National Aeronautics and Space Administration

System Failure Case Studies

MAY 2008 Volume 2 Issue 4

TWO RODS DON'T MAKE IT RIGHT

On July 17, 1981, nearly one year after its completion, the Hyatt Regency Hotel in Kansas City, Missouri filled its lobby with guests participating in and watching the evening "tea dance." Suspended above the lobby were concrete walkways designed to connect both sides of the 2nd, 3rd, and 4th floors. Shortly into the dance, two of the walkways, packed with spectators, collapsed onto the crowded atrium floor below (Figure 1). The event was triggered by a failure in the connection between a supporting rod and the box beam of the fourth floor walkway. This disaster killed 114 people and injured approximately 200 more, which at the time was the deadliest structural collapse in U.S. history.

Figure 1: Pieces of the collapsed walkways in the atrium.

BACKGROUND

The initial planning for the Hyatt Regency Hotel began in 1976. The basic elements of the hotel design consisted of a 750 guest-room tower, a top-floor revolving restaurant on the 45th floor, and a four-story open atrium. Suspended across the atrium were three hanging walkways connecting opposite sides of the 2nd, 3rd, and 4th floors. The 2nd floor walkway was placed directly below the 4th floor walkway as shown in Figure 2.

The owner of the project was Crown Center Redevelopment, but primary responsibility for the overall design and construction of the hotel rested on the shoulders of PBNDML Architects as the project manager. The project was divided into three aspects: design team, construction team, and a safety inspection team. PBNDML subcontracted the structural engineering and primary design responsibilities to G.C.E. International, including the roles of the project engineer and the senior project designer. On the construction side of the project, the fabrication and erection of the atrium and steel cable construction, including the walkways, was subcontracted to Havens Steel Co. In addition, Crown Center Redevelopment hired an independent safety inspection team, including an investigating engineer.

Initial Design

In early 1978, G.C.E. concluded its structural drawings, which contained only some of the atrium steel specifications. One of the omitted specifications was the connection between the atrium walkways and the support rods. According to G.C.E.'s testimony after the disaster, it was not uncommon to omit some connection details, such as the walkway connectors that G.C.E. expected to be completed by Havens. Initially, the walkways were to be supported by six suspension (or support) rods, each running in one continuous piece through the 4th story walkway down to the 2nd story walkway. Both walkways would be bolted to the support rods through the box beams that ran

Collapse of Walkways Kills 114.

Proximate Cause:

- Failure of the connection between the walkway box beam and support rod

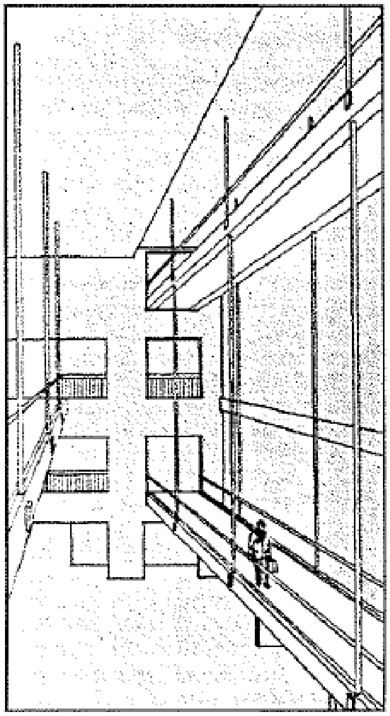
Underlying Issues:

- Inadequate design verification process
- Lack of accountability and oversight
- Poor communication between the design team and the construction team contractors

perpendicular to the length of the walkways.

Design Changes

In order to implement the primary structural drawings, the fabricator, Havens Steel, would have had to thread the entirety of the steel rods below the 4^{th} floor in order to screw on the nuts to hold the 2^{nd} floor walkway in place. To simplify the process, Havens altered the design to a two-rod system, where the rods from the 2^{nd} floor would attach separately to the 4^{th} floor beams, and the 4^{th} floor rods would attach to the same beams and connect to the roof (see Figure 3). This change was intended to make fabrication and connection of the steel rods easier and faster. However, this essentially doubled the load on the 4^{th} floor walkway beams, as these beams now supported the 2^{nd} floor walkway as well. In effect, this design change resulted in a new load path which introduced a compounding shear stress element to the 4^{th} floor walkway box beam.



<u>Figure 2</u>: Hanging walkways.

