Ceiling Collapse in the Interstate 90 Connector Tunnel
Boston, Massachusetts
July 10, 2006

ACCIDENT REPORT

NTSB/HAR-07/02
PB2007-916203

National Transportation Safety Board

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PB2007-916203
Notation 7901A
Adopted July 10, 2007

Highway Accident Report

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Boston, Massachusetts
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**National
Transportation
Safety Board**

490 L'Enfant Plaza, S.W.
Washington, D.C. 20594

National Transportation Safety Board. 2007. ***Ceiling Collapse in the Interstate 90 Connector Tunnel, Boston, Massachusetts, July 10, 2006.*** **Highway Accident Report NTSB/HAR-07/02. Washington, DC.**

Abstract: About 11:01 p.m. eastern daylight time on Monday, July 10, 2006, a 1991 Buick passenger car occupied by a 46-year-old driver and his 38-year-old wife was traveling eastbound in the Interstate 90 connector tunnel in Boston, Massachusetts, en route to Logan International Airport. As the car approached the end of the Interstate 90 connector tunnel, a section of the tunnel's suspended concrete ceiling became detached from the tunnel roof and fell onto the vehicle. Concrete panels from the ceiling crushed the right side of the vehicle roof as the car came to rest against the north wall of the tunnel. A total of about 26 tons of concrete and associated suspension hardware fell onto the vehicle and the roadway. The driver's wife, occupying the right-front seat, was fatally injured; the driver was able to escape with minor injuries.

Major safety issues identified in this accident include insufficient understanding among designers and builders of the nature of adhesive anchoring systems; lack of standards for the testing of adhesive anchors in sustained tensile-load applications; inadequate regulatory requirements for tunnel inspections; and lack of national standards for the design of tunnel finishes. As a result of its investigation of this accident, the National Transportation Safety Board makes safety recommendations to the Federal Highway Administration; the American Association of State Highway and Transportation Officials; the departments of transportation of the 50 States and the District of Columbia; the International Code Council; ICC Evaluation Service, Inc.; Powers Fasteners, Inc.; Sika Corporation; the American Concrete Institute; the American Society of Civil Engineers; and the Associated General Contractors of America.

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ACRONYMS AND ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
AC	Acceptance Criteria
ASCE	American Society of Civil Engineers
AGC	Associated General Contractors of America
ASTM	ASTM International
BOCA	Building Officials and Code Administrators International, Inc.
B/PB	Bechtel/Parsons Brinckerhoff
CA/T	Central Artery/Tunnel [project]
Conam	Conam Inspection Services
DOT	U.S. Department of Transportation
EOTC	Executive Office of Transportation and Construction
ER	evaluation report
FHWA	Federal Highway Administration
FST/HNTB	Fay, Spofford and Throndike, Inc., and HNTB Corporation
Gannett Fleming	Gannett Fleming, Inc.
HOV	high-occupancy vehicle
ICBO	International Conference of Building Officials
ICBO ES	ICBO Evaluation Service, Inc.
ICC	International Code Council
ICC ES	ICC Evaluation Service, Inc.
ICC ESR	ICC Evaluation Service report
I-90	Interstate 90
I-93	Interstate 93
kip	kilo-pound (1,000 pounds)
MassHighway	Massachusetts Highway Department
Mass Pike	Massachusetts Turnpike
MIT	Massachusetts Institute of Technology
Modern Continental	Modern Continental Construction Company, Inc.

MSDS	Material Safety Data Sheets
MTA	Massachusetts Turnpike Authority
NBI	National Bridge Inventory
NBIP	National Bridge Inspection Program
NBISs	National Bridge Inspection Standards
Newman Renner Colony	Newman Renner Colony, LLC
NIST	National Institute of Standards and Technology
Powers	Powers Fasteners, Inc.
psi	pounds per square inch
psf	pounds per square foot
QC	quality control
QC/QA	Quality Control and Quality Assurance
RFI	request for information
SBCCI	Southern Building Code Congress International, Inc.
Walsh	Walsh Construction Company

Selected Entities Involved in the Design and Construction of the D Street Portal

Entity	Role
Federal Highway Administration (FHWA)	Authorized Federal funding for the Central Artery/Tunnel (CA/T) project. Reviewed and approved the preliminary and follow-on CA/T designs. Reviewed and approved all CA/T construction contracts. Provided oversight for all major project recommendations and decisions.
Massachusetts Highway Department (MassHighway)	Processed, approved, and awarded all CA/T design and construction contracts.
Massachusetts Executive Office of Transportation and Construction (EOTC)	Beginning in 1993, approved expenditure of funds for CA/T project.
Massachusetts Turnpike Authority (MTA)	Responsible for completed elements of CA/T project. In 1997, was given authority for CA/T ownership, management, and operation.
Bechtel/Parsons Brinckerhoff (B/PB)	Management consultant for CA/T project. Served as owners' (MTA's) representative to the project. Managed design consultants and was project construction manager. Reviewed all design specifications and was secondary reviewer for all contractor submittals, including the D Street portal anchor adequacy submittal.
Gannett Fleming, Inc. (Gannett Fleming)	Section design consultant for the Interstate 90 (I-90) connector tunnel finishes. Adapted ceiling system design for D Street portal. Primary reviewer for contractor submittals, including the D Street portal anchor adequacy submittal.
Modern Continental Construction Company, Inc. (Modern Continental)	Construction contractor for I-90 connector tunnel finishes. Selected and installed the adhesive anchoring system used in the D Street portal.
Conam Inspection Services, Inc. (Conam)	Hired by Modern Continental to perform required proof testing of all adhesive ceiling support anchors installed by Modern Continental in the I-90 connector tunnel (including the D Street portal).
Newman Renner Colony, LLC (Newman Renner Colony)	Supplied the adhesive anchoring system selected and used by Modern Continental in the D Street portal. The system used epoxy supplied by Powers Fasteners, Inc.
Powers Fasteners, Inc. (Powers)	Supplied (through Newman Renner Colony) the epoxy used for anchors in the D Street portal.
Sika Corporation	Formulated the epoxy that was subsequently packaged and marketed by Powers for Newman Renner Colony and used in the D Street portal.

EXECUTIVE SUMMARY

About 11:01 p.m. eastern daylight time on Monday, July 10, 2006, a 1991 Buick passenger car occupied by a 46-year-old driver and his 38-year-old wife was traveling eastbound in the Interstate 90 connector tunnel in Boston, Massachusetts, en route to Logan International Airport. As the car approached the end of the Interstate 90 connector tunnel, a section of the tunnel's suspended concrete ceiling became detached from the tunnel roof and fell onto the vehicle. Concrete panels from the ceiling crushed the right side of the vehicle roof as the car came to rest against the north wall of the tunnel. A total of about 26 tons of concrete and associated suspension hardware fell onto the vehicle and the roadway. The driver's wife, occupying the right-front seat, was fatally injured; the driver was able to escape with minor injuries.

The National Transportation Safety Board determines that the probable cause of the July 10, 2006, ceiling collapse in the D Street portal of the Interstate 90 connector tunnel in Boston, Massachusetts, was the use of an epoxy anchor adhesive with poor creep resistance, that is, an epoxy formulation that was not capable of sustaining long-term loads. Over time, the epoxy deformed and fractured until several ceiling support anchors pulled free and allowed a portion of the ceiling to collapse. Use of an inappropriate epoxy formulation resulted from the failure of Gannett Fleming, Inc., and Bechtel/Parsons Brinckerhoff to identify potential creep in the anchor adhesive as a critical long-term failure mode and to account for possible anchor creep in the design, specifications, and approval process for the epoxy anchors used in the tunnel. The use of an inappropriate epoxy formulation also resulted from a general lack of understanding and knowledge in the construction community about creep in adhesive anchoring systems. In addition, Powers Fasteners, Inc., failed to provide the Central Artery/Tunnel project with sufficiently complete, accurate, and detailed information about the suitability of the company's Fast Set epoxy for sustaining long-term tensile loads. Contributing to the accident was the failure of Powers Fasteners, Inc., to determine that the anchor displacement that was found in the high-occupancy vehicle tunnel in 1999 was a result of anchor creep due to the use of the company's Power-Fast Fast Set epoxy, which was known by the company to have poor long-term load characteristics. Also contributing to the accident was the failure of Modern Continental Construction Company, Inc., and Bechtel/Parsons Brinckerhoff, subsequent to the 1999 anchor displacement, to continue to monitor anchor performance in light of the uncertainty as to the cause of the failures. The Massachusetts Turnpike Authority also contributed to the accident by failing to implement a timely tunnel inspection program that would likely have revealed the ongoing anchor creep in time to correct the deficiencies before an accident occurred.

The safety issues identified during this investigation are as follows:

- Insufficient understanding among designers and builders of the nature of adhesive anchoring systems;
- Lack of standards for the testing of adhesive anchors in sustained tensile-load applications;
- Inadequate regulatory requirements for tunnel inspections; and
- Lack of national standards for the design of tunnel finishes.

As a result of its investigation of this accident, the National Transportation Safety Board makes safety recommendations to the Federal Highway Administration; the American Association of State Highway and Transportation Officials; the departments of transportation of the 50 States and the District of Columbia; the International Code Council; ICC Evaluation Service, Inc.; Powers Fasteners, Inc.; Sika Corporation; the American Concrete Institute; the American Society of Civil Engineers; and the Associated General Contractors of America.

FACTUAL INFORMATION

Accident Synopsis

About 11:01 p.m. eastern daylight time on Monday, July 10, 2006, a 1991 Buick passenger car occupied by a 46-year-old male driver and his 38-year-old wife was traveling eastbound in the Interstate 90 (I-90) connector tunnel in Boston, Massachusetts, en route to Logan International Airport. As the car approached the end of the I-90 connector tunnel, a section of the tunnel's suspended concrete ceiling detached from the tunnel roof and fell onto the vehicle. Concrete panels from the ceiling crushed the right side of the vehicle roof as the car came to rest against the north wall of the tunnel. A total of about 26 tons of concrete and associated suspension hardware fell onto the vehicle and the roadway. The driver's wife, occupying the right-front seat, was fatally injured; the driver was able to escape with minor injuries. (See figure 1.)

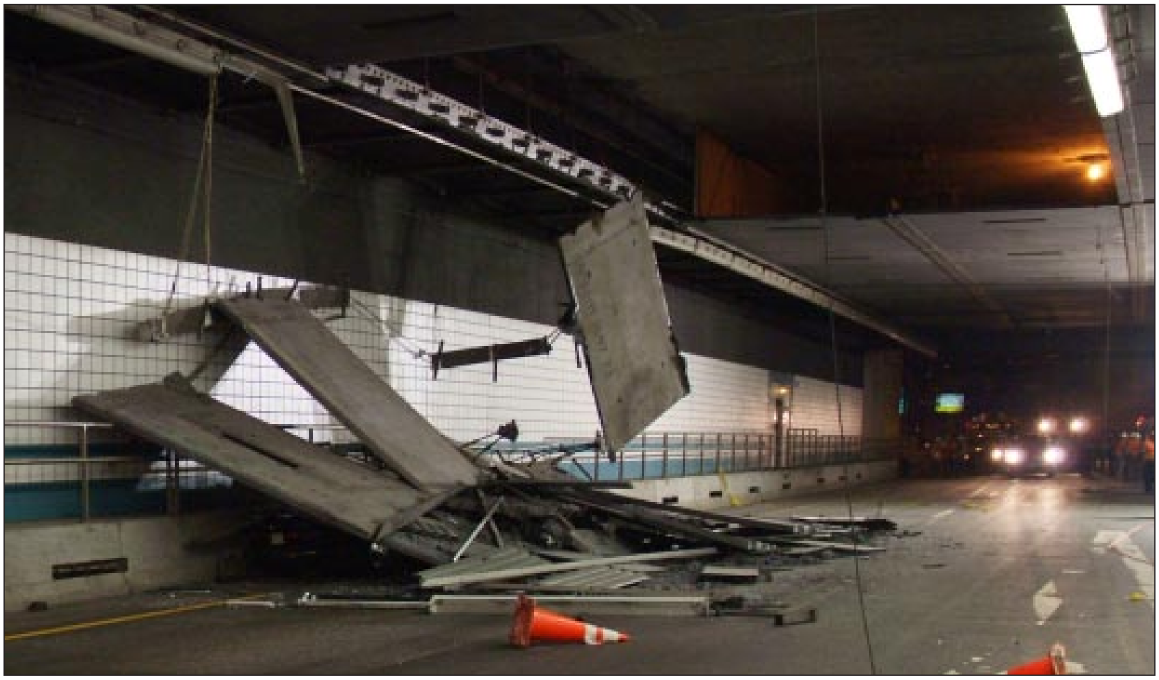

Figure 1. Postaccident scene with the crushed passenger car barely visible under the wreckage. The open area in the ceiling is the original location of the concrete panels. (Photograph courtesy Massachusetts State Police)

Accident Location (D Street Portal)

The accident occurred in the eastbound travel lanes of the I-90 connector tunnel[1] at mile marker 135.25, just west of the entrance to the Ted Williams Tunnel. The Ted Williams Tunnel carries traffic underneath Boston Harbor to Logan International Airport. (See figure 2.) The accident site was within a 200-foot-long section of the I-90 connector tunnel that will be referred to in this report as the D Street portal. The D Street portal actually comprised three tunnels—a two-lane westbound tunnel, a two-lane (with an acceleration lane) eastbound tunnel (the accident location) located south of the westbound tunnel, and a one-lane eastbound high-occupancy vehicle (HOV) tunnel located south of the other two tunnels.[2] (See figure 3.) The Ted Williams Tunnel, the I-90 connector tunnel, and the D Street portal were all built as part of Boston's Central Artery/Tunnel (CA/T) project. (The CA/T project will be discussed in more detail later in this report.)

Figure 2. Accident site.

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[1] In this report, "I-90 connector tunnel" refers to the I-90 tunnel between the Interstate 90 and 93 interchanges in downtown Boston and the entrance to the Ted Williams Tunnel.

[2] A short one-lane westbound exit ramp (Ramp F) tunnel paralleled the other tunnels at the accident location, but this tunnel had no suspended ceiling and will not be considered in this report.

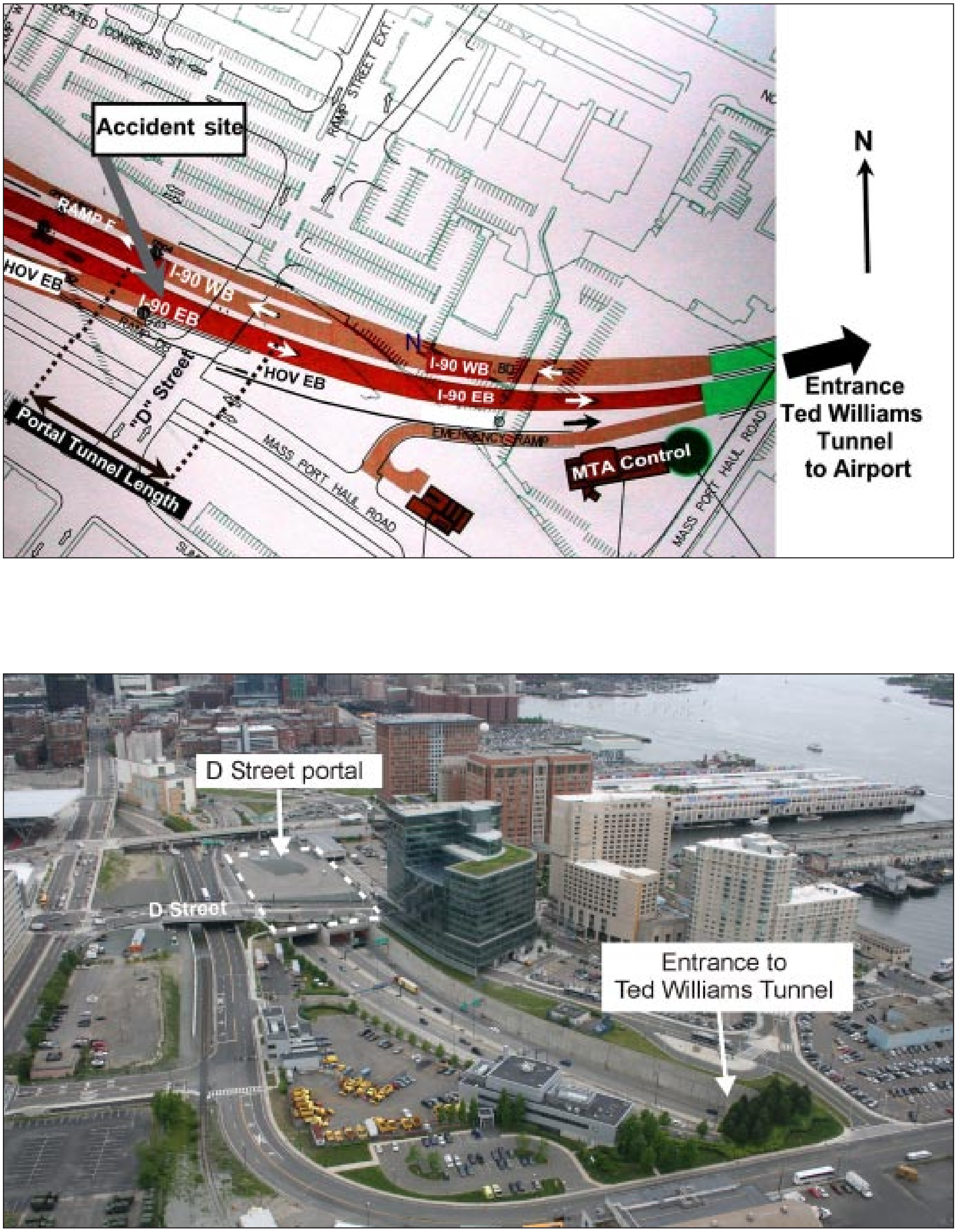

Figure 3. Plan view (top) and aerial view (bottom, looking west) of the D Street portal.

The D Street portal was built in 1993, before completion of either the Ted Williams Tunnel or the remainder of the I-90 connector tunnel. The portal was completed first in order to coordinate the construction sequencing with the traffic plan. That traffic plan required a temporary above-ground ramp to carry traffic from D Street to the entrance to the Ted Williams Tunnel in order to provide access under Boston Harbor to the airport before work was finished on the remainder of the I-90 tunnel. To accommodate the weight of a parking deck that was expected to be built over the portal, the tunnel roof was constructed of heavily reinforced[3] concrete, which was 5 to 7 feet thick.

The D Street portal was constructed by Kiewit/Perini/Atkinson/Cashman, JV (joint venture), of Boston, which was under contract to the Massachusetts Department of Public Works to construct the landside west tunnel approach to the Ted Williams Tunnel. The work consisted of approximately 2,600 feet of I-90 cut-and-cover tunnel[4] and one section of depressed open highway, as well as the D Street portal and a temporary ramp. The designer (the section design consultant) for this portion of the project was HDR Engineering, Inc., headquartered in Omaha, Nebraska.

The D Street portal was opened to traffic in phases. The accident site area was opened to traffic on December 14, 2000. Traffic was not routed through all the bores of the tunnel until the remainder of the connector tunnel was completed and opened to the public in January 2003. According to 2005 data provided by the Massachusetts Turnpike Authority (MTA), eastbound traffic through the I-90 connector tunnel (including the D Street portal) averaged 43,000 vehicles per day.

Site Description

The roadway in the eastbound D Street portal tunnel at the accident site consisted of two 12-foot-wide travel lanes and, along the south side of the tunnel, an 18-foot-wide acceleration lane. Raised walkways with 3 ½-foot-high steel handrails were on either side of the tunnel. The walkway on the north side of the tunnel was about 3 feet wide, elevated about 2 ½ feet above the road surface, and separated from the travel lanes by a 5-foot-wide shoulder. The south walkway was about 2 ½ feet wide, elevated 3 feet above the road surface, and separated from the acceleration lane by a 1 ½-foot shoulder. (See figure 4.)

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[3] The reinforcement was in the form of steel reinforcing bars of varying thicknesses (often referred to as "rebar") embedded in the concrete in both transverse and longitudinal directions.

[4] *Cut and cover* is a construction technique, typically used for shallow tunnels, in which a trench is dug and then roofed over.

