from 44-mm (1¾-in.) to 32-mm (1¼-in.) diameter rods to enhance appearance. Because the rods would later be covered by fireproofing, there would actually be no visible difference.
- At roughly the same time, mid-1978: The original W 8 × 10 purlin (wide flange 8 in. or 203 mm deep, weighing 10 lb per linear foot, or mass 14.9 kg per linear meter) was changed to the box beam with 2 MC 8 × 8.5 channels. The engineer's revised sketch showed a single rod, a notation for a yield strength (F_y) of 414 MPa (60 kip/in.^{2}) for high-strength steel, and an axial load of 98 kN (22 kip). The weld between the channels was not shown. The intent of the load notation was to indicate to the fabricator that the connection still needed to be designed.
- August 1978: The draftsman transcribed the detail to the final drawings, but the rod yield strength and axial load were missing. The plans and specifications were issued for construction.
- December 1978: The fabricator started in-house work on the shop drawings, including heavy truss connections and all beam connections for which the forces were shown on the drawings. The $390,000 contract was not considered to be particularly large for the fabricator.
- January 1979: The fabricator called the structural engineer's project manager requesting a change from the continuous rod to two rods, offset, as shown in Figs. 2-4a and b. The project manager checked the moment and shear in the box beam and responded that the change was acceptable. He asked the fabricator to submit the request through channels for approval, but the fabricator never did this.
- January 12, 1979: The fabricator landed a large contract and transferred the shop drawings for the Hyatt Regency to an outside engineering firm. The drawing showed that the box beam had been started but not completed. The new firm assumed that the connection design had been completed and added the weld for the box beam.

- February 7, 1979: The detailer checked the shop drawings for internal consistency and completeness and did not find any problem with the hanger connection.
- February 16, 1979: The structural engineer received the shop drawings for approval. The contractor requested expedited approval, so the engineer assigned the checking to a senior technician. The technician noted that the hanger rod was not large enough using A36 steel, and the engineer responded from memory that it was high-strength steel. The drawings were returned on February 26.
- Summer 1979: Construction problems arose at an expansion joint because embedded plates had been left out. A repair detail using supporting seat angles (directly under the beam) and expansion bolts was developed, but only 5 of 14 bolts were installed correctly. Earlier, the first testing lab had been fired, and now the second testing lab was fired for poor performance on concrete testing. The project was completed without a testing lab.
- October 14, 1979: The expansion bolt repair detail failed during a fall cold snap, and two bays of the roof collapsed. Fortunately, there were no injuries. A complete design check was performed (by Luth). Again, the strength of the hanger rod was questioned, and the same assurance was provided (without checking the project documents). The design check revealed that W 6 × 16 members in the sunscreen truss had replaced the original W 6 × 15.5 sections, which were no longer available. The correction was completed by November 1979. The general impression of the project team was that disaster had been averted.
- July 1980: Hotel grand opening.
- July 1981: Collapse.

Legal Repercussions

Kansas City did not convict the Hyatt Regency engineers of criminal negligence because of lack of evidence. However, the billions of dollars in damages awarded in civil cases brought by the victims and their families dwarfed the half-million dollar cost of the building (Roddis 1993).

Feld and Carper (1997, p. 215) suggest that this was the most heavily litigated failure in history until that point. Claims under review at one point were up to $3 billion, with a single class action suit settled for $143 million. The 72 rescue workers sued for $150 million for emotional trauma and long-term psychological effects; the claim was settled out of court for $500,000.

Technical Concerns

Neither the original nor the as-built design for the hanger rod satisfied the Kansas City building code, making the connection failure inevitable under service loading conditions. If, however, the building design had provided for redundancy, this failure might not have resulted in the complete collapse of the walkway. The technical issues in this case are not particularly difficult. The procedural concerns are of much greater interest.

Procedural Concerns

The Hyatt Regency walkway collapse highlighted the lack of established procedures for design changes, as well as the confusion over who is responsible for the integrity of shop details (Roddis 1993). The legal repercussions experienced by the Hyatt engineers established the engineer of record's responsibility for the structural integrity of the entire building, including the shop details. It is important for all parties to understand fully and accept their responsibilities in each project (Feld and Carper 1997).

