National Aeronautics and Space Administration

System Failure Case Studies

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TUNNEL OF TERROR

At approximately 11 p.m. on July 10, 2006, I-90 eastbound traffic was winding its way toward Logan Airport via the Ted Williams Tunnel in Boston, MA when a massive section of the connector tunnel roof collapsed. As their anchor bolts ripped loose from the ceiling, about 24,000 lbs of suspended concrete panels crashed onto a car below, killing 38-year-old Milena Del Valle and injuring her husband, Angel Del Valle (Figure 1). This tragic event was only the latest in a series of mishaps involving the most expensive road construction project in US history, referred to as "The Big Dig." While lawsuits and litigation continue to this date, settlements have totaled over $400 million and have resulted in six indictments. Repairs cost $54 million in the first year.

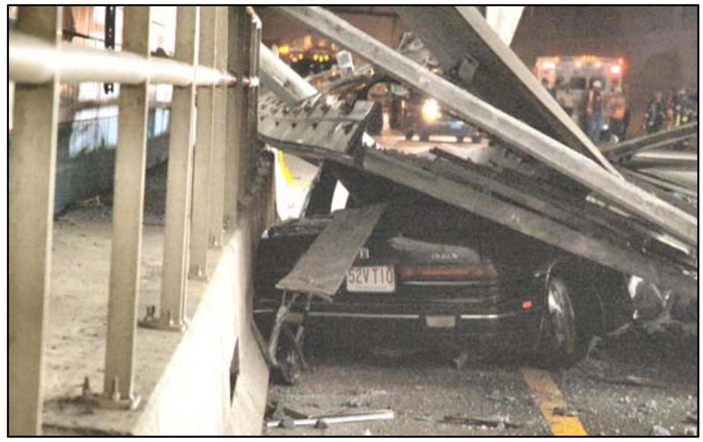

Figure 1: The passenger seat was completely crushed by the fallen concrete panels.

BACKGROUND

The stretch of highway where the 2006 failure occurred is referred to as the D Street portal, an element within the Interstate 90 (I-90) connector tunnel project, a part of the Central Artery/Tunnel (CA/T) Project, known colloquially as the "Big Dig." The D Street portal is at the end of the I-90 connector tunnel, opposite to the entrance to the Ted Williams Tunnel, which runs under the Boston Harbor to Logan International Airport. While the tunnel itself was completed in 1996, suspended ceiling panels were installed in 1999 as part of the ventilation system. The panels consisted of reinforced concrete slabs (5,000 to 6,000 lbs each) inserted into steel frames which were suspended from the tunnel ceiling by bolts secured with epoxy resin (Figure 2).

The responsible agency and construction contract signatory was the Massachusetts Highway Department (MHD). Daily oversight of the contract and the CA/T project was assigned to the Massachusetts Turnpike Authority (MTA). The general contractor responsible for overall engineering management was the firm of Bechtel/Parsons Brinkerhoff (BPB). Gannet Fleming (GF) was the BPB subcontractor responsible for structural design of the roofing system. Other important participants included Powers Fasteners Incorporated (PFI), the manufacturer of the Fast Set formulation of the Power-Fast epoxy injection gel, and Modern Continental Construction Company (MCC), the firm actually performing the construction.

The Big Dig project achieved national recognition as the most expensive roadway project in US history ($15 Billion), subject to schedule delays, cost overruns, supplier issues, potential fraud, hundreds of leaks, as well as continuous political conflict between MTA Chairman Anthony Amorello and Massachusetts Governor Mitt Romney.

In July 2006, massive suspended ceiling panels fell and crushed a passing car below.

Proximate Cause:

- Anchor bolts ripped loose from the ceiling as the epoxy adhesive failed

Underlying Issues:

- Design flaws and ineffective communication
- Bypassed verification and maintenance due to insufficient understanding of epoxy materials
- Lack of emphasis on system safety resulted in reduced safety margins and failure to identify epoxy as a key safety critical component
- Management ignored "warning signs" due to cost and schedule pressures

What Happened?

Collapse

On July 10, 2006, at approximately 11 p.m., thousands of pounds of concrete collapsed onto a passing Buick sedan in the D Street portal tunnel, killing the front seat passenger and injuring the driver (Figure 1).

Proximate Cause

The epoxy adhesive material underwent creep deformation and fracture, allowing the anchor bolts to pull free from the tunnel roof. It was later determined that the anchor epoxy employed in the D Street anchors was the wrong formulation, one which was known to have poor creep resistance under sustained tensile loads.