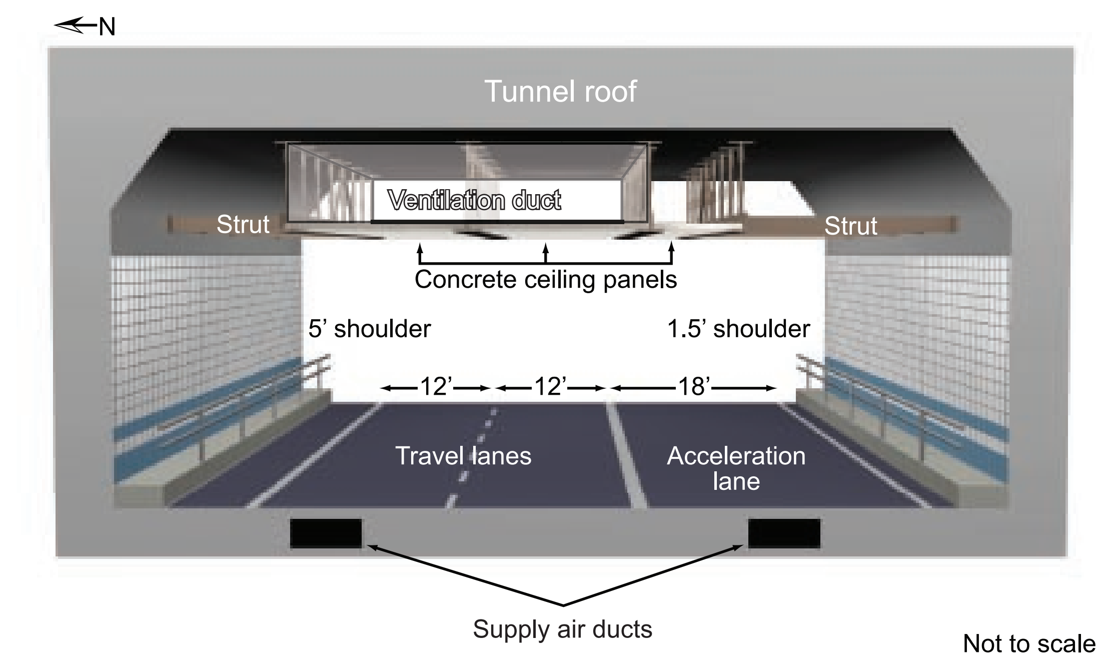

Figure 4. Cross section of the eastbound portal tunnel at the accident location.

Suspended over the roadway at the time of the accident was a ceiling consisting of concrete panels supported by a steel framework. This framework was, in turn, supported by a system of steel rods and turnbuckles attached to steel hanger plates. These hanger plates were affixed to the tunnel roof by stainless steel threaded rods (anchors) inserted into holes drilled in the concrete roof[5] and held in place with an epoxy adhesive.[6] (This anchoring system will be described in detail in the “Design and Specifications for the D Street Portal Ceiling” section of this report.) The distance from the road surface to the suspended concrete ceiling was about 17 feet. The distance from the top of the suspended ceiling to the tunnel roof was about 5 ½ feet.

The ceiling “module” at the site of this accident (designated module EB081) comprised 15 panels of reinforced concrete: two rows of five 12- by 8-foot concrete panels about 4 inches thick, each weighing about 4,700 pounds, and a single row of five 6- by 8-foot concrete panels about 4 inches thick, each weighing about 2,500 pounds. (See figure 5.) The larger panels made up the north and center rows of ceiling panels; the smaller panels made up the south row.[7] All 10 of the large panels

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[5] These holes were core-drilled using a cylindrical diamond drill bit.

[6] Although these threaded rods were sometimes referred to in CA/T project documents as “bolts,” in this report, they will be referred to as “anchors.” The combination of epoxy, threaded rod, and seal plug make up the anchoring “system.”

[7] This description applies to the eastbound tunnel only; the number and arrangement of panels differed in the westbound and HOV tunnels because of the different roadway widths.

fell onto the roadway in this accident, with only one corner of one panel remaining attached to the ceiling support structure. The row of smaller panels remained in place.

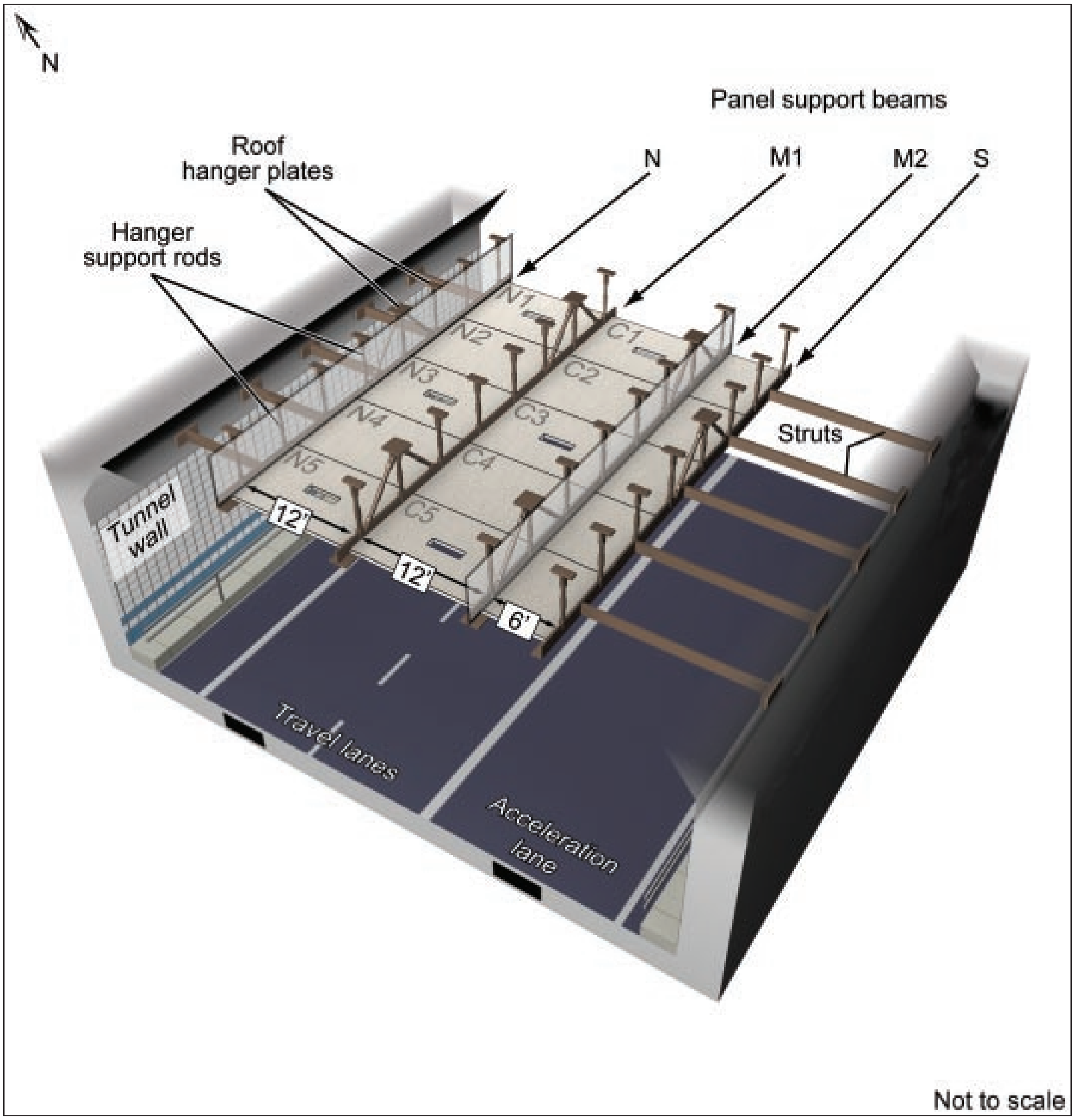

Figure 5. Overview of the support structure for the accident ceiling module. Panels and support beams show alphanumeric designations that were assigned during postaccident reconstruction.

Supporting the 15 concrete panels of the accident module were 4 steel support beams oriented parallel with the roadway—1 on the north side, 1 on the south side, and 2 toward the middle. The beam to the north (designated "N" by investigators) supported only the north ends of the five large panels in the north row. The first beam to the south (designated "M1") supported both the south ends of the northern row of panels and the north ends of the center row. The next beam ("M2") supported both the south ends of the large center panels and the north ends of the row of smaller 6- by 8-foot panels. The south beam ("S") supported only the south ends of the smaller panels.

Each beam was supported by eight vertical hanger rods attached by clevis connections to the support beam at the bottom and to the roof hanger plate at the top. (See figure 6.) In addition to the vertical support rods, angled (diagonal) hanger rods at several locations prevented movement of the ceiling system in the longitudinal direction (parallel to the travel lanes). Metal struts extending from the tunnel walls to either side of the ceiling module prevented transverse movement.

Two adhesive anchors (see figure 7) secured each of the 26 roof hanger plates (of the accident module) to which only vertical hanger rods were attached. Four anchors were used to secure the six roof hanger plates (two each for beams M1 and M2 and one each for beams N and S) that had both vertical and diagonal rods. Thus, beams N and S were each secured by 18 anchors, while beams M1 and M2 each used 20 anchors. The entire module was supported by 76 anchors. For reasons that will be discussed later in this report, the 200-foot-long D Street portal was the only section of the CA/T tunnel system to have a ceiling of this particular design supported solely by adhesive anchors.

A portion of the area between the suspended ceiling and the tunnel roof was used as a ventilation duct. The tunnel ventilation system was designed to maintain air quality in the tunnel and to remove smoke in the event of fire. Large-volume fans in above-ground buildings adjacent to the connector tunnel drew air into the tunnel from fresh air ducts underneath the roadway and exhausted it along the tunnel ceiling. Once the ceiling panels had been hung, two rows of corrugated metal panels were installed as sidewalls extending from the suspended ceiling up to the tunnel roof, creating (at the accident site) a ventilation duct 24 feet wide and 5 ½ feet high. (Refer to figure 4.) Air was drawn into this exhaust plenum through 3 ½ -feet by 9-inch exhaust ports in the center of some of the panels in each module. (Six of the 12- by 8-foot ceiling panels in the accident module had exhaust ports.)

The complete ceiling module at the accident site measured 30 feet wide and 40 feet long. The weight of the 15 concrete panels was about 60,000 pounds; the support beams, rods, hanger plates, and ductwork weighed an additional 17,000 pounds, for a total module weight of about 77,000 pounds. The weight of the concrete panels and supporting hardware that fell in this accident was about 52,000 pounds.

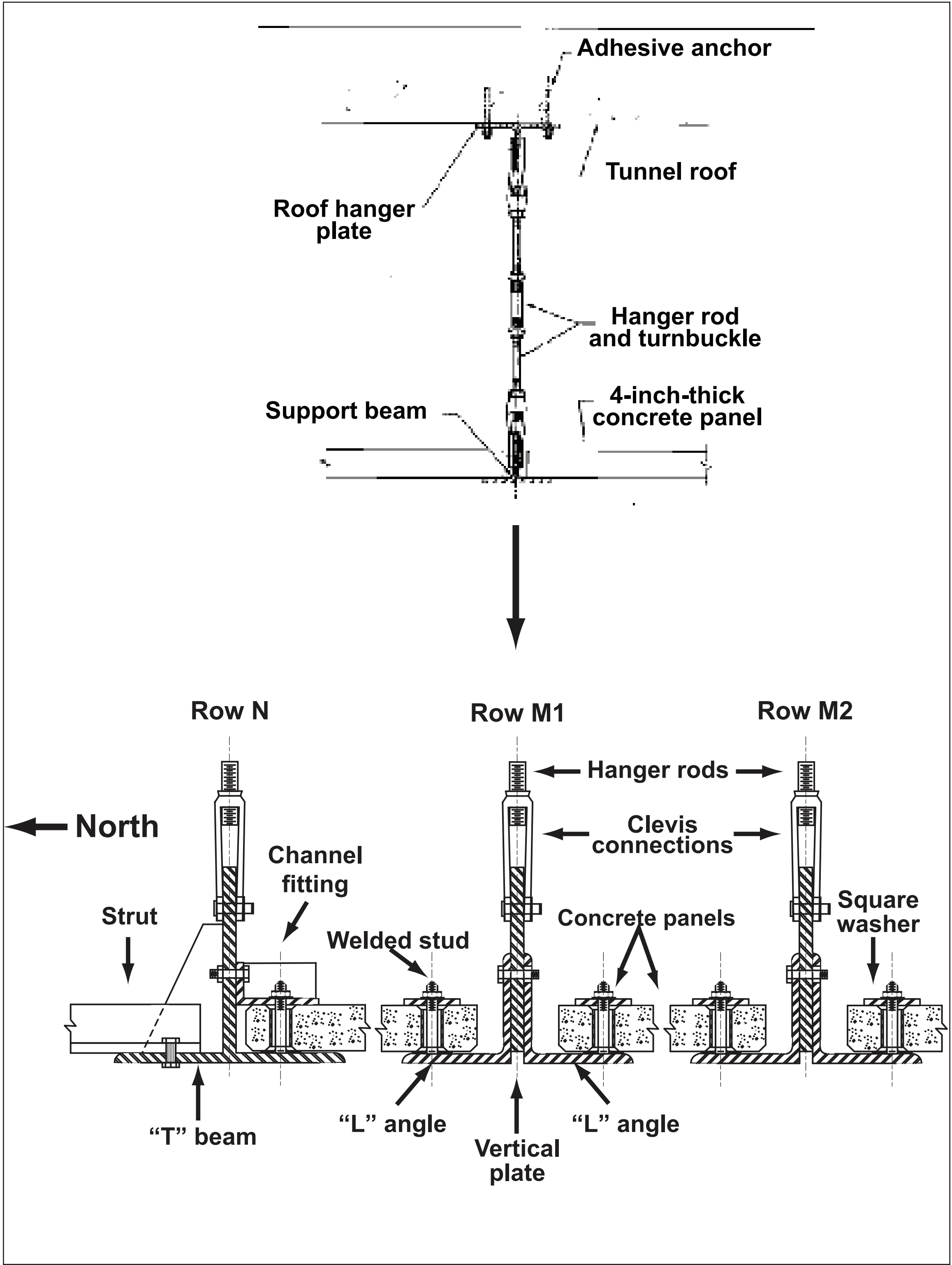

Figure 6. Cross section of the I-90 tunnel ceiling showing support beam and concrete panel connections (looking east, not to scale).

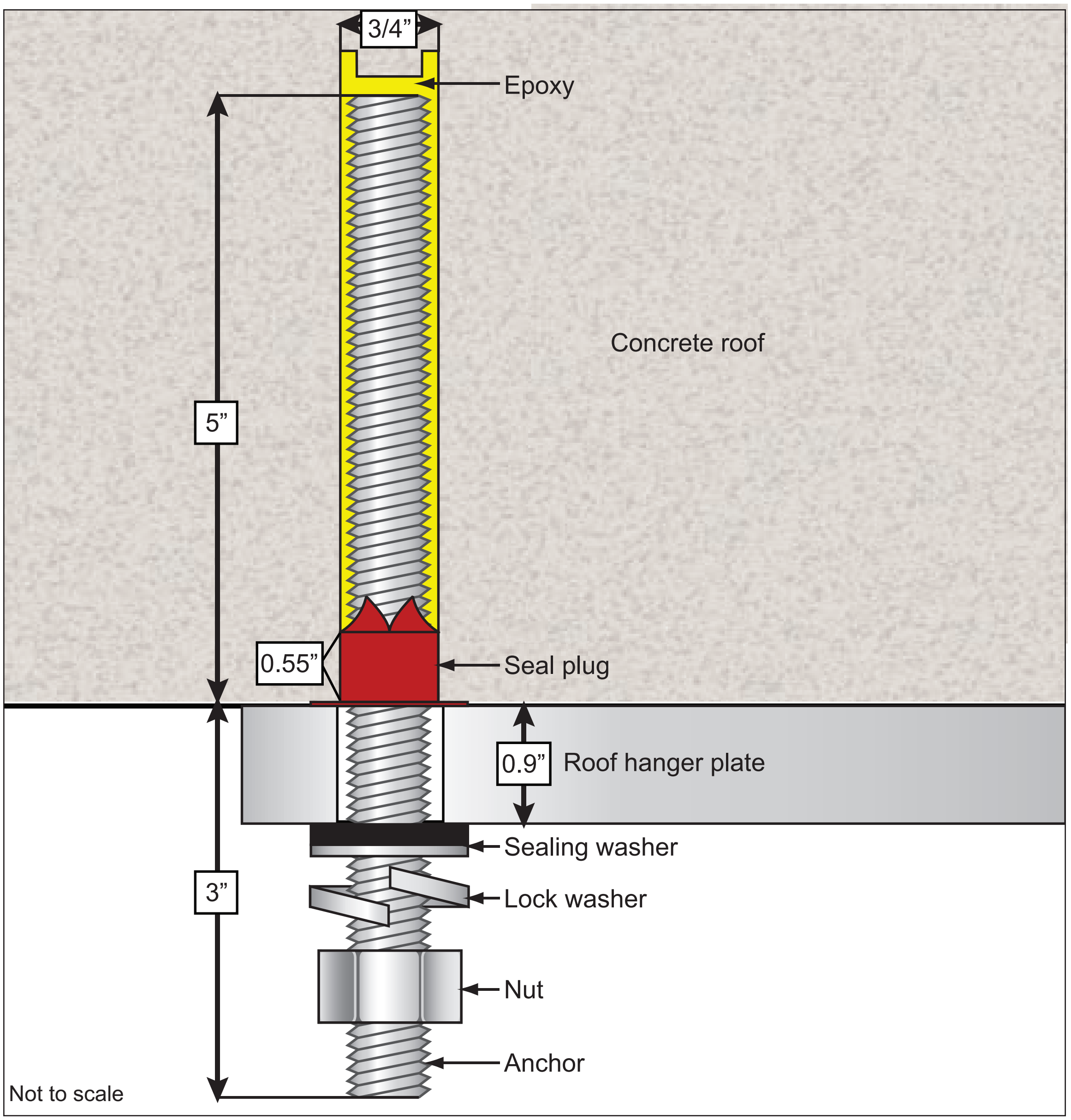

Figure 7. Typical adhesive anchor and roof hanger plate assembly.

The ceiling in the D Street portal was installed by Modern Continental Construction Company, Inc. (Modern Continental), of Cambridge, Massachusetts, between June 1999 and April 2000. The ceiling module that collapsed in this accident was installed in November 1999. Modern Continental installed the last ceiling module of the I-90 connector tunnel in July 2002.

Postaccident Inspection

The collapsed ceiling structure is shown in figure 8. For purposes of identification, investigators designated the individual concrete panels "N1" through "N5" (the north row) and "C1" through "C5" (the center row), from east to west (refer to figure 5). The relative positions of the fallen panels indicate that panels C1 through C5 and the south ends of panels N1 through N5 swung down and to the north. Panel N2 remained attached at its northeast corner to support beam N. Panels N1 and N3 fell back to the south on top of the center panels, thus their lower surfaces are visible in figure 8. Panels N4 and N5 came to rest leaning against the north wall or railing, and their upper surfaces are visible. The fallen panels were later removed from the tunnel and reconstructed as shown in figure 9.

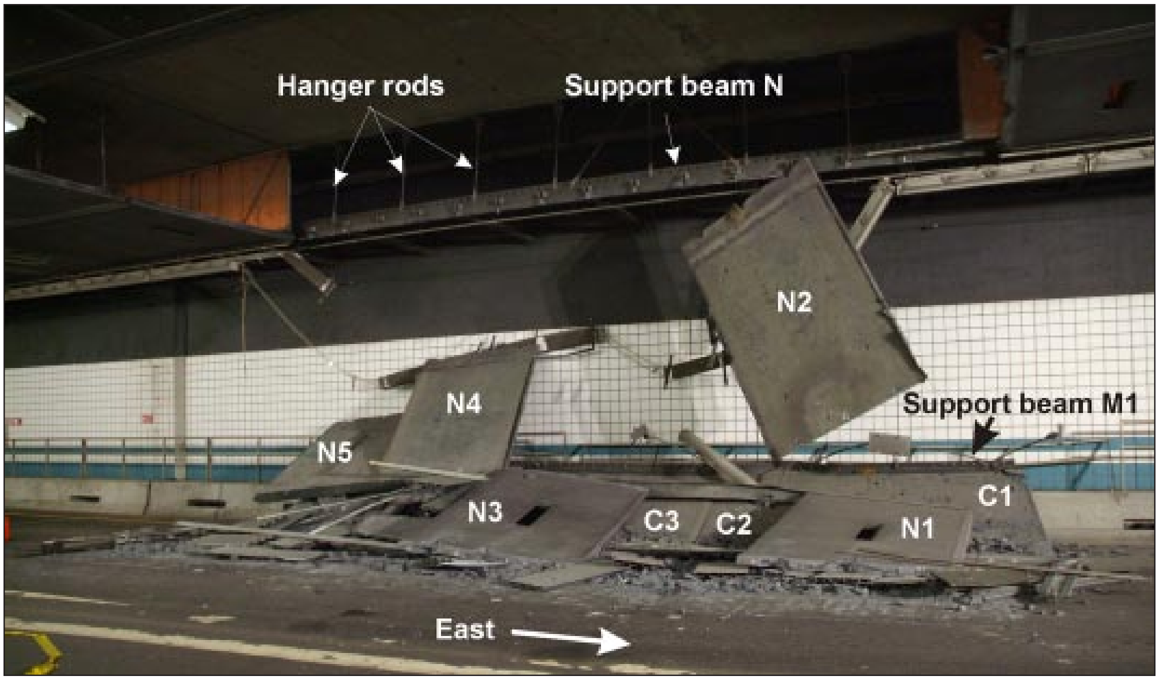

Figure 8. Looking north at the collapsed concrete panels before removal from the tunnel. Components shown as labeled for postaccident reconstruction. (Photograph courtesy Massachusetts State Police)

In addition to the concrete panels, the entire 40-foot length of support beam M1 and its hanger assembly fell onto the roadway or onto the wreckage. The hanger assembly included 8 vertical and 4 diagonal rod hangers, along with all 8 hanger plates and the 20 anchors that had attached the support beam to the tunnel roof. The north side of the ventilation duct enclosure also fell.