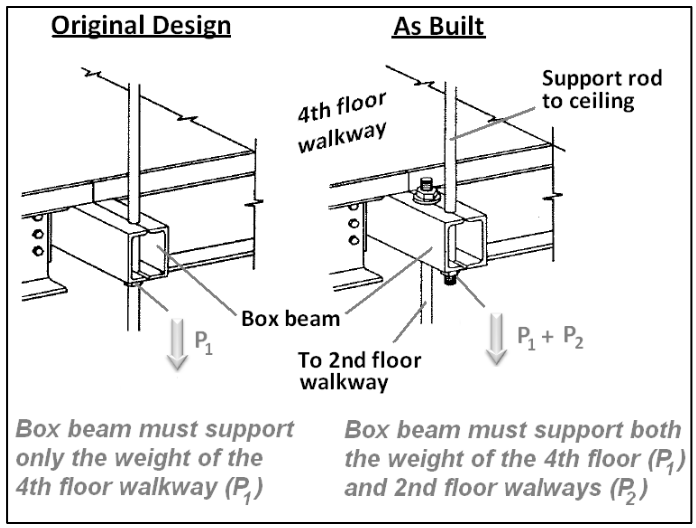
Design Change Review

Havens prepared 42 structural shop drawings to return to G.C.E. for final approval. Included in these drawings were changes to the atrium design, as well as that of the walkway. The new shop drawings for the two-rod system were submitted to the structural engineers, G.C.E., for final approval. In February of 1979, the plans were approved and signed by the program engineer at G.C.E. After the collapse, National Bureau of Standards (NBS) investigators could not find any final calculations for the loads at each connection. This also includes calculations of any sort of safety factor. It is unclear why there appear to be no additional calculations on this change.

WHAT HAPPENED?

Walkway Collapse

A year after the grand opening of the hotel, in 1981, during the evening "tea dance," spectators noticed slight movements and swaying of the hanging walkways. Within moments, one of the connectors on the 4^{th} floor walkway failed, as the weight of the 4^{th} and 2^{nd} floor walkway separated the box beam and pulled the beam loose of the nut and washer of the support rod. The jolt of the connectors breaking free caused a progressive failure of each of the remaining five connectors. As the 2^{nd} floor walkway was attached to the 4^{th} floor walkway, they both crashed down onto the crowded atrium floor below. Figure 4 shows the warped beam after the collapse.



<u>Figure 3</u>: Single-rod design versus two-rod modification.

PROXIMATE CAUSE

An investigation by the NBS after the incident determined that the proximate cause of the collapse was a failure of the walkway box beam at a support rod connection. The box beam split open along the weld, allowing the nut and washer on the support rod to slip through the beam. In fact, the box beams on the 4^{th} floor had already begun to yield even before the increased weight by the spectators. The weld on the 4^{th} floor box beam had ruptured, allowing the beam to further yield and bend upward under the weight of the two walkways. The bending of the metal went far enough to allow the nut and washer to slip through the beam and break free. Once the first connection failed, the others failed almost immediately after.

Underlying Issues

Inadequate Design Verification Process

G.C.E., the structural engineering design contractor, created only a partial design and left the most safety-critical design decisions to the fabrication/installation contractor, Havens Steel. Havens created the design without any documented engineering analysis and submitted it to G.C.E., who approved the design, without any documented engineering analysis either. NBS investigators were unable to find any significant recorded calculations of safety factors or yield strengths of the walkway connections. After weighing sections of the collapsed walkways, viewing footage of the crash, and re-creating sections of the walkways, NBS investigators determined that the load capacity on each connector was approximately only 60% of the Kansas City Building Code's required load capacity for that type of connection.

Figure 4: **Ruptured box beam on the collapsed walkway.**

Lack of Accountability and Oversight

All parties involved had a responsibility to identify and recognize the walkway as a safety-critical suspended load, which warranted special consideration and care. During construction in 1979, the atrium roof had collapsed, prompting G.C.E. to ask Crown Center Redevelopment for an on-site inspection of the entire site. Three different requests were denied due to the additional costs. According to G.C.E.'s safety inspector, as noted in the administrative hearings after the collapse, had he been instructed to inspect all the connections in the atrium (instead of just the roof), he most likely would have discovered the flaws in the walkway.

Clear delineation of accountability was absent with shared design responsibilities, numerous contractors and sub-contractors, and overlapping design verification processes. PBNDML failed to exercise oversight of support contractors. And the Kansas City Division of Public Works Department failed to provide adequate oversight and evaluation of design documents when it approved of the original design, which NBS investigators said violated the building codes even *before* the design change. The Public Works Department denied that it had been notified of or had approved of the design change.