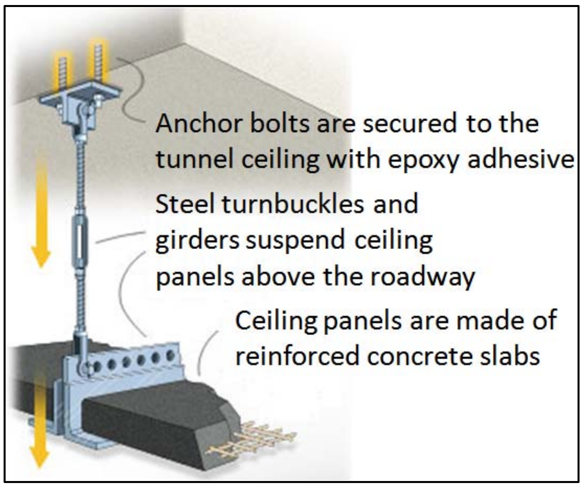

Figure 2: Design of the suspended panels.

Underlying Issues

Design Flaws and Ineffective Communication of Hazards

MCC engineers were cited to have expressed concerns with the heavy suspended concrete panels as an inherently hazardous tunnel roof design. The massive ceiling panels were justified on the basis of avoiding vibration while enhancing ventilation in the tunnel, but counter arguments by industry observers asserted that ventilation requirements could have been met without any suspended ceiling panels, denouncing them as a strictly cosmetic architectural feature.

The epoxy adhesive played a critical role in securing the ceiling anchor (Figure 3). No documentation was provided by the supplier, PFI, identifying which epoxy formulation was supplied, and neither GF nor BPB questioned which epoxy was used. All parties, including MCC, assumed that the epoxy provided by the supplier was suitable. The National Transportation Safety Board (NTSB) report cited PFI for failing to adequately communicate known material properties of its epoxy formulations, in particular with regard to long-term performance under tensile loads. NTSB also cited GF for failing to adequately communicate the safety critical importance of using the correct epoxy formulation for long-term applications: "The supplier should have made a clear distinction in all its literature between the relative capabilities of its Standard and Fast Set formulations … The company had conclusive evidence that its Fast Set epoxy was susceptible to creep." MCC management claimed to have been unaware that its employees had utilized an epoxy susceptible to creep.

"People should not have to drive through the Turnpike tunnels with their fingers crossed."

Mitt Romney
Governor, Massachusetts

Bypassed Verification Steps and Poor Maintenance

Prior to official opening of the I-90 connector tunnel in 2003, the chief engineers of the MHD and MTA were required to jointly certify the safety of the roadway for public use. Instead, the MHD chief engineer abrogated his independent role and asked the CA/T project director (an MTA employee) to certify on behalf of MHD.

During installation in 1999, every bolt in the D Street portal was subjected to a tensile proof test. But no subsequent testing or inspection was conducted during the following seven-year period leading up to the failure. The Massachusetts Inspector General (IG) noted that "requests failed to produce a single document indicating that any regular maintenance was ever performed on the I-90 connector ceiling system from its construction in 1999

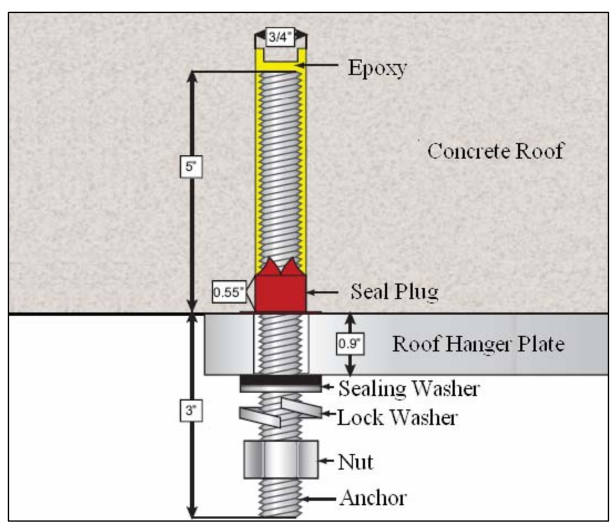

Figure 3: The epoxy adhesive was a critical component in securing the anchor bolts.

onward."

The design verification process reflected a lack of understanding of the performance environment (long term tensile loading). "This accident investigation revealed a striking lack of awareness among designers, contractors, managers, and overseers about the nature and performance of polymer adhesives, even as those adhesives were being approved for use in applications where a failure would present an immediate threat to the public."

The NTSB noted use of an International Code Council (ICC) standard (ICC AC58) which includes an optional accelerated (120-day) creep test protocol for adhesive anchors. If no creep test is performed or if the adhesive fails the creep test, a design factor of safety of 5.33 is required; if the creep test is conducted and passed, the design factor of safety can be reduced to 4 (the design factor of safety is the ratio between the average strength of an anchor installation and the force to be applied to the anchor as specified in the design). PFI provided an Evaluation Report, which included bond strength tables specifying a safety factor of 5.33 for Fast Set epoxy but not results from any creep tests. The NTSB learned during the investigation that Fast Set epoxy had been tested for creep performance in 1995 and 1996 (by an independent testing laboratory hired by PFI) and failed to meet the standard.