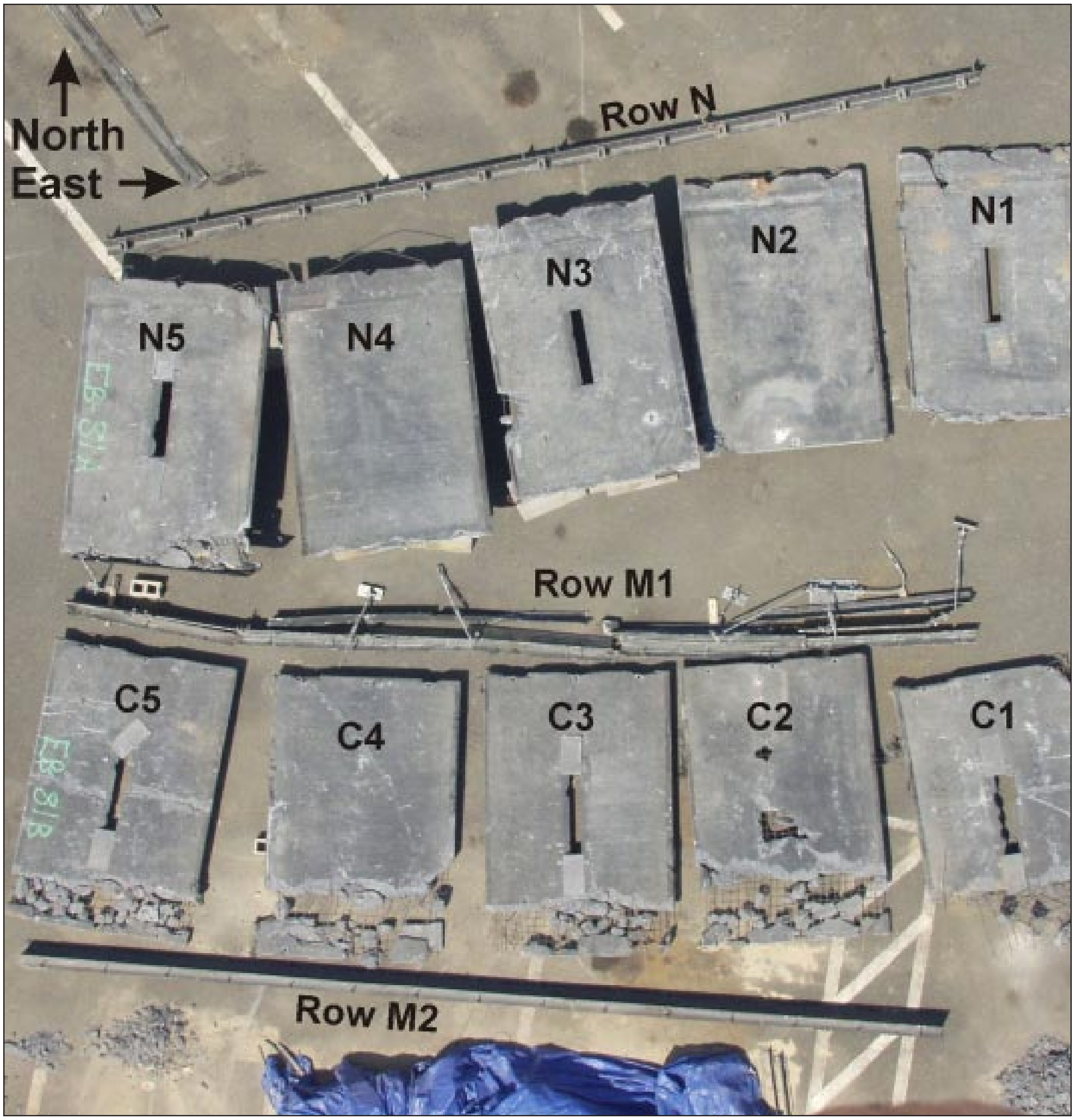

Figure 9. Collapsed panels after removal from the tunnel as rearranged in their original positions within the ceiling module. The upper surfaces of the panels are shown. (Photograph courtesy Massachusetts State Police)

Figure 10 shows some of the roof hanger plates and anchors in the westbound tunnel portion of the D Street portal as they were just after the accident (though they were not involved in the accident). Several of these hanger plates show evidence of significant displacement (movement downward from their originally installed positions).

Figure 10. This photograph, taken in the westbound D Street portal tunnel after the accident, shows a number of roof hanger plates that have begun to pull away from the tunnel roof, including the two-anchor hanger plate in the foreground and the four-anchor plate adjacent to it.

After the accident, all the ceiling panels and their support structures, except for the anchors themselves, were removed from all bores of the D Street portal. Each remaining adhesive anchor was subsequently examined to determine how much, if any, it had displaced from the tunnel roof since it was originally installed.

The examinations revealed that, in the westbound tunnel, 78 of the 198 anchors had displaced. In the eastbound tunnel, 57 of the 248 remaining (after the accident) anchors had displaced. In the HOV tunnel, 26 of the 188 anchors had displaced. The amounts of displacement ranged from less than 0.1 inch to more than 1.0 inch.

Displacement measurements taken by Safety Board investigators for all the anchors securing a particular hanger plate (either a two-anchor or four-anchor fitting) were averaged to generate a single number to represent the amount the hanger plate had moved downward. Figure 11 shows the relative displacement of the roof hanger plates in the three D Street portal tunnels as well as the distribution of displaced hanger plates within each module.

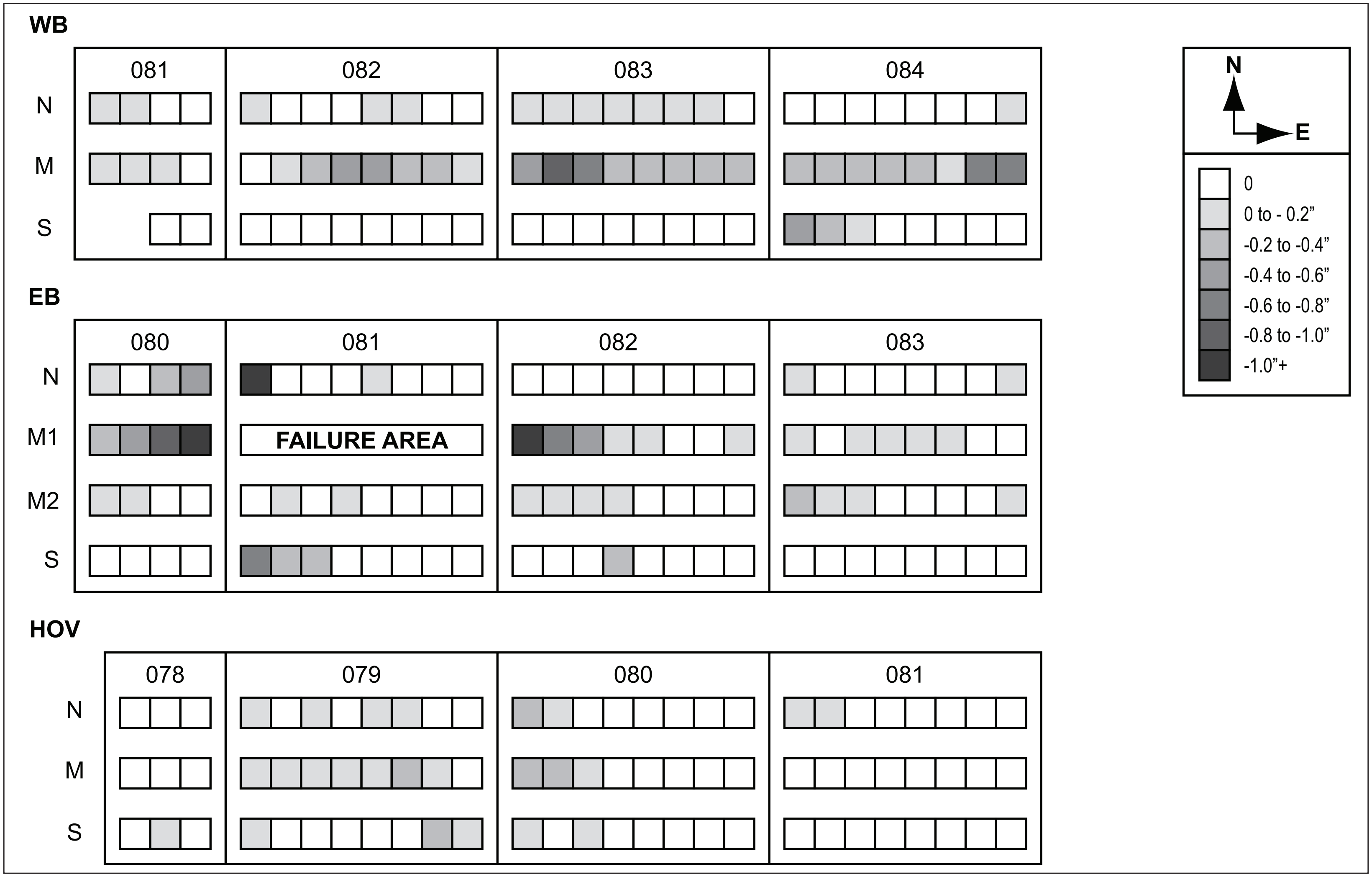

Figure 11. Graphic display of the displaced roof hanger plates found during postaccident inspection of the D Street portal tunnels. Each square on the chart represents a roof hanger plate (whether a two- or four-anchor plate). Shading of each square represents the amount of displacement.

Postaccident Actions

After the accident, State and local authorities closed the I-90 connector tunnel and its access ramps. The entire eastbound HOV tunnel (through both the I-90 connector tunnel and the Ted Williams Tunnel) was also closed. One I-90 access ramp, which was closed on July 10, 2006, was reopened on July 11 after shoring was installed for a portion of the ramp tunnel ceiling where a row of adhesive anchors showed displacement. This ramp was closed again on July 18 when concerns arose about anchor displacement that was found outside the shored area.

Over the succeeding weeks and months, engineers from the Massachusetts Executive Office of Transportation and Construction (EOTC), the Massachusetts Highway Department (MassHighway), the Federal Highway Administration (FHWA), the CA/T project, and independent consulting firms inspected the ceiling structures of the closed tunnels and ramps and the Ted Williams Tunnel to identify sites where corrective actions might be needed.

As part of these inspections, all of the adhesive anchors in the Ted Williams Tunnel (eastbound and westbound) were inspected, and 37 anchors from the three tunnel bores were proof tested.[8] Two anchors failed the proof test and were replaced with undercut anchors.[9] At four locations in the westbound Ted Williams Tunnel, the roof hanger plates had displaced from the tunnel roof. Two of these areas were shored temporarily until new hanger plates could be fabricated and installed using undercut anchors. The Massachusetts Executive Office of Transportation and MassHighway performed sustained load tests on selected anchors in an area of the westbound Ted Williams tunnel that could be closed to traffic long enough to conduct the tests. None of the tested anchors displaced during the tests.

The I-90 connector tunnel (except for the D Street portal area), including ramps to and from the tunnel, was surveyed, and 1,097 roof hanger plates were found to be installed with adhesive anchors.[10] Some of the approximately 2,200 adhesive anchors were found to have displaced by some amount from the tunnel roof. All of these anchors were replaced with undercut anchors, and at some locations, additional hanger plates were fabricated and installed, also with undercut anchors.

The suspended ceiling structure in the D Street portal was removed. During subsequent tunnel evaluations, it was determined that, because of the short length

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[8] A *proof test* is a nondestructive test in which a load greater than the expected normal service load is applied to a component. If the component is not permanently deformed by the test, it is considered acceptable.

[9] *Undercut* anchors are threaded mechanical fasteners that fit into holes that are drilled wider (undercut) at their deepest point. When installed, the tip of the anchor expands into the undercut area, holding tension loads by bearing against the concrete in the undercut area.

[10] Although the roof of the I-90 connector tunnel (other than the D Street portal section) was constructed with cast-in-place channel inserts for attaching ceiling supports, some of these channels were missing or misaligned, requiring the use of adhesive anchors at those locations.

of this tunnel section and its proximity to a tunnel opening, the suspended ceiling was not necessary for adequate tunnel ventilation. The ceiling structure was not replaced.

The closed tunnel sections and access ramps were reopened beginning in November 2006 as corrective measures were completed. The last closed tunnel section, the eastbound HOV tunnel, was reopened in May 2007.

Overview of the CA/T Project

The CA/T project—informally known as the "Big Dig"—was a 20-year effort (more than 14 years in the major construction phase) that is generally regarded as one of the most complex and costly public infrastructure projects ever undertaken in the United States. It was intended to improve traffic flow in downtown Boston by (1) replacing a deteriorated and congested elevated roadway (Interstate 93 [I-93], the "Central Artery" through Boston), (2) extending I-90 (the Massachusetts Turnpike, or Mass Pike) to Logan International Airport, (3) providing an interchange for Interstates 90 and 93, and (4) replacing the I-93 bridge over the Charles River. (See figure 12.)

The project, which is owned and managed by the MTA, is part of the Metropolitan Highway System. Although originally scheduled to be completed in 1998 at a cost of $2.6 billion, the main construction phase of the CA/T project was actually completed in 2006 at a final project cost in excess of $14 billion.

Construction of the CA/T project presented a number of significant, possibly unique, engineering challenges. Many of these challenges resulted from the need to conduct a major construction effort while minimizing disruptions to commerce and inconveniences to the public. In the case of I-93, the old elevated central artery roadway had to continue in use while the new highway was tunneled beneath it. In another instance, the new highway tunnel had to cross underneath an existing subway tunnel without disrupting subway train service. A portion of the I-90 connector tunnel was built beneath nine railroad tracks without affecting daily commuter and intercity passenger rail traffic.

Early in the construction phase of the project, CA/T owners and managers began to encounter construction delays and cost increases that attracted additional public and political attention to what was already a high-visibility project. According to officials responsible for oversight of the project, a major emphasis throughout the construction phase was keeping the project on schedule while keeping costs under control.

Figure 12. Central/Artery Tunnel project at completion. (Graphic courtesy MTA)

The project at completion consisted of 161 lane miles of highway along a 7 ½-mile corridor, with 5 miles of tunnel, 6 interchanges, and 200 bridges. The new I-93 north-south central artery is an 8- to 10-lane limited access underground expressway. The new east-west artery extends I-90 (Mass Pike) from its previous terminus south of downtown Boston through the new Ted Williams Tunnel under Boston Harbor to Logan Airport.

Management and Oversight of the CA/T Project

The CA/T project adopted a conventional design-bid-build approach to the various project sections and was set up with layers of public oversight and checks and balances, as described below.

Program Management

The Massachusetts Secretary of Transportation initially assigned overall responsibility for the CA/T project to the Massachusetts Department of Public Works.[11] Because no State agency had sufficient personnel or expertise to provide day-to-day management of a project of this magnitude, the Department of Public Works was directed to hire an experienced contractor as project manager.[12] Over the course of the CA/T project, this project manager would provide the following major services:

- Preliminary design
- Final design coordination and review
- Construction coordination and monitoring by inspectors and resident engineers
- Cost estimate preparation and actual cost reporting to project owners
- Right of way and other property acquisition
- Computer-aided design record-keeping
- Utility engineering and coordination
- Internal quality assurance
- Construction safety programs
- Construction contract administration as owners' authorized representative
- Standard drawings for the program
- Geotechnical engineering services
- Environmental services
- Engineering materials testing

In 1985, the Department of Public Works entered into an agreement with Bechtel/Parsons Brinckerhoff (B/PB)—a joint venture formed between Bechtel Corporation and Parsons Brinckerhoff Quade & Douglas—to prepare a preliminary project management plan. Later the same year, the department issued a 1-year

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[11] The information in this section is based on CA/T project contracts, reports, and other documents, historical data from a number of sources, and interviews with B/PB representatives and others responsible for or involved in the management or oversight of the project.

[12] This means of managing large projects is often used by State and local governments.

contract to B/PB to develop a comprehensive work plan for managing design consultants and reviewing their work. This contract was followed by a number of limited-term contracts with B/PB, called "work programs," that extended through the life of the project.

In its role as management consultant, B/PB was accountable initially to the Department of Public Works. In 1991, the Department of Public Works became MassHighway, and B/PB fell within the purview of that department. Between 1986 and 1993, the CA/T project was managed as a special, separate project of the Department of Public Works/MassHighway and was administered by a project director and staff.

In 1993, the EOTC signed a memorandum of agreement with MassHighway under which the CA/T project director would report directly to the EOTC rather than to MassHighway. The project director would approve the expenditure of funds, and the Board of Commissioners of MassHighway would process and approve contracts.

By 1995, as various CA/T highway segments were completed, more and more day-to-day management of the CA/T project had been transferred to the MTA, and in 1996, the project director for the CA/T project was transferred to that agency. In 1997, the Massachusetts Metropolitan Highway System was created, and the MTA was designated as the owner and operator. Because all elements of the CA/T project were included in the Metropolitan Highway System, the MTA was given authority for the ownership, management, and operation of the complete CA/T project.

Also in 1997, an agreement was entered into whereby key personnel of B/PB, the MTA, and MassHighway would work together as an "integrated project organization." Under this structure, the project staffs worked as a single organization under the direction of the MTA, which had authority to act on any matter relating to the management and administration of the CA/T project. The stated goal of the change in management structure was to streamline project management and improve cost effectiveness.

Throughout the project, the relationship between the MTA and B/PB was governed by the work program in place at the time. Subject to general MTA oversight, B/PB continued to function as the owner's representative in day-to-day administration of CA/T design and construction contracts.

All funding for the CA/T project continued to be provided through MassHighway, which was the State agency authorized to receive and disburse Federal funds. As the funding source, MassHighway also retained responsibility for awarding and executing design and construction contracts.[13] As part of

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[13] For that reason, all CA/T section design and construction contracts were with MassHighway, not the MTA.

the owners' oversight role, MassHighway and MTA engineers and project management staffs reviewed and evaluated B/PB's work. The FHWA also participated in reviews and oversight of almost all major B/PB recommendations and MassHighway/MTA decisions.

B/PB served as management consultant for the I-90 connector tunnel as described above until the MTA assumed responsibility for operations, inspections, and maintenance of the tunnel in January 2003.

Design

B/PB prepared the concept studies and preliminary design basis for about 25 percent of the total CA/T design effort. For greater manageability, the CA/T project was subdivided into a number of sections, each of which was designed and constructed under separate contracts. The final design of each project section, as well as the construction specifications, was the responsibility of the design engineering firm or firms[14] that had been selected as the "section design consultant" for that part of the project.[15]

The section design consultants were responsible for developing detailed, "stamped"[16] designs sufficient for construction contractors to bid and build the various sections of the project. The section design consultant was the primary reviewer of all construction proposals, with B/PB as the secondary reviewer. During construction, the section design consultants performed such services as reviewing shop drawings and submittals and preparing responses to construction contractors' requests for information. (RFIs) [17] B/PB's review of the section design consultants' designs focused primarily on determining whether the designs met the requirements of the CA/T project. Contractor questions or RFIs or clarification relating to the final design were typically referred to the section design consultant for resolution rather than to B/PB.

Construction

MassHighway, with the advice and assistance of B/PB, advertised the section design consultant's final design and specifications for bid, typically receiving proposals from three or more construction contractors. The selected contractor (usually the low fee proposal) was responsible for constructing the

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[14] Some project sections were large enough to support the efforts of two or more engineering firms working as a joint venture.

[15] The section design consultant for each part of the project was selected by a group of public employees impaneled for that particular contract. The selection was approved by MassHighway's Architect and Engineering Board.

[16] A plan is *stamped* when a Massachusetts registered professional engineer approves it and affixes an official seal.

[17] An RFI is a document used by a contractor to request additional information or to obtain clarification about some aspect of the construction.

project section in accordance with the contract design and specifications and its own quality control program. (The contractor was responsible for quality control, in accordance with the CA/T contract and general industry practice.)