Poor Communication

G.C.E. management failed to retain safety-critical design information when two key structural engineers, involved in preliminary design activities, left the company. The senior project designer and project engineer, both of whom had an exceptional knowledge of the design, left G.C.E. midway through the design process. The switch to the alternate design of the walkway support structure was never fully communicated to the new G.C.E. design engineers, and the downgrade in structural integrity went unnoticed.

Aftermath

A grand jury investigation into the collapse found no criminal actions linked to the accident. Nonetheless, after two years of civil suits involving all parties totaling more than $100 million, G.C.E. International Inc. had its license revoked. In addition, the two lead structural engineers working for G.C.E. were found guilty of gross negligence, misconduct, and unprofessional conduct in the practice of engineering. The board of the American Society of Civil Engineers finally placed the accountability for this disaster on the G.C.E. engineers and defined the necessity of determining individual roles in overlapping responsibilities.

> **"…While the engineer may properly delegate the work of performing engineering design functions, he cannot delegate his responsibility for the structural engineering design … This responsibility is not delegable."**
>
> **American Society of Civil Engineering - 1985**

Before the disaster, the city of Kansas City had a small subdivision of the Division of Public Works in place to review building plans. However, after the collapse, the city created a Codes Administration Department dedicated to reviewing building plans.

Applicability to NASA

The case underscores the need to incorporate Safety and Mission Assurance engineering support into design and design verification processes. Of particular importance is early incorporation of system safety activities, including 1) identification of hazards; 2) identification of control and/or mitigation measures; and 3) specification of methods to verify controls have been implemented. Further, the case reminds NASA engineers and program teams to develop an in-depth understanding of concepts such as yield, margin, and factors of safety when working with safety-critical structures. The case also underscores the need for requirements ownership, requirements clarity, and requirements change control. Ambiguity associated with overlapping responsibilities, matrixed support relationships, and complex supply chains must be overcome by implementation of rigorous configuration management with formal requirement change boards that include independent engineering and assurance representation. It must be remembered that responsibility is ultimately not delegable. Finally, it is important to consider how big projects can and do fail when small details are overlooked. The case examined a single system failure within the context of a 750-room hotel project, which one can reasonably assume included innumerable safety-critical design details and decisions. The sheer magnitude of the undertaking further underscores the need for disciplined design-build processes that include appropriate independent reviewers to ensure that every single safety-critical detail is addressed with rigor and care.

Questions for Discussion

- Are hazard control requirements managed with the same rigor as other performance requirements?
- When working with multiple contractors and subcontractors, are the responsibilities and accountability of each group well defined?
- Who within your organization's program/project environment has the authority to waive hazard control requirements? Who are the other participants within that process?

Questions for Discussion (cont)

- Are primary structures within your program/project designed with adequate margin and factors of safety when one assumes worst-case environmental stress/strain or loading?
- Are these margins, factors of safety, and other safety critical design details independently reviewed?

References:

Luth, Gregory P. "Chronology and Context of the Hyatt Regency Collapse." Journal of Performance of Constructed Facilities. May 2000, pg. 51-61.

"1981: Kansas City Hyatt Regency Skywalk Collapse." *Engineering Ethics: An Industrial Perspective*.

"Engineering Ethics: The Kansas City Hyatt Regency Walkways Collapse." Department of Philosophy and Department of Mechanical Engineering. Texas A&M University. http://ethics.tamu.edu/ethics/hyatt/hyatt1.htm

Missouri Board for Architects, Professional Engineers and Land Surveyors vs. Daniel M. Duncan, Jack D. Gillum, and G.C.E. International, Inc. Administrative Hearing Commission. 1985. Case No. AR-84-0239.

"Walkway Collapse." Engineering.com. http://www.engineering.com/Library/ArticlesPage/tabid/85/PageID/1

Lowery Jr., Lee. Pieces of the Collapsed Walkways, Ruptured Box Beams, [Online images], http://ethics.tamu.edu/ethics/hyatt/hyatt2.htm, Accessed August 2007.

Pfrang, E.O. and Marshall, R., Hanging Walkways. [Image], Collapse of the Kansas City Hyatt Regency Walkways, *Civil Engineering ASCE*, July 1982, 52, pg. 65-68.

Single-Rod Design vs. Two-Rod Modification. [Online images], www.rose-hulman.edu/Class/ce/HTML/publications/momentold/winter96-97/image.gif, image2.gif, Accessed August 2007.

System Failure Case Studies
A product of the NASA Safety Center

Executive Editor: Steve Wander stephen.m.wander@nasa.gov
Developed by: ARES Corporation

To view this document online and/or to find additional System Failure Case Studies, go to http://pbma.nasa.gov