Certain procedural changes have been suggested to help prevent similar collapses (Kaminetzky 1991, p. 220):

- The engineer of record (EOR) should design and detail all nonstandard connections, although perhaps American Institute of Steel Construction (AISC) standard connections do not require similar care.
- All new designs should be thoroughly checked.
- All of the contractor's modifications to design details should require written approval from the EOR.
- Redundancy must be provided to prevent progressive or disproportionate collapse.
- Cross plates or stiffeners must be used for similar box beam-type connections to improve bearing capacity.

Given the history, this type of connection detail is unlikely to see much use in the future.

Ethical Concerns

Pfatteicher (2000, pp. 62–63) notes that this collapse provided a first test of the new ASCE Code of Ethics, officially adopted by the Board of Direction in 1976. The most significant change was the addition of Fundamental Canon 1: "Engineers shall hold paramount the safety, health, and welfare of the public in the performance of their professional duties." This canon has since been revised to encompass sustainable development. The ASCE Code of Ethics is provided in this book as Appendix B.

Once the NBS had completed its investigation (published as NBS 1982), the Missouri licensing board began a quiet inquiry. The public was outraged at the failure and the loss of life, and the local newspapers were filled with calls for justice (Pfatteicher 2000).

The county prosecutor and assistant district attorney announced more than two years after the collapse that they would not file any criminal charges because they did not find enough evidence to support them. The Missouri licensing board continued with its investigation of Jack Gillum and his employee, David Duncan. The board did not contact them during the investigation, nor did it investigate the architects, despite the fact that the board had jurisdiction over architects as well as engineers. At the end of its investigation, the Missouri Board of Architects, Professional Engineers, and Land Surveyors convicted the EOR and the project engineer of gross negligence, misconduct, and unprofessional conduct in the practice of engineering. Both had their Missouri professional engineering licenses revoked. The two combined had licenses in 30 jurisdictions, and most of those licenses were also revoked (Pfatteicher 2000, pp. 64–65).

After the Missouri board's action, the ASCE Committee on Professional Conduct held a confidential hearing on the matter. The committee deliberated for 12 h and recommended that Gillum be expelled for three years. Duncan was not an ASCE member (Pfatteicher 2000, p. 65).

Writing within a few years after the collapse, two attorneys believed that the punishment was appropriate. Their paper appeared in the ASCE *Journal of Performance of Constructed Facilities*.

The attorneys Rubin and Banick concluded:

1. Based on the facts found by the administrative law judge regarding the events that led up to the Hyatt collapse, license revocation was more than warranted. The engineers' conduct cannot be justified under any standard of professional practice. They were callously indifferent to life and safety after questions relating to the particular connection that failed were repeatedly brought to their attention. They were not hapless victims of the system in any sense.
2. It is paradoxical that while tragedies such as the Hyatt failure provide an incentive to change practices, the Hyatt failure is a poor example on which to base recommendations for change, because essentially no change in practices would likely have averted the Hyatt tragedy.

> 3. Examination of the facts discloses an ironic twist. With all of the alleged deficiencies in current practices, oddly enough, Hyatt proves that the system really does work. The right people asked . . . the right questions before the collapse occurred . . .
>
> The need to police professions (law and engineers alike) and to continually punish professional misconduct must be recognized. It is healthy; it is necessary. It instills public confidence—it removes from practice those who may cause loss of life. . . . *Most* important, however, is its prophylactic effect on the profession. It is an effective weapon against complacency. (1987, pp. 165–166)

Undoubtedly, some engineers continue to hold this harsh view, but the opinions of others have mellowed somewhat with time and with understanding of the complexity of the case.

The Human Factor

Jack Gillum, the EOR, was well respected. He published an excellent paper discussing the failure, his actions before and after, and the responsibilities of the EOR. His paper addressed two fundamental issues: the role and responsibility of the EOR and whether design responsibility can be delegated (Gillum 2000).

He presented his paper at ASCE's Second Forensic Congress, held in San Juan, Puerto Rico, in May 2000 (Rens et al. 2000). His presentation followed those of Moncarz, Luth, and Pfatteicher and closed a special plenary session for the congress. At the end of his presentation, the audience of engineers gave him a standing ovation. I was present and deeply moved, and I believe that the ovation was for his courage in presenting his story to his fellow engineers. Surely, the temptation to turn his back on the case and avoid discussing it must have been great. He has spoken on this topic to many groups across the country, including ASCE student chapters.