Before the work started, B/PB reviewed the contractor's project-specific quality control program for conformance with the standards set out in the contract. During construction, the contractor performed quality control, to include, as necessary, providing material certificates and arranging for proof testing by a materials testing consultant approved by MassHighway. Certain materials used by the contractor were also tested by the CA/T project's construction laboratory, which was managed by B/PB, certified by the American Association of State Highway and Transportation Officials (AASHTO),[18] and independently assessed by MassHighway. The materials tested were predominately structural components such as asphalt, structural steel, and Portland cement concrete. Adhesive epoxy was not tested but was accepted based on materials certificates provided by the manufacturer.

From the onset of construction, B/PB was responsible for quality assurance, a responsibility carried out primarily through the office of the resident engineer. B/PB field engineers within the resident engineer's office were present in the field during construction to monitor the contractors' activities and to record all work being done in the field engineer daily report. The daily report was used to verify payment and resolve claims and to document acceptability of work and compliance with environmental requirements. All field engineer daily reports were required to include the acceptance and rejection criteria for the work, including any tests or inspections that were performed and their results, as well as any unusual events or deficiencies.

When deficiencies in the contractor's work were recurring, remained uncorrected, became irreversible, or resulted in unapproved deviations from the contract specifications, the resident engineer was required to create a deficiency report documenting the unacceptable performance, which was then transmitted to the contractor for resolution. If the contractor failed to take corrective action acceptable to the resident engineer, payment for the work could be withheld. No further payments would be made toward that part of the contract until the deficiency had been corrected in a manner acceptable to and verified by the resident engineer.

The resident engineer was also responsible for the receipt and verification of construction materials on the job site. This included responsibility for comparing the product delivered to the site with the product described in the approved submittal to ensure that it was the product approved for use on the job.

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[18] *AASHTO* comprises representatives of highway and transportation departments in the 50 States, the District of Columbia, and Puerto Rico. The association's mission is to advocate transportation-related policies and to provide technical services to help improve transportation safety and efficiency. AASHTO conducts research and performs data analysis and provides States and jurisdictions with written guidelines and standards on a variety of transportation topics.

B/PB was to facilitate the resolution of issues between or among contractors, section design consultants, and the project owners. Significant issues and challenges that arose during the design and construction of the CA/T project were typically brought to the attention of the project interface committee, a group that met weekly and that comprised representatives from the MTA, MassHighway, the FHWA, and B/PB.

Federal Oversight

The projected cost of the CA/T project exceeded the threshold ($5 million) necessary to qualify it for "full oversight" by the FHWA. The project also met this requirement because it was a part of the Interstate Highway System. As a project costing $1 billion or more (a threshold that has since been lowered to $500 million), the CA/T project also qualified as a "major project."

In its full oversight role, the FHWA was responsible for ensuring that the project adhered to Federal regulations and standards and for evaluating the State's programs and providing technical assistance, as necessary. The FHWA office in Boston, according to officials there, had as many as 15 staff members (in an office of about 30) working full- or part-time on the CA/T project. More typically, 6 to 8 staff members were assigned to the project at any one time. Staffing for the CA/T project began in 1986 when, for the first time in that office, a project engineer was assigned responsibility for this single construction project. Two additional engineers later joined the staff, at which time oversight of the I-90 and I-93 portions of the project were separated into the areas of environment, design, and construction. The addition to the team of structural and other engineers led to the creation of a project administrator position above the project engineer.

The FHWA reviewed and approved the preliminary and follow-on CA/T project designs. Because it was responsible for authorizing Federal expenditures for the project, the FHWA was required to review and approve all CA/T project construction contracts. The agency also reviewed and approved all plans, specifications, and estimates, although highway administration officials said that they did not have the time, the personnel, or the expertise to "review every detail of every design." Boston FHWA officials said they relied heavily on B/PB, which in this project was performing the role that would normally be carried out by a government agency, specifically, the State highway department.

Evolution of Ceiling Design in CA/T Project Tunnels

Ted Williams Tunnel

The sequence of construction for the CA/T project was developed based on the desire to provide, as early as possible, a third link from downtown Boston to Logan Airport. The main element of this link would be the new 3,850-foot-long immersed-tube[19] Ted Williams Tunnel, which, along with the smaller Boston Marine Industrial Park and Bird Island Flats tunnels, made up the I-90 (partial) route that was opened to traffic on December 15, 1995. At both ends of this route, temporary facilities were built to allow traffic to enter and exit the tunnels before the permanent facilities connecting to them were completed. At the west end of the route, a portion of the permanent tunnel structure had to be built to allow construction of a temporary ramp above it. This tunnel structure, the D Street portal, was thus constructed well before the other portions of the I-90 connector tunnel.

The Ted Williams Tunnel was designed by Sverdrup Civil, Inc., and constructed by J. F. White/Morrison–Knudson/Interbeton. Design documents did not require that the tunnel roof incorporate provisions for attaching a suspended ceiling, and no such provisions were made in the final design. The design documents did note that a ceiling would be installed after the roof was constructed. Construction began on the tunnel in 1991.

The ceiling system for the Ted Williams Tunnel was designed in 1992 by Domenech Hicks and Krockmalnic, Inc., of Boston, the section design consultant for the Ted Williams Tunnel finishes.[20] The ceiling design developed by the consultant consisted of 2-inch-thick precast panels of lightweight concrete[21] totally enclosed in porcelain-enameled sheet steel. The installed ceiling panels were typically bolted to the bottom flanges of longitudinal structural steel channel stringers, which, in turn, were suspended from the tunnel roof by steel pipe struts. Each hanger and brace was connected to the concrete roof slab or tunnel liner by two epoxy adhesive anchors. The panels extended to the tiled sides of the tunnel to create a uniform finish for the tunnel tube.

The support system for the ceiling panels had to be designed to accommodate the suction loads (calculated as 55 pounds per square foot in the Ted Williams Tunnel) created when the tunnel ventilation system was activated. Because the weight of the panels was less than the negative load created within the ventilation plenum above the ceiling, the ceiling support system was required to work in both tension and compression.

A typical panel in the Ted Williams Tunnel was about 11 feet long (although 5 ½-foot lengths were also common) and 4 feet wide. The cost of the panels was about $50 per square foot, or about $2,200 for a typical panel. The design dead

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[19] In *immersed-tube* tunnel construction, the tunnel segments are built elsewhere, usually floated and sunk into place, and then welded together.

[20] Tunnel *finishes* included ceiling panels and their structural support systems, light fixture support systems, tile sidewalls, walkway finishes, utility room cross passages finishes, floor and wall finishes, roadway-level exit doors and egress signage, and roadway paving and striping.

[21] *Lightweight concrete* is made by replacing some or all of the normal-weight aggregate with lightweight aggregate, which is typically a heat-expanded slate, clay, or shale. The cast density of lightweight concrete is about 115 pounds per cubic foot versus about 145 pounds per cubic foot for normal-weight concrete.

load[22] of the panels was about 28 pounds per square foot, for a typical panel weight of about 1,200 pounds. A total of about 20,000 panels and their associated 24,400 epoxy adhesive anchors[23] were installed in the Ted Williams Tunnel by general contractor Walsh Construction Company (Walsh) of Chicago, Illinois.

For the anchor adhesive in the Ted Williams Tunnel, Walsh selected UltraBond Epoxy supplied by U.S. Anchor Corporation (now Adhesives Technology Corporation). This material was approved for use by MassHighway in January 1994. In April 1994, Walsh submitted for approval another anchor adhesive, Epcon Ceramic 6 Epoxy, supplied by ITW Red Head of Wood Dale, Illinois. The stated purpose of the second submittal was "to ensure product availability in order to meet project schedule." The CA/T project laboratory commented on this submission, noting that this material did not meet the material specifications and that the manufacturer was not on the State's approved list. No documentation was found regarding resubmittals by Walsh for this product, but sometime in June 1994, according to the B/PB field engineer daily report, the contractor began using the Epcon material instead of, or concurrent with, the UltraBond product.

According to project documentation, installation of the ceiling in the Ted Williams Tunnel proved to be problematic. Contract specifications required that the installation contractor, before drilling, use x-ray or other technology to locate rebar in the tunnel roof. If rebar was encountered during drilling, workers were to abandon the hole and drill a new one 2 inches away. This proved to be unworkable. For a variety of reasons (density of the roof concrete, the amount of rebar in the roof, the epoxy coating on the rebar), neither x-ray nor any other technology could consistently locate the rebar.

At one point, almost half the drilled holes had encountered rebar and had been abandoned and patched. The delays caused by the redrilling threatened to delay the tunnel opening, and in November 1994, B/PB recommended, and MassHighway approved, drilling through rebar.

Early in construction, when the installed anchors were proof tested before being placed in service, failure rates ranged between 8 and 16 percent. A deficiency report was issued in response to the "extraordinarily high failure rate" for anchors that had been installed when water was visible on the tunnel roof. Project documents attributed other test failures to insufficient curing time for the epoxy, holes that were drilled too deep, an inadequate amount of epoxy, or holes that had not been properly cleaned. Dampness in the tunnel roof was also cited as an issue, and the anchor installation was delayed briefly because cold weather was thought to be inhibiting the curing of the epoxy.

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[22] *Dead load* is the weight of the materials and all fixtures and attaching parts. *Live load* refers to the transient load created by operation, environment, personnel, and equipment. The design live load for the Ted Williams Tunnel panels was 40 pounds per square foot.

[23] About 12,200 roof hanger plates were used in the Ted Williams Tunnel, each supported by 2 anchors. The maximum design load supported by each anchor ranged from 2,550 to 2,950 pounds, depending on the location.

In addition to the problems encountered during the drilling, setting, and testing of the anchors, the design of the panels also presented difficulties. The geometry of the tunnel required that many of the panels be fabricated to the dimensions of a specific location, which complicated the installation process and increased the time needed to fit the panels. Project managers and owner representatives also expressed concern about the long-term costs associated with maintaining the enameled ceiling.

In response to the high costs associated with the Ted Williams Tunnel finishes,[24] the FHWA, in February 1995, convened a value engineering[25] team to study tunnel finishes and develop recommendations for alternative finish systems. The stated purpose of the workshop was to "look at Tunnel Finishes…to determine if the overall material and construction costs might be reduced by adopting less costly design alternatives while still meeting finish system functional requirements."

Before the value engineering team issued its recommendations, the FHWA and MassHighway asked B/PB to expedite the identification of cost-saving alternative tunnel finishes that could be incorporated into the subsequent tunnel finish contracts for the I-93 and I-90 tunnels. The management consultant developed medium- and low-cost tunnel finish system options, which it presented to MassHighway and the FHWA. The finish options chosen by MassHighway combined elements of the medium- and low-cost options and included changing ceiling panels "to epoxy painted precast panels."

When the value engineering report was issued in March 1995, it offered the following options regarding tunnel ceiling finishes:

> **Option 0—**Panel weight 30 [pounds per square foot], cost $50 [per square foot] approximate: porcelain enameled steel face precast panels on a 4′ x 6′ grid of hangers (current design).
>
> **Option I—**Panel weight 35 [pounds per square foot], cost $44.69 [per square foot]: precast panels supported on a 4′ x 6′ grid (current design modified to remove porcelain enamel facing).
>
> **Option II—**Panel weight 50 [pounds per square foot], cost $34.55 [per square foot]: precast lay-in panels supported on continuous inverted steel tees at 12′ on center (tees are aligned with the lane edges).
>
> **Option III—**Panel weight 50 [pounds per square foot], cost $46.23 [per square foot]: cast-in-place concrete supported on continuous inverted steel tees at 12′ on center (tees are aligned with the lane edges).

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[24] The tunnel finishes contract for the Ted Williams Tunnel was valued at $49.5 million when it was issued in January 1993. When the work was completed in July 1996, the contract costs had risen to $78.2 million.

[25] *Value engineering* is a process used to improve the ratio of function to cost, that is, to achieve increased function at the same cost or equal function at a lower cost.

The report recommended that Option II be adopted for subsequent ceiling finishes. B/PB concurred in the recommendation "on the basis of maximum cost containment, for an estimated total projectwide savings of $65 million."

The recommendation was approved by the MTA and MassHighway, and in June 1995, cost containment measures were implemented that included changing "porcelain faced concrete ceiling panels to precast concrete ceiling panels supported on steel tee beams." It was thought that, because the dead weight of the panels was greater than the suction load created by the tunnel ventilation system, the ceiling suspension system, required to work in tension only, could be simplified.

I-93 Tunnel

The design consultant chosen for the I-93 tunnel finishes was a joint venture between Fay, Spofford and Throndike, Inc., and HNTB Corporation (FST/HNTB). FST/HNTB was responsible for designing a ceiling system for the I-93 tunnel that would incorporate the heavier precast concrete panels mandated by the FHWA, the MTA, MassHighway, and B/PB. The design requirement provided to FST/HNTB by B/PB specified that the support system for the ceiling be designed such that the failure of one support hanger would not result in a failure of the entire module. According to FST/HNTB representatives, this "one-hanger-out" scenario was considered in all design calculations and specifications.

In late 1996, the FST/HNTB team tasked with designing the ceiling system for the section of I-93 tunnel between Congress and North Streets developed a design that used steel beams, hanger rods, turnbuckles, and attachment plates to support a ceiling module of precast concrete panels. (Except for the way it was attached to the roof, this is the ceiling system that would later be used in the D Street portal.)

As with other sections of the I-93 tunnel, the section between Congress and North Streets had steel roof girders (I-beams) extending across the width of the tunnel. The ceiling support design developed by the team called for ¾-inch-diameter threaded steel studs to be welded to the roof girders. The hangers for the ceiling support beams would then be attached to the welded studs using nuts and washers. Because the hanger attachment was steel-to-steel, a safety factor[26] of at least 3 was specified, and calculations indicated that the design met this criterion. FST/HNTB provided preliminary drawings of the proposed ceiling support system through B/PB to MassHighway and the FHWA, both of which approved this design.

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[26] As used here, s*afety factor* is the ratio of the predicted *ultimate* load (maximum load before failure) to the calculated maximum *service* load. The safety factor is used to allow for uncertainties in the design and construction process. These uncertainties could involve design calculations, material quality, installation practices, or the operational environment. Considerations that influence the selection of an appropriate safety factor include the degree of uncertainty in the design and the potential consequences if the structure should fail.

Design Policy Memorandum No. 107

On March 13, 1997, MassHighway issued Design Policy Memorandum No. 107, subject: Tunnel Finish Details, which contained, "Clarifications to CA/T Directive Drawings & Implementation of Cost Containment Proposals Related to Tunnel Finishes." This memorandum gave new guidance to the section design consultants who would be responsible for subsequent tunnel finishes.

The cost-containment changes in the memorandum related to the tiled concrete tunnel side wall panels and to the suspended ceiling panels. In regard to the latter, the memorandum directed that, in the remainder of the tunnels, ceiling panels were to be installed only over the travel lanes (as opposed to covering the entire ceiling) except as required to accommodate the tunnel ventilation system.

The clarifications and changes to the directive drawings included changes to the ceiling support system "in response to constructibility & schedules issues and lessons learned from the [Ted Williams Tunnel]." Included as attachments to the memorandum were the FST/HNTB preliminary design sketches related to the proposed suspended ceiling for the I-93 tunnel between Congress and North Streets. The design policy memorandum directed that the section design consultants responsible for subsequent tunnel finishes use the ceiling system design shown on the attachments, adapting it as necessary to address location-specific issues.

I-90 Connector Tunnel

The tunnel finishes section design consultant for the I-90 connector tunnel (which included the D Street portal) was Gannett Fleming, Inc. (Gannett Fleming), headquartered in Camp Hill, Pennsylvania. Modern Continental was the construction contractor.

Because of the problems installing adhesive anchors in the roof of the Ted Williams Tunnel, MassHighway had directed that the roof of the 6,300-foot-long I-90 connector tunnel (except for the D Street portal portion, which had already been built) be constructed with cast-in-place channel inserts (Unistruts[27]) embedded in the concrete. For the suspended ceiling, Gannett Fleming engineers, as directed by Design Policy Memorandum No. 107, adapted the ceiling system developed by FST/HNTB, using the embedded steel channel inserts (instead of roof girders) for the roof attachments.

Project records show that about 2,000 adhesive anchors were installed in the Unistrut portion of the I-90 connector tunnel at locations where the builder either did not install a section of steel channel, installed it too deeply into the concrete to be used, or installed it such that the roof hangers supporting the ceiling could not be aligned properly. At these sites, which represented about 10 percent of the total number of anchor locations in the Unistrut portion of the tunnel, Modern

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[27] Unistrut is a registered trademark of the Unistrut Corporation and its affiliates.

Continental used adhesive anchors to secure the ceiling hanger plates to the tunnel roof. Because the D Street portal was constructed without the embedded Unistrut channels, all of the ceiling hanger plates in that part of the tunnel were secured to the tunnel roof with adhesive anchors.

Design and Specifications for the D Street Portal Ceiling

Anchor Alternatives

In 1996, according to project documents, Gannett Fleming planned to specify the use of undercut anchors to attach the suspended ceiling in the D Street portal. B/PB became aware of these plans and, in a January 13, 1997, telephone call to Gannett Fleming, directed the design consultant not to use undercut anchors. According to Gannett Fleming records, B/PB cited problems another project contractor had experienced while installing the undercut anchors.[28] The B/PB representative told Gannett Fleming that the directive not to use undercut anchors would apply project-wide and that previously installed undercut anchors would be removed.

After receiving this directive, Gannett Fleming continued to pursue approval to use undercut anchors. The company researched various types of anchoring systems, with particular emphasis on identifying the type of anchor that would perform best should flexure cracking occur in the concrete base material. In an August 25, 1997, letter to B/PB, Gannett Fleming summarized the company's findings for three types of anchors—resin-bonded (adhesive), undercut, and expansion[29]—that could be used in the D Street portal. The research focused only on applications in which the anchors would be in pure tension in cracked concrete.

Resin-Bonded. In regard to resin-bonded anchors, the Gannett Fleming letter referenced a research finding that, in cracked concrete, the common resin-bonded anchor may retain only 40 percent, and possibly as little as 20 percent, of its normal (in uncracked concrete) ultimate load capacity. The letter also cited manufacturer's literature to the effect that the anchor would lose strength at temperatures between 120° F and 230° F. The letter stated that, "Meeting high temperature requirements as well as maintaining design capacity appears difficult with resin bonded anchors."

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[28] According to the written phone record, B/PB noted that unless the holes were placed accurately and undercut properly with specialized equipment, the anchors could be pulled out by hand.

[29] *Expansion* anchors are mechanical fasteners that expand when tightened, transferring tension loads from the anchor to the concrete substrate by friction.

Undercut. In regard to undercut anchors, the letter cited a report finding that such anchors in cracked concrete would retain 65 to 70 percent of their normal ultimate load capacity and would perform similarly to steel under high temperatures. The letter stated that, "These anchors appear to have the desired characteristics for supporting the ceiling in the subject tunnel."

Expansion. In regard to expansion anchors, the letter cited research indicating that such anchors, which typically do not have the capacity to post-expand in cracked concrete, are unsuitable for use in pure tension applications.

The letter concluded by suggesting a meeting "as soon as possible to discuss our findings and to obtain direction on the anchor preferred by B/PB." Although no written record could be found of a subsequent meeting or discussion regarding anchor alternatives, B/PB at some point directed, and Gannett Fleming accepted, that undercut anchors would not be used in the D Street portal.

Ceiling Panel Alternatives

On January 13, 1999, Modern Continental submitted a value engineering cost proposal[30] to B/PB suggesting an alternative ceiling system for the I-90 connector tunnel. The company proposed using a Celline metal panel structural ceiling system provided by Environmental Interiors, Inc., of Hudson, New Hampshire, in lieu of the precast concrete panels. The proposal stated that, based on reduced cost of materials, transportation, and labor, use of the Celline system could save the project $4 million. According to Environmental Interiors, "The entire Celline system (including optional full backer sheet) weighs less than 10 pounds per square foot."

On February 24, 1999, B/PB responded that project personnel had evaluated the proposal and concluded that, as presented, it was unacceptable. The response advised that final acceptance of the proposal and permission to proceed would be withheld pending

> 1.) Review and acceptance of the vendor's revised design and their structural calculations by the Project;[[31]] 2.) Review and acceptance of prototype panel testing results; and 3.) Project assessment of the initial system cost and its life cycle cost.…

On March 9, 1999, Environmental Interiors, citing a lack of responsiveness from B/PB, withdrew its proposal to provide the Celline ceiling system for use in the I-90 tunnel. On March 25, 1999, B/PB officially notified Modern Continental that the value engineering cost proposal was not considered viable for implementation and should not be pursued further. The notification letter stated

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[30] Contractors were encouraged and offered incentives to submit *value engineering cost proposals* that identified less costly or more effective alternatives for meeting project goals.

[31] Meaning B/PB, MassHighway, the MTA, and the FHWA.

> Considering the current status of your material purchase orders, the precasters expended engineering and buy-out costs, and unresolved engineering issues, we agree that a substantial cost and/or schedule savings for this project do not appear feasible.