Reduced Margins of Critical Components

The NTSB cited both BPB and GF for failing to identify epoxy as a safety critical single point failure mode, failing to implement safeguards to ensure selection of the appropriate material, and failing to verify that the installation was in accordance with appropriate procedures. Engineering critics subsequently noted the intrinsic vulnerability of single load path design (no side supports for ceiling panels) for such a safety critical application. BPB and GF should have taken measures to identify the epoxy as a "key characteristic" (on all engineering drawings) and implemented appropriate safeguards and checks and balances to ensure that the proper material was being used.

In addition, under pressures to reduce costs and save time, the BPB management team had GF cut the number of anchor bolts by 40%. While anchors installed with "best practices" still averaged a measured factor of safety of 7.8 (according to the Federal Highway Administration) before the epoxy creep, BPB was giving up margin and moving the design closer to the edge of safety.

Although the NTSB identified creep in the epoxy as the primary issue, they also studied a number of other potential issues which may have contributed to less than optimal anchor performance under load including: method of hole drilling, dust and debris left in anchor holes, improper epoxy mix, inadequate volume of epoxy leading to voids, excessive torque applied to attachment nuts, and anchor holes drilled through rebar of the concrete roof. Each of these process errors could degrade performance and should have been characterized and managed as safety critical key process characteristics.

Management Ignored "Warning Signs"

The Big Dig management environment was one of extreme pressure to regain control over exploding costs and schedule delays, with cascading effects on decision making regarding design margin, verification testing and inspection frequency. The Massachusetts IG noted that BPB had been informed and advised by other MTA tunnel operators (such as, Fort McHenry Tunnel) as early as 1989 of the need to conduct no less than annual inspections of well documented, troublesome bolted ceiling systems. The NTSB cited MTA for failing to implement an aggressive inspection program in the aftermath of known roofing system failures in 1999 and 2001. Had MTA acted, it is believed that the anchor creep in the D Street tunnel would have been detected.

<u>Figure 4:</u> Numerous anchor bolts were found to have been affected by creep.

Aftermath

Post failure inspections showed that a significant number of adhesive anchors in the D Street portal and in other isolated locations in the I-90 connector tunnel were at risk for imminent failure (Figure 4). State inspectors deemed over a thousand hangers suspended by epoxy anchors unreliable. The ceiling in the D Street portal was taken down and not replaced; since the portal was at the end of the tunnel, the ceiling was not needed for ventilation in that area. A second mechanical expansion anchor bolt was ordered to be installed next to each suspect bolt in the remaining tunnel roof. On June 2, 2007, after nearly a year of repairs costing $54 million, the tunnel was fully operational.

The NTSB provided numerous recommendations to state and Federal transportation officials, as well as voluntary standards organizations, related to the need for design and design verification testing standards to be developed and implemented for the use of adhesive anchors in sustained overhead tensile loading applications. Further, NTSB recommendations addressed the need for establishing and implementing inspection and periodic maintenance protocols for suspended ceilings in tunnels.

Innumerable lawsuits were still pending a year later concerning accountability in a highly charged political environment. The extent of the finger-pointing speaks to the issue of shared culpability.

APPLICABILITY TO NASA

The engineering management adage of "listen to the hardware" is indeed an important thought in considering applicability of this case to NASA. Multiple occurrences of roofing failure (1999, 2001) provided a strong hardware "voice" calling out for scrutiny and understanding of root causation in a safety critical application. It is important not to allow cost and schedule pressures to overrule such warnings. One must consider non-catastrophic failures and off-nominal behavior a "second chance," or gift − an opportunity to forestall mission failure. While another important theme familiar to NASA engineers is "Never Fly with a Known Unknown," it is also important to reveal the "unknown knowns" – that is, issues that should be known but lack understanding due to omitted information, either on purpose or by accident. Making some decisions based on imperfect information is inevitable, but it is imperative that anomalous performance be exposed and understood. Reducing margins and factors of safety increases susceptibility to both known and unknown risks, and it is important for NASA to consider worst case scenarios. Inherently hazardous designs must be analyzed and determined if they are absolutely necessary. In such designs, the key safety critical components must be properly identified and given the appropriate attention. System safety awareness is necessary to see or seek connections between failures of safety critical components in one part of a project with the possibility that similar (or identical) components might fail elsewhere. NASA engineers and project team members should stay connected with sources of component and material failure information available through the Government-Industry Data Exchange Program (GIDEP). The critical role of independent assurance is also an important theme for the NASA community to consider. Evolution of streamlined independent assurance activities must not result in compromise of independence, depth of penetration, rigor or frequency of assurance activities.

Questions for Discussion

- Are cost and schedule pressures detracting from safety critical design and/or design verification? Is there an effective pathway to express your concerns?
- Are safety critical maintenance activities being identified and conveyed to others by the proper authorities? Are inspections implemented in a timely manner?
- Have all stakeholders worked to understand root causes associated with any unexpected results or off-nominal behaviors in development, testing or integration?
- Are you fully knowledgeable concerning the performance characteristics of all the materials you are working with (including polymers, composites)? Are you assuming engineering accountability or are you delegating?

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