Gillum's paper begins with the phone call that engineers dread.

> It was a Friday evening at about 7:45 P.M. when my wife and I returned home to a ringing telephone. The call was from Herb Duncan, one of the principal architects with the Kansas City firm of Patty, Berkebile, Nelson, Duncan, Monroe, Lefebvre (PBNDML), the firm with whom we had worked on the Kansas City Hyatt. His first words to me—"There has been a collapse at the Hyatt"—shattered me to the core. Herb told me that one of the walkways had collapsed, and upon questioning he

> indicated, "Several may have been killed and many injured." I asked him what had happened and he had no answer. He had called to inform me of the collapse and asked me what the weight of an individual walkway unit was, as the rescue workers had to determine the type of equipment needed to remove the debris. (Gillum 2000, p. 67)

Gillum continued to narrate the events of the hours and days after the phone call. He picked up Dan Duncan and chartered a plane, arriving by 11:15 P.M. that evening. The rescue effort was well underway. Arriving at the site, they quickly identified the problem with the connection, and quick calculations verified that the as-built capacity was grossly inadequate. Over the weekend, they met with the architects, their company personnel, and their attorneys. Gillum immediately took steps to clarify his firm's procedures for responsibility and accountability of design work (Gillum 2000, pp. 67–68).

The collapse was of great interest to the engineering profession. Many letters to the editor of *Engineering News Record* (*ENR*) discussed the problems with the original connection. An initial round of letters claimed that the connection could not be built, and a second round suggested several possible solutions, such as sleeve nuts and other details (Ross 1984, pp. 398–402). All of these writers knew, in hindsight, that the connection was critical and that it had failed.

Many articles written referred to the connection as a "designed connection," and many alternate, satisfactory designs were presented. Two are shown in Fig. 2-9, based on Kaminetzky (1991, pp. 220–221).

The NBS report recommended that concentrated loads never be applied to flanges of steel sections. Load-distributing plates (shown in Fig. 2-9) should be used (Feld and Carper 1997, pp. 222–223).

Of course, this analysis misses the point. It was not a poor connection design; it was a critical connection that somehow made it through the entire project *without* being designed. A proper design of this connection would have been easy if it had been flagged at any point during the process. The review of the facts presented in the Gillum paper closely follows Luth's analysis.

Gillum closes his paper by saying,

> There is hardly a day that goes by that I don't think about the Hyatt collapse, the lives that were lost or marred forever, the relatives that lost their loved ones, and the effect it has had on Kansas City, the construction industry, and everyone connected with the project. My hope is that we, as a profession, can and will continue to learn, practice, dis-

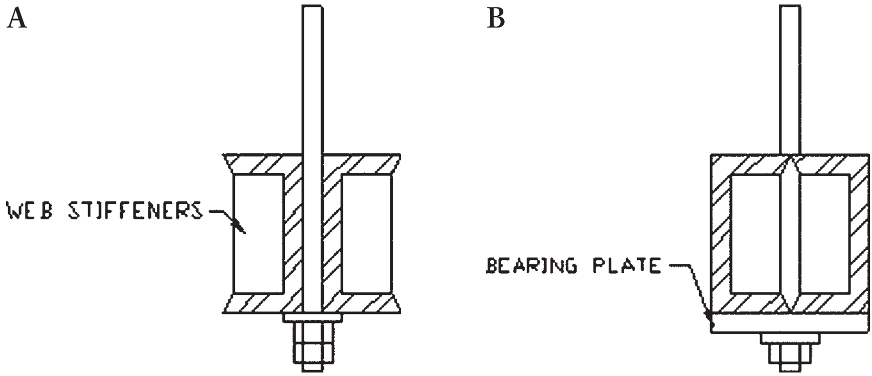

Figure 2-9a, b. Proposed alternative connection designs.