Anchor Loading Calculations

In an August 4, 2006, written response to a Safety Board inquiry,[32] Gannett Fleming officials explained the design principles and load factors used in the contract specifications for the ceiling suspension system for the I-90 connector tunnel (including the D Street portal). According to that submittal, Gannett Fleming engineers calculated the maximum service load for each anchor as follows:

For the two-anchor roof hanger plates supporting a single vertical hanger rod (26 plates and 52 anchors in the accident module)

> Load per anchor: 2.6 kips[33] (1.8 kips dead load plus 0.8 kips live load) based on a 5-foot by 12-foot tributary area consistent with a hanger spacing of 5 feet and a panel of 12 linear feet.
>
> Suction load that would result from maximum activation of the tunnel ventilation system was specified as 42 pounds per square foot negative load (–1.3 kips), reducing the dead load under those conditions to 0.5 kips per anchor.

For the four-anchor roof hanger plates supporting one vertical hanger rod and two diagonal rods (6 plates and 24 anchors in the accident module):

> Load per anchor: 2.15 kips (1.3 kips vertical dead and live loads plus 1.6 kips vertical component of seismic load, with this total reduced for allowable overstress while under seismic load).

According to the letter, Gannett Fleming specified that the construction contractor must use epoxy anchors capable of supporting a load of 4.0 kips (instead of the calculated maximum service load of 2.6 kips) to allow for possible flexure cracking in the concrete. A safety factor of 4 was also specified. The required average ultimate load of the anchor would thus be 16 kips (a 4-kip specified load with a safety factor of 4) or 16,000 pounds.

A Gannett Fleming memorandum documenting an October 9, 1998, meeting between Gannett Fleming and B/PB representatives indicates that B/PB directed, for the one-hanger-out scenario, "use of a safety factor of two (2) applied to the

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[32] The submittal was updated by Gannett Fleming on November 2, 2006.

[33] One *kip* (kilo-pound) equals 1,000 pounds of force.

manufacturer's ultimate capacities."[34] The letter to the Safety Board stated that Gannett Fleming engineers calculated the additional load that would be transferred to the remaining anchors in the event of a failure of an end hanger (identified as most critical). They determined that those hangers would retain a safety factor of 2 after application of the additional load from a failed end hanger.

Anchor Selection

As the construction contractor for the I-90 connector tunnel finishes, Modern Continental was responsible for choosing, installing, and arranging for proof testing of the anchors in the D Street portal in accordance with Gannett Fleming and B/PB specifications. B/PB authorized Modern Continental to proceed on the contract on November 16, 1998.

The I-90 connector tunnel finishes contract contained two specifications for adhesive anchors. One of these, Specification 960.050, "Miscellaneous Metals for Buildings," addressed "the requirements for miscellaneous fabrications for tunnel finishes and for tunnel stairways, utility spaces and passages."

The specification regarding the ceiling support anchors was "Precast Concrete Ceiling System" Specification 723.480. This was a performance-based specification prepared by Gannett Fleming that required that the contractor

> Provide chemical adhesive type anchor system to anchor support system to concrete structure. Provide rods, washers and nuts fabricated of compatible steel in the diameters and embedment lengths shown on the drawings. Provide adhesive consisting of 2 component (plastic resin and catalyst hardener) mixture. Resin material shall remain unaffected by continuous humidity and by chemicals present in a vehicle exhaust type of air duct environment.

In the specification, Gannett Fleming defined the minimum design service loads, the minimum factors of safety, and other design criteria and installation requirements that had to be met with the choice of anchor. The specification did not contain criteria for assessing long-term performance of the anchoring system or detail an appropriate inspection program.

The anchoring system selected by Modern Continental used a two-part (generically, a "resin" and a "hardener") epoxy material formulated by Sika Corporation, of Lyndhurst, New Jersey; packaged by Powers Fasteners, Inc. (Powers) (formerly The Rawlplug Company, Inc.),[35] of New Rochelle, New York;

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[34] According to Gannett Fleming, the safety factor was within the guidelines established for the portions of the I-90 tunnel with embedded channel inserts.

[35] In the 1990s, The Rawlplug Company, Inc., which marketed its epoxies and anchors under the Rawl brand, became Powers Fasteners, Inc. During the transition from Rawlplug to Powers Fasteners, the company was sometimes referred to as Powers *Rawl*.

and distributed by Newman Renner Colony, LLC (Newman Renner Colony), of Westwood, Massachusetts. Sika Corporation supplied the epoxy resin and hardener in bulk[36] to Powers, which packaged, marketed, and distributed the material first as Foil-Fast (supplied in foil packages under the Rawl name), then as Power-Fast Epoxy Injection Gel. Serving as a wholesaler, Powers packaged this same product for Newman Renner Colony as NRC-1000 Gold epoxy, and this is the name under which it was purchased by Modern Continental. On June 3, 1999, Modern Continental signed an agreement with Newman Renner Colony to purchase fasteners, hangers, anchor rods, and miscellaneous metals, in addition to the epoxy. The anchors themselves were threaded rods ⅝ inch in diameter and 8 inches long.

The accident investigation revealed that, although the epoxy provided by Powers was available in either slow-setting (Standard Set) or quick-setting (Fast Set) formulations,[37] at the time Modern Continental entered into the purchase agreement for the anchoring system, Powers was packaging only the Fast Set version of its Power-Fast epoxy for "private label" distribution by Newman Renner Colony. The NRC-1000 Gold cartridge labeling at the time did not indicate that the material was Fast Set but showed the catalog No. 8431, which was identified by Powers as the Fast Set formulation.

According to internal Powers correspondence dated June 3, 1999 (the same day Modern Continental signed the purchase agreement with Newman Renner Colony), Powers was beginning the process of having the Standard Set Power-Fast epoxy also packaged as NRC-1000 Gold. According to this correspondence, the Standard Set material was being provided to Newman Renner Colony in anticipation of a need for the slower-setting epoxy for future projects. The addition of Standard Set epoxy to the Newman Renner Colony line would require new labeling to indicate Fast Set or Standard Set. The correspondence indicated that Newman Renner Colony had placed an order for 1,000 units of the catalog No. 8431 (Fast Set) material and had placed an initial order for 120 units of the newly packaged Standard Set epoxy to be used for U.S. Department of Transportation (DOT) projects requiring an International Conference of Building Officials certificate (the correspondence did not indicate which DOT projects were being referenced). The correspondence stated, "We [Powers] have told them [Newman Renner Colony] that production for this product [the Standard Set formulation packaged as NRC-1000 Gold] would be 4-6 weeks."

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[36] Sika Corporation supplied the epoxy components in bulk to Powers until 2002, when the company began to market the product itself under the Sikadur brand. At that time, the company began supplying the material to a third company, which then packaged the epoxy both for Sika Corporation and for Powers. Sika Corporation's fast-setting version is marketed as Sikadur Injection Gel AnchorFix-3.

[37] Powers product literature reports that its Standard Set formulation takes about twice as long to gel (begin to harden) as the Fast Set. For example, at 75° F, the listed gel time for Standard Set epoxy is 35 minutes versus 15 minutes for Fast Set. Qualification testing indicated that, at a base material temperature of 75° F, minimum curing time (during which the anchor should not be disturbed) was 2 hours for Fast Set and 6 hours for Standard Set. Full curing (the minimum time required for maximum load capacity) was 24 hours for both formulations.

The Powers manual current at the time of the D Street portal ceiling design was the *Fastening Systems Design Manual,* second edition (dated 1997).[38] In regard to the two epoxy formulations, the manual stated

> *Power-Fast* Epoxy Injection Gel is available in either fast and slow setting versions to provide the installer with a choice of gel and curing times. For example, in warmer weather, the slower setting version is normally used as it allows the installer time to properly fill anchor holes prior to the point at which the material begins to gel or solidify.

The manual provided different values for the Fast Set and Standard Set versions in regard to tensile strength, flexural strength, and slant shear strength, but it did not indicate any differences in the bond strength or long-term behavior of the two epoxy types in anchor applications. The tables of ultimate strength and allowable strength (calculated from the ultimate strength using a safety factor of 4) for various anchor and base material combinations applied to both formulations.

The Power-Fast[39] anchoring system (at that time, the Rawlplug Foil-Fast Injection Gel anchoring system) had been tested in 1992 in accordance with standards established by the International Conference of Building Officials (ICBO),[40] an organization that promulgated standards and published independently generated physical property data on manufacturers' products, including adhesive anchors. The test results for the Power-Fast system (as well as for Powers Chem-Stud Capsule adhesive anchoring system) were contained in the April 1992 version of ICBO Evaluation Service, Inc. (ICBO ES), evaluation report (ER) 4514 (ICBO ER-4514). That report made no distinction in the bond strength or long-term performance of the Powers Fast Set versus Standard Set epoxies.[41]

By 1997, Powers was in the process of expanding and updating the information in the ICBO evaluation report for its Power-Fast epoxies. As part of this process, additional testing was performed on the epoxies by CTI Engineering (subsequently CEL Consulting), of San Lorenzo, California, in accordance with ICBO Acceptance Criteria (AC) 58, *Acceptance Criteria for Adhesive Anchors in*

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[38] The information in the 1997 version of the Powers manual was identical to that in the 1992 version of ICBO Evaluation Service, Inc., evaluation report 4514, also discussed in this section.

[39] All the data pertaining to this product would apply equally to the NRC-1000 Gold epoxy used in the D Street portal.

[40] In 1994, the ICBO, along with the Building Officials and Code Administrators International, Inc. (BOCA), and the Southern Building Code Congress International, Inc. (SBCCI), founded the International Code Council (ICC) to develop a single set of international codes without regional limitations.

[41] Although testing done for ICBO (now ICC) qualification is performed by independent testing agencies, the testing is funded by the manufacturer of the product being evaluated, and the manufacturer has substantial influence on the content of the final evaluation report.

Concrete and Masonry Elements and ASTM[42] E 1512, *Standard Methods for Testing Bond Performance of Adhesive-Bonded Anchors*.

A CTI Engineering report initially issued in March 1996 and reissued in March 1997 detailed the results of a 120-day creep[43] test performed by the company on the Power-Fast Standard Set epoxy. This test was performed in accordance with the provisions of the January 1995 edition of AC58, and the Standard Set epoxy passed.

AC58 did not require creep tests, but the criteria did specify it as an optional test. The optional test was a pass/fail test under which the tested material was subjected to one load at a single temperature for a specified time. Powers representatives confirmed that the Rawl Foil-Fast (later renamed Power-Fast) Fast Set epoxy had been creep tested in 1995 and 1996. These tests were done in accordance with AC58 standards, which required that the anchors be tested at 110° F under a load of 40 percent of the ultimate anchor strength as measured at 70° F. The Fast Set epoxy failed the tests. Documents acquired by the Safety Board showed that, in this same time frame, Powers pursued additional creep testing of Fast Set epoxy anchors at lower loads or lower temperatures than those specified in AC58. Some anchors were tested at 110° F under loads of 40 percent and 25 percent of the ultimate anchor strength at 70° F. All of these anchors pulled out in less than 2 days. Anchors also failed when tested at 90° F and 70° F under a load of 40 percent of the ultimate strength at 70° F. No evidence was found that the Fast Set epoxy formulation that was available in the mid-1990s had ever passed a creep test at any temperature.

The Safety Board obtained a copy of an August 15, 1996, letter from Powers to the epoxy formulator (Sika Corporation) in which Powers referenced the failed creep test on the Fast Set material. The letter asked Sika Corporation to compare the Powers Fast Set epoxy with other epoxies that had passed the creep test in an attempt to determine whether the Fast Set could be reformulated to pass the test. No source of the difference in performance was identified by the test method used, and the epoxy was not reformulated.

Powers representatives told the Safety Board that the company was not able to recover all of its quality control records for 1997 and 1999 but that, based on records that were available, no anomalies had been identified in the Fast Set or Standard Set epoxies sold in that time frame. Additionally, recovered records for two batches of the Power-Fast epoxy sold under the NRC-1000 Gold label from 1997 through 1999 did not indicate any anomaly in the product.

Sika Corporation representatives reported that between 1997 and 1999, a single batch of the resin that failed to satisfy the company's internal quality control

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[42] ASTM International, formerly known as the American Society for Testing and Materials, is an international standards organization that develops and publishes standardized testing methods used to evaluate a wide range of materials, products, systems, and services.

[43] *Creep* is a gradual, continuing deformation of a material under sustained load.

tests was discarded. One batch of the hardener was also rejected before quality control testing. All batches of the resin and hardener provided in bulk by Sika Corporation to Powers from 1997 to 1999 met Sika Corporation's internal quality control standards.

Anchor Approval

The D Street portal construction contract required that Modern Continental submit for approval documentation that addressed the technical qualifications of the chosen adhesive anchoring system. These documents would be evaluated and approved by Gannett Fleming and reviewed by B/PB for acceptability and compliance with the contract specifications.

The first three anchor adequacy submittals forwarded by Modern Continental for approval were returned, unapproved, with a request for additional information. In December 1999, Modern Continental prepared a fourth anchor adequacy submittal. The anchor service load data in the submittal were the values calculated and specified by Gannett Fleming. The anchor load capacity data were taken from the Powers design manual, second edition. According to the manual, the Powers adhesive anchors were capable of supporting up to 6,350 pounds[44] each (in 4,000-psi concrete) while maintaining a safety factor of 4 against ultimate load (in this case, 25,400 pounds). The data included in the submittal made no reference to which epoxy formulation was to be used.

This fourth submittal also included a copy of a draft revision of ICBO ER-4514 dated October 1999. Modern Continental included this draft report in response to a specific request by the Gannett Fleming engineer based on his review of a previous submittal. The draft report revision limited the use of the Power-Fast Fast Set epoxy to "short term loads such as those resulting from wind or earthquake forces." For anchors embedded 5 inches into 4,000-psi concrete, the allowable load tables showed lower loads (than the then-current Powers manual) for Standard Set epoxy and specified an additional 25-percent reduction in the allowable loads for Fast Set.[45]

On December 17, 1999, the anchor capacity structural calculations were certified by a registered professional engineer employed by Sigma Engineering International, Inc., of Lincoln, Rhode Island. A note adjacent to the engineer's seal stated

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[44] This value was interpolated from data contained in the 1992 version of ICBO ER-4514 and in the second and third editions of Powers design guides (1997-2001), which did not provide load capacities for exactly 5 inches of anchor embedment.

[45] The 1999 draft and February 2000 final versions of the ER-4514 reissue did list data for 5-inch embedment, and these data indicated an allowable load of 5,150 pounds when using Standard Set epoxy, resulting in an allowable load of 3,862 pounds for the Fast Set formulation for these anchors. The current Powers design manual lists the same allowable loads. ICBO ER-4514 was being reissued at the request of Powers as part of the effort by that company and Newman Renner Colony to have the anchors qualified for use on California Department of Transportation projects.

> The calculations were performed to compare the anchor minimum design service loads, per project specification…with the allowable loads provided by the anchor bolt manufacturer only.

The anchor adequacy submittal was received by Gannett Fleming on December 30, 1999. On January 7, 2000, Gannett Fleming authorized the contractor to proceed with the anchor installation (which had been underway since the previous July) pending final approval of the anchors. The contractor was also directed to provide the final version of the revised ICBO ER-4514 when it became available.

The final version of the reissued ICBO ER-4514 was dated February 2000. This version of the report, like the October 1999 draft that had preceded it, distinguished in the report text between the Fast Set and Standard Set formulations. The "Findings" section of the report advised

> That the…Power-Fast Adhesive Anchor System described in this report comp[lies] with the 1997 *Uniform Building Code*,™ subject to the following conditions [abridged from the 13 conditions listed in the report]:
>
> 4.10 Use of Power-Fast Epoxy Adhesive…anchors in concrete to resist earthquake loads, wind loads, dead loads or live loads is permitted as noted in the tables. The tabulated allowable load values in the tables may be increased by 33 1/3 percent for short-term loads, such as wind or earthquake loads…as permitted in the tables. The allowable load values for the Power-Fast Epoxy Adhesive, Standard Set, installed with threaded rod, fully threaded bolts, or reinforcing steel may be increased for short-term loads, such as wind or earthquake loads. **The allowable load values for the Power-Fast Epoxy Adhesive, Fast Set, installed with threaded rod or fully threaded bolts is permitted for short-term loads, such as those resulting from wind or earthquake forces only.** [Emphasis added.] The allowable load values for Power-Fast Epoxy Adhesive, Fast Set, used with reinforcing steel is permitted for short-term wind loads only.

Tables included in the report showed that, for a ⅝-inch-diameter anchor in a ¾-inch-diameter, 5-inch-deep hole in 4,000-psi concrete, the allowable tension load, based on a safety factor of 4, was 5,150 pounds. From this, an average ultimate load capacity of 20,600 pounds can be calculated. Footnotes to the tables of allowable loads indicated that the safety factor for the Fast Set formulation should be 5.33 rather than 4 as recommended for the Standard Set epoxy. This reduction would result in an allowable tension load of 3,863 pounds for Fast Set epoxy anchors.[46]

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[46] These values address only the load capacity of the epoxy bond, which in all cases is less than the tensile strength of the 5/8-inch by 8-inch 316 stainless steel threaded rod.

Provisions of AC58 at that time required that a safety factor of 5.33 be applied to adhesives that had not passed the optional creep testing (either because they had not been tested for creep or because they had been tested and failed) and that these adhesives be used for short-term loads only.

On February 4, 2000, Gannett Fleming (with secondary review by B/PB) approved Modern Continental's anchor submittal, thus authorizing use of the anchoring system that had been installed in the failure area in late summer 1999.

None of the approval documentation identified the epoxy formulation that was being used or that was approved for use in the D Street portal. The only mention of two epoxy formulations was in the revised ICBO ER-4514 that was included with the final anchor adequacy submittal. Representatives of Modern Continental initially told Safety Board investigators they were "99 percent" certain that Standard Set epoxy had been used in the D Street portal ceiling installation. Later, they said they did not know which formulation had been used.

Project documents dated September 1999 show the purchase and delivery, from Newman Renner Colony, of Power-Fast epoxy, catalog No. 08402, which has been identified as the Fast Set material. Additional invoices and packing slips were located for the years 2000 and 2001 that show NRC-1000 Gold, catalog No. 8431 (the Fast Set version), being purchased for this contract. No documentation was found of any other epoxy being delivered for use on the D Street portal contract.

Anchor Testing Requirements

The section design consultant for the tunnel finishes in the Ted Williams Tunnel had specified a progressive testing program under which a portion of the installed adhesive anchors were to be proof tested to 125 percent of their maximum design service load. The procedure was considered progressive because the number of anchors that would be tested would be based on the failure rates; that is, if a higher than expected number of anchors were to fail the initial proof tests, additional anchors would then be tested. If the failure rates were lower than expected, fewer additional anchors would require testing.

A December 1998 report by the Massachusetts Inspector General[47] characterized these testing specifications as "confusing and unclear," resulting in numerous change orders and changes to specifications, which in turn led to additional costs to the project. Based on this experience, the testing procedures were modified for the D Street portal. In a September 23, 1998, facsimile transmittal, B/PB directed that Gannett Fleming's contract specifications require that *all* anchors installed in the D Street portal be tested to 125 percent of their maximum design service load.

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[47] Commonwealth of Massachusetts, Office of the Inspector General, *A Review of the Central Artery/Tunnel Project's Use of Anchor Bolts on the C05B1 Tunnel Finishes Contract*, Publication No. 18248-40-5C-12/98 IGO, December 1998.

On the basis of this requirement and the company's calculated maximum design service load, Gannett Fleming required that the installation contractor employ an approved independent testing agency to test each anchor to 3,250 pounds (1.25 x 2,600 pounds).

Anchor Installation Procedures

Contract Requirements

Requirements for the installation and testing of the adhesive anchoring system to be used in the D Street portal were set out in the contract between Modern Continental and MassHighway. The contract emphasized that the epoxy manufacturer's instructions should be followed, but it also specified certain procedures related to the locating, drilling, and cleaning of anchor holes. The contract specified that anchors should not be disturbed or loaded until after the manufacturer's minimum cure time.

During the bid phase, an addendum was added to the contract that contained additional directives regarding the installation of the adhesive anchors. Compliance with the manufacturer's instructions was again stressed, and the proof testing procedure was specified. The addendum also permitted drilling through rebar.

Epoxy Supplier's Recommended Procedures

The second edition of the *Powers Rawl Fastening System Design Manual,* which was current at the time of the D Street portal ceiling installation, addressed drilling and preparing anchor holes and using the product in cold weather. The manual also provided specific installation guidelines. For solid base materials, the (abridged) instructions are as follows:

- Drill a hole to the size and embedment required.
- Blow the hole clean with compressed air, brush the hole, and blow it clean again. Holes should be clean and sound. They may be dry or damp, but should be free of standing water or frost.
- Be sure to properly balance the mixing nozzle prior to dispensing and when changing cartridges…. Fill the hole approximately half way with epoxy starting from the rear of the hole. Slowly withdraw the static mixing nozzle as the hole fills to avoid creating air pockets within the hole.
- Push the threaded rod or reinforcing bar into the hole while turning slightly to insure positive distribution of the epoxy. Be sure the rod is fully seated at the bottom of the hole and that some epoxy has flowed

from the top of the hole. The threaded rod or reinforcing bar used should be free of dirt, grease, oil, or other foreign material.