> seminate, change, and adopt procedures and policies that will prevent a tragedy like this from occurring again. (2000, p. 70)

Educational Aspects

The free-body diagram is the basic equilibrium analysis tool to determine forces acting on a body. If the diagram is not drawn correctly, the forces cannot be calculated accurately, and the design may be unsafe. The importance of a correct free-body diagram may be shown through analysis of the Kansas City Hyatt Regency walkway collapse. Isolating the force of the box beam bearing against the nut shows that the force transfer changes between the configurations shown in Figs. 2-4a and 2-4b. The load on the connection was doubled, and it failed.

However, the issues of communication and responsibility in engineering and construction are of even more interest than the technical issue of the overloaded connection. This is not really a case study about free-body diagrams. This is about the design and construction process, the pressures for speed and economy inherent in any engineering endeavor, and the care and failure literacy necessary to protect the public.

This case was revisited in four papers published in a special issue of the ASCE *Journal of Performance of Constructed Facilities* (Gillum 2000, Luth 2000, Moncarz and Taylor 2000, and Pfatteicher 2000). In addition, authors of all four papers published and presented abbreviated versions of the papers at ASCE's Second Forensic Congress (Rens et al. 2000a). In his editor's note to the issue in which the four papers appear, the editor of the journal, Ken Carper, asked how much the business of designing and constructing buildings had truly changed.

Lessons Learned

According to Luth (2000, p. 59), some lessons have been learned from this failure:

- Procedures must ensure that every connection is designed. It must be possible to verify the capacity of every connection on the job without referring to the piece drawings.
- A formal peer review must be performed on every detail in structural drawings. Spot-checking is not sufficient.
- When questions come up, such as the strength of the hanger rods, they must be answered by referring to the project documents, in case the engineer's memory does not reflect what is actually on those documents.
- Changes in personnel require careful management to ensure that the project is handed off without errors creeping in.
- Any changes in concept must be handled by a formal review process. Changes should not be approved over the phone.

Gillum (2000, pp. 69–70) cites additional procedural changes that resulted from the Hyatt Regency collapse:

- Florida and Connecticut have mandated special inspection procedures for "threshold buildings," where some components are designed by registered engineers working for suppliers and manufacturers.
- New York State has adopted rules that state, in essence, that each engineer is responsible for his or her own work.
- ASCE published *Quality in the Constructed Project* in 1990, which was updated a decade later (ASCE 2000). This publication assigns responsibility for connections, as well as for other design elements.

Lessons Not Learned

According to Luth, the lessons that were not learned were the following:

1. The implications of structural failures, even though they are relatively rare, are far too serious for the scope of services to be defined through a "low bid" process.
2. City building departments do not—and cannot—provide adequate checking on major projects. A formal peer-review process on such

projects should be mandatory. Peer reviewers should be excluded from liability by law and should be held to a higher standard of qualifications than ordinary engineers.

3. Structural engineers cannot continue to allow the legal profession to define the duties, obligations, and specific actions that constitute "good engineering practice" on a case-by-case basis after the fact. (Luth 2000, p. 59)

Conclusions

According to Moncarz and Taylor (2000, p. 46), the collapse was due to "the doubling of the load on the connection resulting from an ill-considered change of an ill-defined structural detail." They blame the design process control and note that most investigation efforts concentrated on the design procedures, but not the process.

Petroski has commented that,

> Just as no one who knows of the Tacoma Narrows Bridge is likely to ignore the effect of wind on a suspension bridge, so no one who remembers the Hyatt Regency skywalks is likely to let another rod-beam connection escape close scrutiny. Thus the tragedy no doubt made a lot of inexperienced detailers suddenly much more experienced. And it is precisely to keep these lessons in the minds of young engineers that failures should be a permanent part of the engineering literature. (1985, p. 91)

When Petroski wrote those words, the disaster was still fresh. However, this collapse occurred before most current undergraduate students were born, and today's students are thus not likely to be familiar with the story unless it is discussed in the classroom.

Essential Reading

Essential reading for this case is the four papers published in the May 2000 special issue of the ASCE *Journal of Performance of Constructed Facilities* (Gillum 2000, Luth 2000, Moncarz and Taylor 2000, and Pfatteicher 2000), along with the editor's note by Carper. An excellent discussion of this case, with emphasis on ethical issues, is provided by Roddis (1993). This case study is featured on the History Channel's Modern Marvels series *Engineering Disasters 11* videotape and DVD.