- Allow the epoxy to cure for the specified time prior to applying any load. Do not disturb or load the anchor until it is fully cured.

The manual stated that Power-Fast Epoxy Injection Gel can be used for overhead installations of threaded anchor rods. The overhead anchor holes should be prepared using the standard procedure with the following exceptions:

- After the anchor hole is drilled and cleaned, insert the proper size anchor seal plug [a flanged plastic plug] into the hole [to retain the adhesive and hold the anchor centered in the hole until the adhesive sets].
- Insert the Power-Fast mixing nozzle through the seal plug and fill the hole halfway starting from the bottom or rear of the hole.
- Insert the threaded rod through the seal plug, turning it slightly to ensure proper distribution of the epoxy.
- Be sure the anchor rod is fully seated at the bottom of the hole and some epoxy has flowed from the opening in the seal plug.

The seal plugs used in the D Street portal were made of red polyethylene material. Because such plugs are typically tight against the anchor hole and because epoxy does not bond well to the polyethylene material of the plugs, the installation of the seal plugs reduces the effective embedment depth of the anchors (by an amount between 0.5 and 0.9 inch owing to the geometry of the plug). Although the strength of adhesive anchors is highly dependent on the embedment depth, the design manual did not indicate that the use of seal plugs might reduce the load capacity of a particular anchor below that published in the bond strength tables.

Anchor Installation as Described by Modern Continental

Representatives of Modern Continental provided the Safety Board with the procedures the company said were used to install the adhesive anchors in the D Street portal. These procedures essentially followed the Powers installation guidelines.

All anchor holes in the D Street portal were drilled by a two-person crew. The crew would begin by positioning the drill base on the roof of the tunnel at the proper location to center the drill bit. Once in position, the drill unit was held in place through the use of an air pump that created suction between the drill base and the tunnel roof. The suction was sufficient to support the weight of the drill without manual assistance. The crew could usually drill several holes before having to reposition the lift truck on which they were working.

One of the workers responsible for drilling the holes and setting the anchors described the procedure as follows:

Hole Drilling

- A two-person crew, after using a scissors lift to raise themselves and the water-cooled drill to the roof of the tunnel, would line up the drill with a mark placed on the ceiling by the surveyors, secure the drill to the ceiling, and drill the hole using a diamond-tipped wet core drill.[48]
- The crew initially judged the depth of the hole either by markings on the drill bit or a drill stop; once the hole was drilled, the workers lowered the drill and checked the depth of the hole with a tape measure.
- The crew drilled holes for several days or a week before cleaning them using an "iron" (round wire) brush, which was inserted in the hole and moved along its length several times.
- Finally, the crew used compressed air to blow out the holes, which would then be allowed to dry 2 or 3 days.

Anchor Setting

- Two workers installed the adhesive anchors: one worker injected epoxy into the hole, and the other inserted the anchor.
- The workers injected the epoxy through the "red cap" (seal plug) that had been placed in the hole after the hole was cleaned.
- The epoxy nozzle was "bottomed out" in the hole (inserted until it touched the closed end of the hole) and slowly withdrawn as the epoxy was being dispensed.
- After the hole was completely filled with epoxy, a worker inserted a precut anchor (threaded rod) into the hole through the red cap. The anchor was twisted as it was inserted.
- Any excess epoxy was wiped away, and the portion of the bolt extending from the hole was checked for length.

The worker also said that he would run some epoxy out of the gun when using a new cartridge to ensure that the epoxy was mixed properly before it was injected into an anchor hole. The worker stated that he believed the epoxy being used might have been the Fast Set version. The worker said that the training he received on drilling and using the epoxy consisted of instruction, demonstration, and observation during the first days of work.

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[48] A *diamond-tipped core drill* is used primarily for cutting large-bore holes in masonry or concrete. The bit is in the form of a hollow cylinder, and the cutting edge, which is embedded with industrial diamonds, cuts a ring to the depth required. The core is then broken off to form a hole. In a *wet* core drill, water is injected through the bit for cooling. (The water also removes some of the cut material.)

A second worker gave a similar description of the drilling and setting process. He recalled that an electric air compressor was used to clean the holes. The second worker stated that he was trained to use the drill and the epoxy by the first worker.

Safety Board investigators also interviewed the foreman of the installation crews. His account of the drilling and adhesive process was similar to those provided by the two workers. The foreman said that a limited amount of epoxy was maintained on-site in a heated work trailer, and when that supply ran out, he obtained more from the Modern Continental office in Boston, which kept some epoxy on hand and ordered additional cases of cartridges as needed.

Installation of the D Street Portal Ceiling

Hole Drilling

According to the B/PB field engineer daily report,[49] Modern Continental employees and contractors began surveying and laying out the locations of the holes to be drilled in the D Street portal roof on June 7, 1999, and prototype core drilling began 3 days later. Two Modern Continental laborers, working atop a snorkel lift, used a Hilti DD 100 wet diamond core drill to drill the holes. The drilling crews began at the east end of the eastbound tunnel. Two Modern Continental supervisors and a Hilti Corporation representative were on hand to observe the drilling operation and, in the case of the Hilti representative, to provide instruction in the use of the equipment.

B/PB engineers on the scene observed the drilling of eight holes, none of which struck rebar. In drilling additional holes, the Modern Continental drilling crew often encountered rebar. They abandoned some of these holes until, on the advice of the Hilti representative, they adjusted the drilling rig to lower the rpm and decrease the amount of water entering the bit. According to the field engineer daily report, after these adjustments, the crew could drill through rebar "in about 10 minutes." The crew then returned to previously abandoned holes and redrilled them to the proper depth. By June 25, 1999, a total of 117 holes had been drilled, and drilling continued at an average rate of 20 to 40 holes per day.

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[49] Most of the entries in the field engineer daily report regarding anchor installation and testing were made by the field architect for the I-90 tunnel finishes. This same individual had also been the field architect for the finishes in the Ted Williams Tunnel. He told investigators he was assigned this role largely because, as a former boat-builder, he had previous experience with epoxy (though not with epoxy anchors).

Installation and Testing of Anchors

The B/PB field engineer daily report recorded that the first 30 anchors installed in the D Street portal were set in epoxy, in the HOV mock-up area,[50] on July 28, 1999. An additional 52 anchors were set the following day, July 29, at which time the engineer noted that the workers were installing the epoxy and anchors without blowing out the holes with compressed air as recommended by the epoxy supplier.

Proof testing of the installed anchors began on July 30, 1999. The tests were conducted by Conam Inspection Services (Conam) of Auburn, Massachusetts, an independent testing firm hired by Modern Continental and approved by MassHighway. The contract specified that proof testing would consist of applying a tension load of 3,250 pounds (125 percent of the design service load) to each anchor for a period of 2 minutes.[51] (While this testing was in progress, workers were continuing to drill holes and set anchors in other parts of the tunnel.)

The daily report noted that 36 anchors were tested on July 30, with 3 failures. Testing resumed 3 days later, on August 2, 1999. On that day, 35 anchors were tested, and 3 failed. At each failed anchor, workers used a carbide-tipped drill bit to remove the epoxy material from the hole. They then cleaned the hole, injected fresh epoxy, and installed a new anchor. Each replaced anchor was then retested to the same tension load as before.

On August 9, 1999, a crew of ironworkers began installing the ceiling hardware in the HOV tunnel. The B/PB field engineer noted that by the end of the day, the crew had installed 25 roof hanger plates and 17 hanger rod assemblies.

While the ironworkers were attaching hanger plates and rod assemblies, Conam personnel were continuing to perform proof tests in the eastbound and HOV tunnels. The field engineer noted that in the HOV tunnel, four anchors were tested with two failures. Both of these failures were anchors that had failed the test previously and had been replaced. The engineer's daily report stated that one of these anchors passed the proof test but was seen to turn when a nut was threaded onto it. The other anchor held the weight, but during the testing it displaced by about ½ inch from the tunnel roof. Both anchors were to be replaced and retested.

Anchor drilling, setting, and testing continued in the D Street portal through the end of September 1999. The field engineer daily report (which might not have documented all the testing) recorded 548 tests with 38 failures.

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[50] The HOV *mock-up* area was the first section of the D Street portal where anchors were set and ceiling panels were installed. This area was used to develop and refine the techniques and procedures that would be used in setting the anchors and installing the ceiling panels in the rest of the tunnel.

[51] The investigation could not confirm that each proof test load was held for the specified time period.

Hanging of Ceiling Panels

Based on contract specifications, the precast concrete panels used for the ceiling in the I-90 connector tunnel were shipped to the construction site on flatbed trailers. A module fabrication area was established as close as possible to the site of the final installation, and a wood timber bed was set up to provide a work space area for module assembly. The structural steel support elements for a module were first set into position on the beds, and the concrete panels were unloaded onto them directly from the flatbed trailers. The panels were then bolted into position and secured to the structural steel.

Once assembled, the ceiling module was placed onto a special trailer-mounted ceiling installation lift and trucked to its intended erection location. The lift then raised the module into position and supported it while a crew of ironworkers attached the panel support beams to the previously installed hanger assemblies. According to the specifications, the lift allowed fine adjustments to be made to module location in both transverse and longitudinal directions and allowed the module to be tilted to follow the roadway profile. The lift supported the ceiling module until all the vertical hangers had been connected, after which the ironworkers made adjustments to plumb and level using the support rod turnbuckles.

An ironworker who worked for a short time installing the ceiling modules told investigators that his crew was responsible for attaching the diagonal rods to the panel supports at the bottom and to the four-anchor roof hanger plates at the top. He said the module would be supported for some period of time, perhaps for as long as a week, from the vertical rods alone before the diagonal rods were installed and final adjustments were made for plumb and level.

According to the field engineer daily report, the ceiling module involved in this accident was one of five modules installed on November 17, 1999. By early December 1999, all the ceiling modules had been erected in the eastbound and westbound D Street portal tunnel bores.

Preaccident Anchor Failures

HOV Tunnel

On October 7, 1999, Modern Continental’s senior project manager for the I-90 tunnel notified B/PB that the company had become aware of problems involving “a small percentage of adhesive anchors in the HOV ceiling mockup….” The letter reported that the anchors showed signs of tensile movement that had created gaps between the roof of the tunnel and the ceiling hanger plates.

The letter noted that the affected ceiling module had been erected in early August 1999 and that no problems were evident at that time. On September 9, 1999, a Modern Continental worker installing tunnel ventilation ductwork above the ceiling noticed that one or more ceiling hanger plates had displaced from the tunnel roof by about 1/16 inch.

Periodic subsequent inspections by Modern Continental revealed increased movement in some of the hangers, with a "worst case" movement, in early October 1999, of 1/2 inch (later reported to be 9/16 inch). This finding prompted Modern Continental to notify B/PB of the displaced anchors. The notification letter concluded

> Whereas these anchors have been installed and tested in accordance with contract documents, [Modern Continental] respectfully requests direction pertaining to any repair or mitigative measures required.

B/PB responded to this notification by letter on October 12, 1999. The letter stated that, while the management consultant concurred that the anchors had been tested in accordance with contract requirements, it could not confirm that the anchors had been correctly loaded. The letter referenced a review of the ceiling system that had found several loose turnbuckles, which "could induce excessive loading to the point that the anchors may be over stressed which may cause movement."

The letter suggested other possible causes for the anchor movement, such as improper ceiling erection procedures (removing lift support too quickly or in such a manner as to overstress the anchors before the uniform loading of all the turnbuckles) or failure to properly prepare and clean the drilled holes "which could cause a bond failure of the adhesive to the concrete over time."

The letter directed that Modern Continental have the supplier of the adhesive anchor bolt system review the installation of the failed anchors and recommend a solution. In the meantime, B/PB would confirm that the ceiling load calculations were correct. The letter concluded

> In summary, [Modern Continental] shall confirm that the ceiling system is properly installed and all connection points are providing the correct support. Anchors that have moved since ceiling installation shall be abandoned and/or removed and replaced. When replacing the defective anchors, insure that proper measures are provided to support the ceiling so that other over stressed conditions are not created.

On October 13, 1999, according to the field engineer daily report, the B/PB field architect met with representatives from Modern Continental and Powers atop the ceiling in the HOV mock-up area to discuss the anchor displacement. According to the daily report, the Powers representative did not offer any conclusions or analysis at that time, instead deferring until he could consult with Powers engineering staff.

On October 21, 1999, another Powers representative met with Modern Continental and B/PB personnel to discuss the possible cause of the anchor displacement in the HOV tunnel. This Powers representative also examined the displaced anchors and reviewed and discussed with B/PB and Modern Continental personnel the anchor installation and testing procedures and the module erection process.

In an October 29, 1999, letter to Modern Continental, Powers documented the findings of the company's examination of the displaced anchors. The letter stated that the Powers representatives had visually inspected the displaced anchors with the objective of answering the question, "Why would an anchor that was successfully proof loaded and believed to be correctly installed, move after the ceiling hanger plates were installed?"

The Powers letter stated that the company representative used a torque wrench to check the applied torque of the anchors that showed movement as well as those that had not moved. He reported torque values of 120 foot-pounds, which were greater than the recommended 50 to 90 foot-pounds.

The Powers letter also included responses to general questions that had been posed by Modern Continental representatives at the time of the anchor assessment. Those responses are summarized as follows (and directly quoted as indicated):

- "Please refer to the attached excerpt from Powers' *Fastening Systems Design Manual, Second Edition*, Section 22.4.1 entitled 'Displacement.'" [The text accompanying the referenced displacement curve stated: "As an anchor is loaded to its ultimate (failure) load capacity, displacement of the anchor relative to the base material will occur."] If an appropriate factor of safety is applied to the ultimate load capacity of the adhesive, then displacement should not occur provided that the proper installation procedures were employed.
- Any movement in the anchor may be an indication that the allowable load capacity of the particular installation has potentially been exceeded.
- It is possible that an improperly installed anchor could pass a proof load test provided a sufficient safety factor has been used. Powers Fasteners recommends a safety factor of 4, "but it appears that a higher safety factor has been used based on comparing the proof load of your field test with the published ultimate tensile bond strength."
- "Adhesive anchoring problems typically reveal themselves immediately in a testing environment and do not manifest themselves over a period of time." For example, dust in the drilled hole would probably have caused the anchor to move during proof testing. Improperly mixed adhesive

typically would not fully cure and would remain somewhat sticky, which would be apparent during proof testing.

- "Overstress" usually refers to conditions where the nut has been overtorqued.
- Because Powers Fasteners did not design the roof hanger plate assembly, the company cannot address "the different loads that may be acting on these anchors."

The Powers letter concluded as follows:

> While we [Powers] believe that the existing anchors subjected to torque exceeding our recommended range may be acceptable, the only way to verify their suitability is by performing a proof load test. Successful proof load test results would indicate that the anchors are still functional. Nuts should then be reapplied to the tested anchors with a torque that is within our recommended torque range.

No evidence was found that Powers took any further action in regard to the anchor displacement in CA/T tunnels after the 1999 anchor examination and submission of findings.

On November 8, 1999, Modern Continental wrote to B/PB and included the Powers letter as an attachment. The contractor cited the findings by Powers to argue that the anchor displacement in the HOV tunnel was not caused by a failure to properly clean the anchor holes. The company also stated that the ceiling panels were erected in accordance with the approved procedure in the presence of the B/PB engineer. Additionally, the contractor stated that, given the parameters of the ceiling design (approximate module weight, number of anchors supporting the module, and tensile capacity of the anchor) and the applied factors of safety, "it is improbable that the anchors were overstressed as a result of erection loads or the erection procedures."

The letter concluded:

> Per the recommendations of [Powers], Modern Continental Construction will remove and replace the anchors which exhibited movement, and will proof test the anchors subjected to torque values higher than the manufacturer's recommended values in order to verify the anchor capacity….

B/PB acknowledged receipt of this correspondence in a November 11, 1999, letter to Modern Continental. The letter stated that the management consultant did not agree with the contractor's position that all elements of the ceiling had been installed in accordance with the contract in that "adhesive anchors are over torqued and the ceiling hangers are not loaded uniformly. [Only when] the anchors in question are removed and inspected can a determination be made of correct or incorrect installation techniques."

B/PB concurred with the Modern Continental plan to remove and replace the displaced anchors and to proof test anchors subjected to torque values higher than the manufacturer's recommended values. In reference to the action items contained in B/PB's October 12 letter to Modern Continental, the management consultant held "open" (yet to be completed) the requirement that the contractor confirm that all roof hanger plates were correctly loaded and that they were carrying uniform loads. In regard to its own action item, the consultant reconfirmed that the design loads for the ceiling had been correctly calculated.

According to the B/PB engineer daily report, on November 12, 1999, Conam representatives performed a proof-load test on the HOV anchor that had shown the most displacement (9/16 inch). The reports indicated that this anchor had passed the 3,250-pound proof test on July 30, 1999, the first day of anchor proof testing. The engineer noted that, when the standard test load was applied on November 12,

> the bolt held for a few seconds, then began to pull out with almost no resistance…. Upon examining the pulled-out bolt, it appeared to lack sufficient epoxy to fully fill the drilled hole. Also, there was a significant amount of concrete dust adhered to the epoxy surrounding the bolt, usually an indication that the drilled hole was not completely cleaned out prior to installation. The epoxy nearest to the embedded tip of the bolt was brittle and easily crumbled, usually an indication of improper mixing of resin and hardener. The epoxy near the exposed end of the bolt (but still in the embedded portion) appeared to be fully and properly cured. This would indicate the mixture of resin and hardener was not uniform during the injection of epoxy into the drilled hole. In spite of this combination of installation deficiencies, it appears the bolt was able to develop just enough strength to pass the pull-out [proof-load] test. However after several weeks of constant loading by the ceiling module, the bond was broken, and the bolt began to slip out.

Field reports for November 9 and November 15, 1999, documented tests performed by B/PB and Modern Continental engineers to verify the torque values of adhesive anchors in the D Street portal (in response to the Powers findings). For the November 9 tests, the engineers randomly selected 66 anchors (one-third of the installed total) in a section of the westbound tunnel. On November 15, a random selection of 64 anchors from a section of the eastbound tunnel was tested. According to the daily report,

> All tested bolts were found to require between ⅛ and ¼ turn to 'click' the torque wrench, which was set at 75 ft-lbs. The manufacturer's recommended torque for ⅝" bolts is 50 to 90 ft-lbs, hence 75 ft-lbs is acceptable.

On December 1, 1999, B/PB issued Deficiency Report 001 regarding the failed anchors. The report noted that, "At least five adhesive anchors in the area of ceiling module HOV079 have failed, that is pull-out has been observed, since the hanging of the ceiling module." A diagram included with the report showed hanger displacements from 1/16 to 9/16 inch. The diagram also identified four loose vertical hanger rods and one loose diagonal rod in the affected module.

Modern Continental responded to the deficiency report on December 2, 1999, detailing the actions the company was taking to resolve the issue. The response referenced the October 21, 1999, on-site review by a Powers representative and noted that, "Based on information gathered on site, which included a visual inspection of the anchors in question, a determination of failure could not be made."

Modern Continental proposed to address the deficiency by following procedures recommended by Powers in a November 30, 1999, submittal to the contractor. These procedures were similar to those that Modern Continental had used when anchors had failed in initial proof testing; that is, the displaced anchors would be extracted and all debris removed from the hole. The hole would be blown out with an air compressor, brushed out with a nylon brush, and blown clean again. A new anchor rod would be installed in accordance with the manufacturer's recommendations. After the epoxy was cured, the anchor would be proof tested "per job site specifications."

According to internal B/PB correspondence, the B/PB design manager questioned whether the proposed response to Deficiency Report 001 would be satisfactory. In a December 8, 1999, e-mail to the design project engineer and the B/PB structural engineer (and copied to the B/PB project and resident engineer), the design manager stated, in part:

> You've noted the key piece of information that is missing from the package. That is the cause of the anchor failure and how the repair procedure will overcome that. I'll accept the fact that a single reason cannot be given with certainty, but an educated assessment can be made of the probable causes and a description of how those are being prevented by the reinstallation procedure can be presented.… We are not trying to hold up construction, we are trying to make a determination that the installation is safe and functional.

In a reply e-mail, the B/PB structural engineer noted

> Glaringly absent from [Deficiency Report 001] is any explanation why the anchors failed and what steps are proposed to ensure that this problem does not reoccur.

On December 27, 1999, B/PB returned the submittal to Modern Continental, rejecting the proposed response to Deficiency Report 001. The document stated

> Prior to beginning the repair process the contractor needs to submit documentation on the manufacturer of epoxy and type being used by Powers Fasteners. i.e., If it is a SIKA [Chemical Corporation] product what type is it?

The submittal then detailed the repair/replacement procedures to be used for the failed anchors. The only significant difference between these procedures and those that had been proposed by Modern Continental/Powers was in the proof test loads. Modern Continental was directed to proof test all the replaced anchors to 7,900 pounds instead of 3,250 pounds as specified in the original contract documents. (This value was 125 percent of the maximum allowable load of 6,350 pounds calculated for these anchors from the data in the Powers catalog.) The submittal also stated that

> Because of evidence concerning installation problems, i.e. dust in the hole and insufficient adhesive in the hole, the capacity of all of the other anchor bolts is in question and will need to be addressed.

In this regard, the submittal provided two options for Modern Continental: Remove and replace all the previously installed anchors using the procedures and test values outlined in the submittal, or retest all previously installed anchors to 7,900 pounds. In subsequent correspondence, the 7,900-pound proof test load was reduced to 6,350 (the calculated allowable load for the anchor), but the issue remained as to who would pay for the retesting of the previously installed anchors. B/PB, in a January 7, 2000, letter to Modern Continental, stated

> In the case of the ceiling anchor bolts, the bolts failed after the ceiling panels were installed. Examination of the one anchor that has been removed, indicated that the anchor bolt was improperly installed. There is evidence that the drill hole was not brushed clean…, and the anchor was not free of dirt, oil or foreign matter. Additionally the anchors were over torqued when the ceiling supports were installed.
>
> The calculated allowable bond strength for a properly installed adhesive anchor system is 6350 lbs tension. [Modern Continental] is required to demonstrate correct installation techniques of the adhesive anchor bolt system, therefore it is the Project's position that the re-testing of the bolts is required.…Retesting that confirms the manufacturer's calculated bond strength of 6350 lbs will be covered by a subsequent Contract Modification.

In February, the management consultant and the contractor reached an agreement under which all the failed anchors would be replaced in accordance with the approved procedures and proof tested to 6,350 pounds. Additionally, all previously installed anchors in the HOV ramp area would be retested to the higher value. The CA/T project agreed to pay the testing cost for any anchor that passed the test at the higher value. The project and the contractor would split the cost of any anchor that had previously passed the test at 3,250 pounds but failed at 6,350. Finally, all subsequently installed anchors in the I-90 tunnel would be tested to the higher proof load.

Modern Continental retested a total of 187 anchors in the HOV area and experienced 19 failures. An internal B/PB memorandum addressing the disposition of Deficiency Report 001 made the observation that

> There were only two failures in the modules located outside of the [HOV] ceiling mock-up area. This could be the result of better installation techniques being used by the contractor as gleaned from going through the 'learning curve' in the mock-up area. These better installation techniques include: (1) cleaning holes out better and not using first epoxy out of the gun during the installation of the epoxy anchors and (2) not over torquing the nuts when the ceiling plates are installed over the anchors.

The corrective actions taken by Modern Continental were verified by B/PB in late 2000, and Deficiency Report 001 was closed on January 26, 2001. No evidence was found of any followup actions taken by Modern Continental or B/PB in regard to the anchor displacements in the HOV tunnel.

I-90 Connector Tunnel

On December 17, 2001, a Modern Continental quality control inspector initiated a noncompliance report to B/PB informing the management consultant of anchor displacements noted in another section of the I-90 connector tunnel. The defective anchors were those that had been used where the Unistrut channel inserts embedded in the roof were either missing or not aligned properly. The report stated that

> Several anchors appear to be pulling away from the concrete. The subject anchors were [previously] tested to the revised value of 6350 lbs., all of which passed…. Reason for failure is unknown.

B/PB directed Modern Continental to "set new anchors and retest." As with the HOV tunnel 2 years before, all the displaced anchors were removed and replaced, then retested to more than 6,000 pounds. No additional actions were reported.

The investigation revealed other instances of anchor displacement in the Unistrut portion of the I-90 tunnel that were identified and reported by B/PB field engineers (as anchor "slippage") in 2001 and again in 2002. These did not generate deficiency reports, and no documentation was found to indicate what actions were taken in regard to these displaced anchors.

Tests and Research

Anchor Examination

During the accident, all 20 anchors attaching ceiling support beam M1 to the tunnel roof pulled out and fell onto the roadway. All the anchors reportedly remained within their roof hanger plates immediately following the accident, trapped between the flange of the polyethylene seal plug above the hanger plate and the nut and washers below the plate (refer to figure 7). During the recovery process, 16 of the 20 anchors were removed from their hanger plates without a record having been made of which anchors came from which plates. Even though the remaining four anchors stayed in their four- or two-anchor hanger plates, in the end it was not possible to match any of the 20 failed anchors with their respective anchor holes.

The 20 anchors from the failure row were all examined in the Safety Board Materials Laboratory, as were an additional 65 anchors from outside the failure area.[52] Some of these anchors were chosen for laboratory examination randomly, but most were chosen because of specific anomalous conditions. Of these additional anchors, 7 came from within the accident module, 11 came from the adjacent module to the west, and 19 came from the two modules immediately to the east of the accident module. The remaining anchors came from three modules in the westbound tunnel (20 anchors) and two modules in the HOV tunnel (8 anchors).

All of the examined anchors were stamped with "316" on each end, consistent with a marking for 316 stainless steel, and this composition was confirmed during laboratory testing. The undamaged surfaces of the anchors were generally smooth and reflective and showed no evidence of corrosion.

The anchors from both within and outside the M1 failure row were examined for (1) damage, including bending deformation, (2) the extent of epoxy coverage on the anchor, and (3) the epoxy's condition. Forces involved in the collapse of the ceiling or in the subsequent extraction of anchors from the tunnel roof caused some epoxy to separate from the original anchors, making that epoxy unavailable for inspection. Features associated with the epoxy included void areas, fractured epoxy, adhesively failed epoxy, yellowed epoxy, and overflow epoxy, as described below.

Void areas are unbonded epoxy surfaces along the embedment length of the anchor where the epoxy did not completely fill the gap between the anchor and the hole wall.

Fractured epoxy is epoxy along the embedment length of the anchor that has been sheared or otherwise separated.

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[52] FHWA personnel removed 49 of these 65 anchors, and many others, from the tunnel roof as part of the on-scene portion of the accident investigation.

Adhesively failed epoxy is epoxy along the embedment length of the anchor that appears to have separated from the surface of the anchor hole and remained attached to the anchor as the anchor was pulled out.

Yellowed epoxy is fractured (or, in some cases, adhesively failed) epoxy with a distinct yellow tint.

Overflow epoxy is epoxy that extends below the seal plug and onto the threads of the anchor.

Figure 13 illustrates some of the features found on the failed anchors.

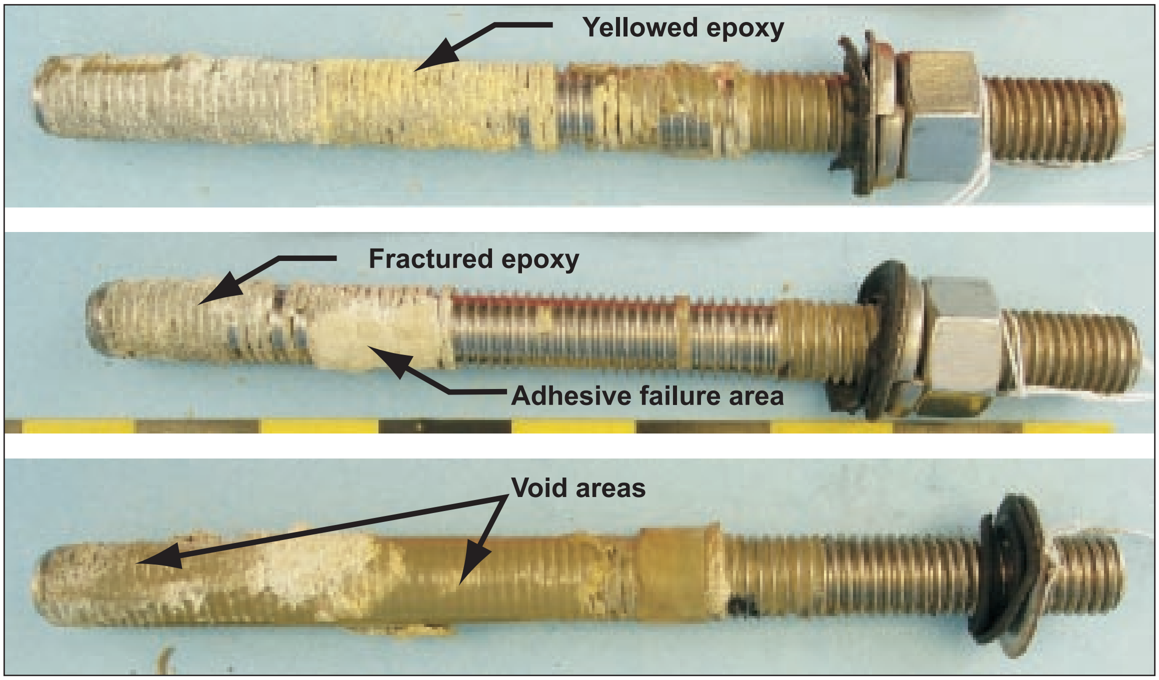

Figure 13. Three of the 20 failed anchors from the accident site illustrating epoxy features found on some of the anchors.

Of the 20 failed anchors from the accident site, all but one were found to have void areas that encompassed from 1 to 40 percent (average 10 percent) of their total embedment areas. Five of the anchors showed evidence of adhesive failure, with the most significant involving 29 percent of the embedment area. All of the anchors were missing epoxy, and 13 of the 20 had yellowed epoxy. Twelve of the anchors were bent. All but one showed evidence of overflow epoxy, typically extending ¾ inch below the embedment area. On three of these anchors, the nut had been threaded onto the area of overflow epoxy.

Of the 65 tested anchors from outside the M1 failure row, 62 were found to have void areas that encompassed from 1 to 70 percent (average 15 percent) of the total embedment area. Twenty-three of the anchors showed evidence of adhesive failure, and 44 were missing epoxy. Twenty-seven anchors had yellowed epoxy. Forty of the 65 anchors had displaced from the tunnel roof before being removed, with displacement ranging from 0.625 to 2.65 inches.

Yellow discoloration of the typically white fractured epoxy was found on 13 of the 20 failed anchors. As with all the anchors with yellowed epoxy, the discoloration was on the lower portion of the embedment depth, extending above the seal plug. In the most extreme case, the yellowed epoxy encompassed 4 inches of the 5- to 5 ½-inch original embedment depth of the anchor. In examining the other anchors removed from the tunnel roof, investigators noted that yellowed epoxy was found only on those anchors that had been displaced a significant amount from the tunnel roof. No yellowed epoxy was found on anchors that had not displaced, suggesting that the discoloration resulted from environmental exposure of the yellowed portion while the rest of the anchor remained in the roof.

When the amount of yellowed epoxy was compared with the amount of anchor displacement for the anchors examined in the laboratory, yellowed epoxy was not found on any of the examined anchors with a displacement of less than 0.375 inch and was found on all but one of the examined anchors with displacement of 0.5 inch and greater. The one anchor that did not fit this pattern had one of the greatest amounts of displacement. Because this anchor was from the north row of the accident module, directly adjacent to the failure area, the displacement might have occurred at the time of the accident rather than over time before the accident.

The embedment length of the laboratory-examined anchors containing yellowed epoxy corresponded closely with the measured displacement; the yellowed appearance was typically about 0.3 inch greater than the measured displacement length. On some anchors, the yellowed epoxy extended around the perimeter of a void, consistent with environmental exposure extending up into the hole through the void.

A significant amount of dark brown epoxy was found on six of the anchors from outside the failure row;[53] a smaller amount of brown epoxy was noted on one of the failed anchors. On several of the anchors from outside the failure row, the dark brown epoxy was soft and pliable immediately after the anchor was pulled from the tunnel roof, to the extent that several of these anchors had to be placed in plastic bags before being put into paper evidence bags. In the months after the accident, the dark brown material became harder, although some soft areas remained. For the anchors not from the failure row, a clear relationship was seen between the presence of the dark brown epoxy and the amount of adhesive failure noted on that anchor.

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[53] Two of these anchors were from the south (S) row of the accident module.

Five of the six anchors from outside the failure row having dark brown epoxy were also among the anchors with the greatest displacement. Among the examined anchors, four of the eight anchors with the greatest displacement had dark brown epoxy as well as larger areas of adhesive failure. Samples of the dark brown epoxy from several of the anchors were among the epoxy samples chosen for testing and analysis (discussed later in this section).

Anchor Hole Examination

Safety Board investigators performed hand-held borescope[54] inspections of the failure row (M1) anchor holes on August 9 and 10, 2006. Initial visual and borescope examinations showed the presence in the holes of significant loose epoxy that, in some cases, almost completely blocked the hole. Removal of the loose epoxy revealed that all of the holes had some epoxy remaining at the very top of the hole. This epoxy had separated cleanly from the anchors, leaving the positive mold of the characters "316" that had been stamped onto the anchor ends.

Although the borescope video images showed the features within the anchor holes, they did not allow the precise measurement of the locations or area fractions of the features. Nor was the handheld device able to generate an overall image of the entire hole surface. Thus, arrangements were made to obtain laser-scanned images of the holes. With a few exceptions, the laser images were sufficiently clear to allow the holes to be assessed for void areas, plug areas, fractured epoxy areas, and adhesively failed surfaces, as defined below.

Void areas are unbonded surfaces in the epoxy.

Plug areas are smooth epoxy surfaces that had been in contact with portions of the red polyethylene seal plug.

Fractured epoxy areas are areas where a thickness of epoxy with a rough surface extends from the wall of the hole.

Adhesively failed surfaces are areas where the epoxy had separated from the concrete or rebar surface, leaving behind little or no epoxy.

Of the 20 holes imaged, all but one showed epoxy voids involving from 3 to 38 percent of the hole surface area, with 11 of the 20 holes having void area fractions of 20 percent or more.[55] The void areas were generally oriented longitudinally along the length of the hole. Eleven holes had adhesive failure regions. Of these, two holes had adhesive failure area fractions between 40 and 50 percent, and four

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[54] A *borescope* is an instrument in the form of a rigid or flexible tube with an eyepiece at one end and a lens at the other. It is used to make visual inspection of narrow cavities, such as the bore of a gun.

[55] These percentages are in relation to the area of the scanned surface, which covered 4.5 inches of the typical 5-inch embedment length. The void areas present when the anchors were installed could have been higher than those measured in the laboratory because evidence of voids may have been lost or obscured as the anchors were pulled out.

had adhesive failure areas from 18 to 31 percent. All of the holes showed fractured epoxy covering 42 to 93 percent (average 58 percent) of the hole surface area.

Core Sample Examination

Core samples were removed from four of the anchor positions in the M1 failure row. At each position, the concrete surrounding the anchor hole was cut and removed from the tunnel roof either intact or in several large pieces with multiple smaller pieces. Three of these samples were sectioned at the FHWA Turner-Fairbank Highway Research Center and then examined in the Safety Board Materials Laboratory. The examination, inspection, and sectioning of these three core samples revealed the presence of significant voids in the epoxy between the anchors and the concrete surface of the anchor holes, measured as 31, 27, and 29 percent for the three samples. Areas of adhesive failure were also noted, as well as some dark brown epoxy in the top of the hole for one of the anchor positions.

All four of the core samples contained horizontally aligned sections of No. 11 rebar (nominally 1 ⅜ inch in diameter). Of the core samples examined at the Safety Board, one of the anchor holes had been cored almost directly through the center of No. 11 rebar; and more than half of the circumference of the other two holes was through the No. 11 rebar. Additional pieces of smaller rebar were also found in the core samples. A comparison of the feature maps generated during the direct examination of the opened anchor holes with the laser images of the same holes showed, in general, a strong correlation between the shape of the various feature areas and that minimal epoxy was lost during the coring, cutting, and opening process.

In addition to the core samples from the failure area, core samples were removed from 10 anchor positions in the roof of the westbound connector tunnel and 1 anchor position in the HOV tunnel. At six of the anchor positions, the anchors were extracted before the cores were cut and removed. The reaction load required to extract the six anchors, measured using a hand-operated hydraulic press, ranged from 13,000 to 16,213 pounds and averaged 14,797 pounds.

Of the 11 core samples removed, 5 samples (1 with an anchor and 4 without) were retained by the Massachusetts Office of the Attorney General, and 6 samples (4 with anchors and 2 without) were retained by the Safety Board. Two of the samples retained by the Board contained anchors that had displaced from the tunnel roof before removal. The following information applies only to the six core samples retained by the Board.

The examination, inspection, and sectioning of the core samples retained by the Safety Board revealed the presence of significant voids in the epoxy between the anchors and the concrete surface of the anchor holes, measured as 10, 15, 21, 25, 27, and 31 percent for the six samples. Areas of adhesive failure were also noted.

All six of the core samples contained rebar similar to that found in the core samples from the failure area. Two of the anchor holes had been cored almost directly through the center of No. 11 rebar. All of the anchor holes had intersected one or more pieces of rebar.

Four of the core samples were sectioned for further examination. One core was sectioned at the Safety Board Materials Laboratory, and three cores were sectioned at the Turner-Fairbank Highway Research Center.

Examination of the core sectioned at the Safety Board laboratory revealed that about one-half of the circumference of the hole contained very little epoxy and that significant epoxy remained on the other half of the hole. After further sectioning of the sample, multiple void areas were visible on the side with the bulk of the remaining epoxy. A large void was also found in the epoxy above the upper end of the anchor.

One side of the anchor from this core contained a damaged and deformed layer of epoxy that appeared to have extended out to the surface of the anchor hole. The epoxy along this side of the anchor appeared to have been compressed along the length of the anchor, with the relatively smooth surface of the epoxy apparently corresponding to the surface of the anchor hole.

Examination of one of the cores sectioned at the Turner-Fairbank Highway Research Center showed that the epoxy filled most of the volume between the anchor and the hole surface, with the exception of one large void (an approximately cylindrical area of 0.7 square inch) and some small voids. This sample had epoxy fractures occurring at three locations: at the interface between the epoxy and the concrete hole surface (adhesive failure), through the epoxy in areas without voids, and at the interface between the anchor and the epoxy.

On all of the core samples, it was noted that the anchor was not concentrically located within the hole and that the voids were more predominant on the side of the anchor with greater distance between the anchor and the hole surface.

Ceiling Support Beam Loading

As part of this investigation, the dead load on each row of anchors in the D Street portal was calculated.

In the eastbound tunnel (the vicinity of the accident), the weight supported by the north row of anchors (row N) included half the weight of two of the 12- by 8-foot panels without exhaust port (4,865 pounds), half the weight of three of the 12- by 8-foot panels with exhaust port (6,960 pounds), the full weight of the longitudinal panel support beam (1,800 pounds), the weight of seven 2-anchor roof hanger plates (322 pounds) and one 4-anchor hanger plate (163 pounds), the weight of 20 ventilation duct enclosure panels (1,000 pounds), and half the weight of five transverse ceiling struts (372 pounds), for a total of 15,482 pounds.[56]

Similar calculations for the other rows of anchors in the eastbound, westbound, and HOV tunnels generated approximations of the dead weight supported by each row of anchors in a module. As shown in table 1, the dead load carried by the individual rows ranged from less than 10,000 pounds (south rows in the HOV and eastbound tunnels) to more than 27,000 pounds (westbound middle and eastbound M1 rows).

Table 1. D Street portal ceiling support beam loading.

Tunnel	Support beam	Total dead load (pounds)
Westbound	North	15,647
	Middle	27,452
	South	15,440
Eastbound	North (N)	15,482
	Middle 1 (M1)	27,452
	Middle 2 (M2)	22,834
	South (S)	9,617
HOV	North	15,456
	Middle	21,891
	South	9,699

Anchor Loading and Design Redundancy Analyses

At the request of the Safety Board, FHWA researchers at the Turner-Fairbank Highway Research Center performed a detailed analysis of the ceiling support system in the D Street portal. Researchers modeled the structure to provide an approximation of the load applied to each adhesive anchor and to determine how loads were distributed throughout the system.[57] By showing how loads were redistributed under different "hanger-out" scenarios, the model also allowed researchers to evaluate design redundancy within the system.

Anchor Loading Analysis. According to Gannett Fleming, the design of the D Street portal ceiling did not assign any vertical dead or live load to the diagonal hanger rods in the system.[58] Also, evidence gathered during the investigation indicated that, in some instances, the diagonal rods were not installed until after the ceiling module had been erected. Yet, adjustments could have been made to the diagonal rod turnbuckles after they were installed (to

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[56] Not included in any of these calculations is the weight of the 12-inch-wide by 3/8-inch-thick steel plates that spanned the gap between modules.

[57] The model was created using FEMAP software and was executed using the static analysis module of ABAQUS version 6.6.

[58] The design did anticipate a vertical load component under seismic loading.

level the ceiling, for example) that would have transferred some vertical load to those rods. To account for either possibility, the model was run both with and without the diagonal rods in place to provide an upper and lower bound for anchor forces.[59]

The FHWA analysis indicated that the maximum anchor loads within each row of hangers for the accident module occurred at the west end of the row (where the ceiling support beam was cantilevered about 6 inches farther than at the east end). The maximum calculated anchor load was 2,823 pounds, assuming that the vertical hanger rods resisted both dead and live load and that the diagonal hangers resisted only live load. This is slightly above the maximum load of 2,600 pounds calculated by Gannett Fleming. Figure 14 shows the anchor loads in all rows of the accident module when the diagonal hanger rods were assumed to resist only live loads. When the diagonal hanger rods were fully included in the analysis, the highest calculated anchor load was 2,371 pounds (dead load plus live load).

Design Redundancy Analysis. The structural redundancy of the system was examined by removing anchors from the model and repeating the computer analysis under dead load only and under both live and dead loads. Because the M1 row of anchors in the accident module had the highest proportion of load, and these were the anchors that failed in the accident, this was the only anchor row on which the redundancy analysis was performed. The analysis was performed with the diagonal hanger rods included.

In each failure scenario, all of the anchors (either two or four) were removed from a roof hanger plate to simulate a complete failure of one hanger assembly. The simultaneous removal of all the anchors for a hanger plate also provided a "worst-case" for redundancy evaluation.

Researchers analyzed eight different one-hanger-out scenarios (sequentially removing each roof hanger plate), seven different two-hanger-out scenarios (sequentially removing adjacent pairs of roof hanger plates), and six different three-hanger-out scenarios (sequentially removing three adjacent roof hanger plates).

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[59] Assigning vertical load to the angled rods increased the anchor loading on the four-anchor hanger plates (to which the angled rods were attached) and slightly decreased the loading on the two-anchor hanger plates on either side of the four-anchor plate.

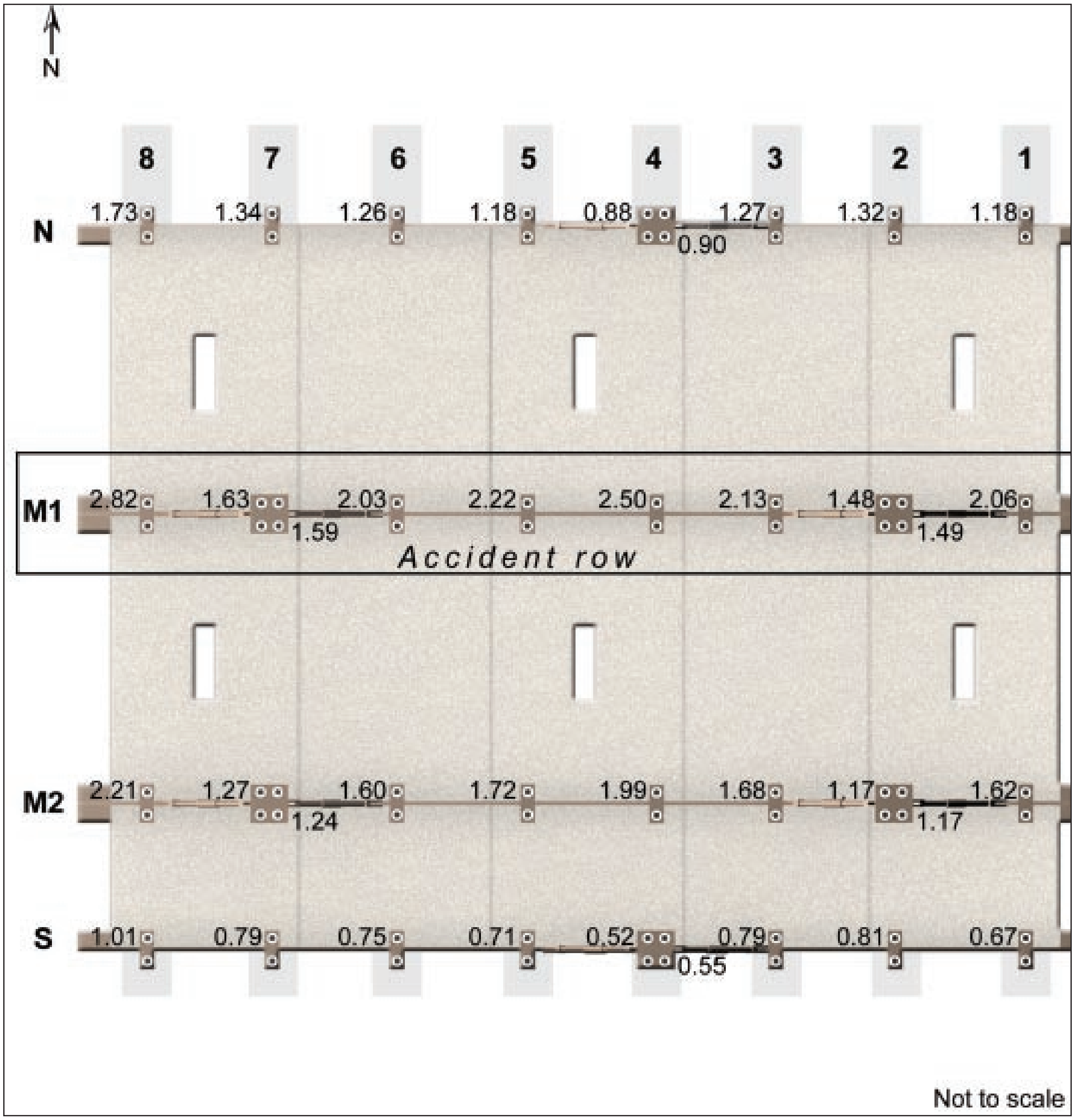

Figure 14. Plan view of the accident module's roof hanger plates showing maximum anchor loading, in kips (1 kip = 1,000 pounds), as calculated for the Safety Board by the FHWA. These "worst-case" calculations assume no vertical load being supported by the diagonal hanger rods attached to the four-anchor hanger plates. Figures at the upper left of the four anchor plates represent the load on the two anchors on the west side of the plate; figures on the lower right show the load on the two east-side anchors. (For ease of identification in this report, hanger plates are numbered from east to west.)

Table 2 shows the highest anchor load in the simulated M1 row of the accident module for the conditions analyzed by the model.

Table 2. Maximum anchor loads in the M1 row of adhesive anchors in the D Street portal under various hanger-failure scenarios.

Condition	Dead load only (lbs)	Dead load plus live load (lbs)
Vertical rods only	2,159	2,823
Vertical and diagonal rods	1,665	2,371
One hanger plate out	3,095	4,412
Two hanger plates out	7,648	10,887
Three hanger plates out	10,504	14,946

The data in the table indicate that, with all roof hanger plates intact or with one hanger out, the maximum anchor loads were below the published allowable loads for Power-Fast epoxy anchors (6,350 pounds as shown in the Powers design manual at the time). The design specifications required that a safety factor of 2 be maintained for the remaining anchors in the event of failure of a roof hanger plate (one hanger out). A safety factor of 2 would have translated to a maximum allowable load, using Powers' published capacities, of 12,700 pounds. The FHWA analysis indicated that even under the two-hanger-out scenarios, the maximum anchor load remained below this value.

Anchor Peak Load Tests

At the request of the Safety Board, FHWA personnel removed a total of 188 anchors from the roofs of the eastbound and westbound D Street portal tunnels and recorded the peak load attained before each anchor pulled free. The loads required to extract the anchors varied widely, from a low of 1,121 pounds to a high of 24,242 pounds.[60] None of the anchor ultimate loads exceeded the 25,400-pound average capacity indicated in the Powers literature. Only five exceeded the 20,600-pound capacity indicated in ICBO ER-4514. The average and median peak loads were about 12,000 pounds.

Of the 188 anchors, 45 had pretest observable displacements up to a maximum of 2.625 inches, and the displaced anchors tended to require less force to remove them. For example, the anchor with the greatest displacement was also the anchor that pulled out at the lowest peak load. The displaced anchors required approximately half as much force to remove from the tunnel roof as those without displacement. Of the 21 anchors requiring less than 5,000 pounds of force to remove them, only 5 had not displaced to some extent before the test.

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[60] One peak load value of 470 pounds was recorded, but test personnel considered this value to be suspect.

Anchor Creep Testing

In addition to performing peak load tests, FHWA personnel performed sustained load (creep) tests on a number of the anchors in the westbound D Street portal tunnel. They first performed preliminary testing to determine if more rigorous testing was needed. For the preliminary test, they selected two anchors that showed no visible signs of distress or displacement. They then suspended a lead weight of approximately 2,000 pounds from each anchor and monitored the behavior of the anchors over the next 2 days. The anchors began to displace shortly after the weight was applied, and this displacement did not stabilize for the duration of the tests. At the end of the 47-hour test period, one of the anchors had displaced by about 0.11 inch and the other by about 0.07 inch. This result, and the fact that these anchors had shown no displacement before the tests began, prompted the more detailed investigation described below.

For the more rigorous testing, investigators used loads of 1,000, 2,000, and 3,000 pounds, representing the approximate range of service loads on the anchors. Initial plans called for testing six anchors in the westbound tunnel, two at each load level. The anchors were to be monitored for up to 3 months. However, anchor failures due to creep during the 3-month test period made it possible for investigators to conduct a total of nine tests. As with the preliminary tests, the nine anchors selected for the more rigorous testing displayed neither signs of distress nor displacement before the tests began. Also, the nine tests were conducted in the south row of the westbound tunnel, one of the more lightly loaded rows available.

During the sustained load tests, two anchors pulled completely free of the tunnel roof. Of these two, one pulled out after supporting 2,000 pounds for 84 hours; the other after supporting 3,000 pounds for 7 hours. One other anchor was relieved of its 3,000-pound load after 377 hours when it became apparent that it was about to pull out. In general, each adhesive anchor failure occurred within the epoxy and not at the epoxy-to-concrete interface. Only one anchor failure exhibited spalling of concrete. All of the anchors that sustained the load for the duration of the tests showed displacement from the tunnel roof of 0.03 to 0.14 inch, and the movement continued through the test period.

The FHWA also performed creep testing of Powers Power-Fast adhesive anchors at its Turner-Fairbank Highway Research Center. These tests were conducted with a variety of weights (1,000, 2,000, 3,000, and 4,000 pounds) and using both Fast Set and Standard Set epoxy formulations. Using best practices to minimize the formation of voids, investigators installed the anchors overhead in concrete slabs.

Regardless of the load level, none of the anchors installed with Standard Set epoxy showed significant movement during the test period (although the slight movement that did occur never completely stabilized). Conversely, anchors installed with the Fast Set epoxy exhibited significant displacement and high displacement rates at all load levels. Both of the anchors that were installed with

Fast Set epoxy and subjected to a 4,000-pound load displaced completely from the concrete slab before completion of the test. Figure 15 shows a graphical comparison of the displacement performance of anchors installed with Fast Set and Standard Set epoxies under a sustained load of 2,000 pounds. The graph displays the much more rapid onset and continuation of creep in the anchors installed with the Fast Set epoxy compared to those installed with the Standard Set version.

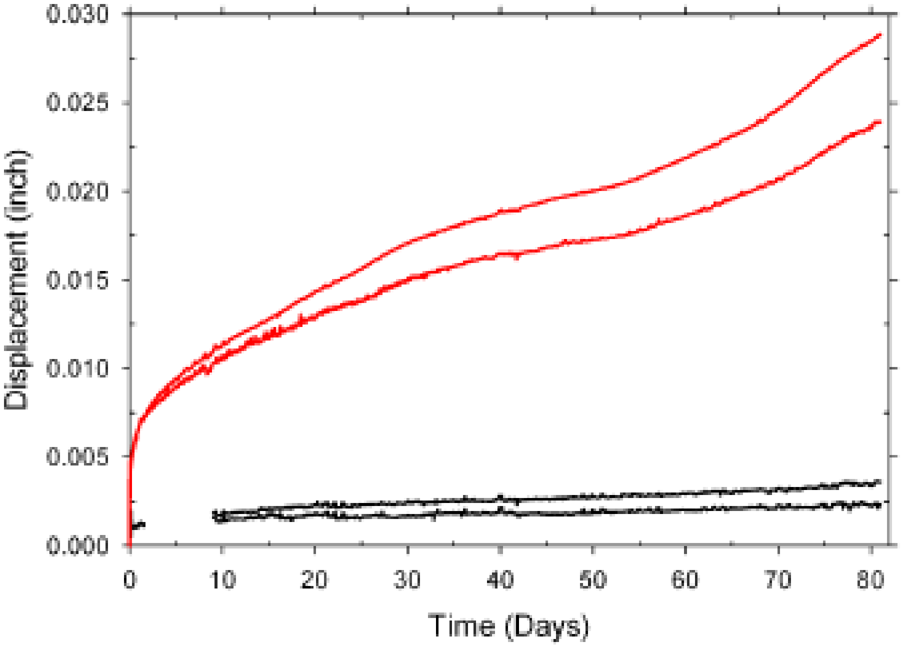

Figure 15. Displacement curves for test anchors installed with Power-Fast Fast Set (two upper curves) and Standard Set (two lower curves) epoxies under a 2,000-pound tension load. (Graphic courtesy Turner-Fairbank Highway Research Center)

The FHWA tests also demonstrated that the displacement rate for anchors using Fast Set epoxy increased by similar amounts (approximately linearly) from the 1,000-pound test to the 2,000-pound test and from the 2,000-pound test to the 3,000-pound test, but the rate increased significantly from the 3,000-pound test to the 4,000-pound test. In other words, the creep rate was approximately a linear function of the applied load up to 3,000 pounds, after which the rate became nonlinear.

Anchor Installation Parametric Study

At the request of the Safety Board, the Turner-Fairbank Highway Research Center conducted a study of the parameters associated with the installation of adhesive anchors in concrete that could affect the short-term load capacity of the anchors. Although most of the testing was done using Powers Power-Fast Fast Set epoxy, one series used Powers Power-Fast Standard Set epoxy, and one series used epoxy from another manufacturer.

To establish a baseline for anchor performance, the test matrix included a series of overhead anchor installations in which best practices were followed for cleaning the holes and minimizing the introduction of voids. These installations resulted in anchors with an average peak load capacity of 22,084 pounds, and this is the load that was used to gauge the effects of various installation parameters. As discussed below, the study revealed the installation parameters that did, and did not, cause reductions in anchor load capacity.

Parameters That Degraded Anchor Load Capacity

- Use of the Fast Set epoxy mixed off-ratio with an excess of hardener (more than 50 percent by volume) greatly reduced the load capacity of the anchors. In a test series with a ratio of hardener to resin of 3:2 (60 percent hardener), the average anchor strength was reduced by about 60 percent.
- Baking a Fast Set epoxy cartridge at 140° F for 56 hours before use caused the hardener portion of the epoxy to partially phase-separate. This phase separation resulted in an oily substance rising to the top of the cartridge where it was the first material extruded before transitioning to a material more consistent with epoxy mixed with the typical gray hardener. This phase separation resulted in a gross reduction (approximately 85 percent) in the load capacity of the first anchor installed with this material, but as anchor installation with this cartridge progressed, anchor performance increased to typical load capacities. Safety Board investigators placed samples of the Fast Set resin and hardener and the Standard Set resin and hardener into separate glass jars and stored them at 140° F for 56 hours. Changes in the appearance of the materials were documented with photographs. After storage, a layer of greenish brown liquid was found on top of the gray Fast Set hardener, and a layer of colorless liquid covered the Standard Set hardener. No change was apparent in the white resin components of either formulation.
- When an air bubble was intentionally created above the injected epoxy and the anchor was twisted during insertion (as specified by the manufacturer's installation instructions), the load capacity of the anchor was reduced by an average of 40 percent.
- When an air bubble was intentionally created above the injected epoxy and the anchor was not twisted during insertion, the load capacity of the anchor was reduced by an average of 32 percent.
- Eliminating individual steps in the anchor hole cleaning process only modestly reduced anchor load capacity. Anchors installed with no cleaning at all (but allowing the hole to dry) showed a reduction of less than 15 percent in average load capacity (after correcting for the reduction in load capacity caused by the presence of voids). Anchors installed immediately after coring of the anchor hole (with no drying or cleaning at all) also showed a reduction of less than 20 percent in

average load capacity (correcting for voids). These results suggest that the water used for cooling and lubrication during core drilling washes away debris, especially when drilling overhead.

Parameters That Did Not Degrade Anchor Load Capacity

- Anchors installed in holes created with a diamond coring bit had load capacities similar to anchors installed in holes created with a carbide-tipped drill bit, which is specified by ICBO ER-4514. The Powers design manual recommended, but did not require, the use of a carbide-tipped drill bit.
- Anchors installed through No. 11 rebar did not show a reduction in load capacity.
- Anchors on which simulated attachment hardware was installed and then torqued to 50, 90, and 125 foot-pounds showed no reduction in load capacity at any torque level.
- Injection of epoxy using a mixing nozzle shortened from 7 to 5 inches (which installation crews may be tempted to do to speed up the installation process)[61] did not affect the load capacity of the anchors.
- Use of Fast Set epoxy mixed off-ratio with an excess of resin (more than 50 percent by volume) increased the load capacity of the anchors.

The testing also found that anchors installed with Powers Standard Set epoxy and with Simpson Epoxy-Tie SET-22 (epoxy from Simpson Strong-Tie Company, Inc.) had average load capacities that were 10 to 20 percent higher than the anchors installed with best practices using Powers Power-Fast Fast Set epoxy. All three epoxies demonstrated some amount of creep displacement during testing when load was held constant; however, the Fast Set epoxy showed substantially greater creep, and at lower load levels, than the other two epoxies.

The testing revealed the difficulty in installing anchors overhead without introducing air bubbles that reduce the area of adhesion between the anchor and the concrete. Despite their best efforts, in a laboratory environment, investigators could not completely eliminate air bubbles—and the resulting voids in the cured epoxy—when they installed the anchors overhead.

After the anchors were pulled from the concrete test slab, the unbonded areas on anchors with significant voids were measured, allowing investigators to determine how these unbonded areas affected peak loads. The calculations indicated that anchors with significant voids in the epoxy produced a lower uniform stress at peak load than anchors without significant voids, suggesting that voids cause stress concentrations that limit the performance of the remaining (bonded) epoxy.

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[61] No evidence was found that workers modified the mixing nozzles during installation of the D Street portal anchors.

Tests of Void Formation During Anchor Installation

Safety Board investigators and representatives of the Turner-Fairbank Highway Research Center conducted a series of tests in order to study void formation in an overhead adhesive anchor system. Clear acrylic tubes were used to simulate the anchor holes so that the void formation process could be directly observed. The tubes were the approximate shape and size of the drilled holes for the anchor adhesive. Each tube was assembled with a flat end plate and a disk at what would be the upper end. The tubes were then clamped to an overhead plate to simulate the orientation of the anchor holes in the tunnel roof. A threaded nylon rod was used to simulate the anchor. In order to observe what occurred during the test procedure, a clear silicone-based caulk was used as a substitute for the opaque two-part epoxy. For comparison purposes, tests were also completed using Powers Power-Fast Fast Set epoxy instead of the clear caulk.

The tip of the injection tube supplied with the epoxy cartridges was flat (perpendicular to the axis of the nozzle). Additional mixing nozzles, available in packs of two, were also acquired and found to be of a one-piece construction (although the box illustrated a two-piece construction), and the tip of the nozzle was cut at approximately 45 degrees.

The installation guidelines printed on the cartridge indicated that

- The anchor hole should be filled approximately half to two-thirds full, starting from the bottom or back of the anchor hole;
- The nozzle should be slowly withdrawn as the hole fills to avoid creating air pockets;
- The anchor should be turned slightly as it is inserted; and
- The anchor should be fully seated at the bottom of the hole.

For the series of tests, the silicone caulk (or epoxy for one series of tests) was injected upwards into the test hole, and a nylon anchor was inserted. Anchors were inserted in one continuous motion, with the speed of insertion controlled by the viscosity of the caulk and estimated at approximately 10 inches per minute. After testing, an estimation of the void area was made. Small voids at the upper ends of the holes were not included in the area calculations.

The results of these tests may be summarized as follows:

- When the epoxy manufacturer's installation instructions were precisely followed, a small bubble of air (0.04 cubic inch) was normally trapped at the upper end of a hole (in the groove produced by the core drill).[62] The simulated anchor could not be maintained concentric with the hole, and

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[62] A core drill cuts a ring to the depth required, and the core is subsequently broken off to produce a hole. Previous examinations revealed that the core normally broke off about 0.25 inch above the bottom of the hole, leaving a generally flat bottom about 0.6 inch in diameter encircled by a groove.

during the last inch of insertion, the air bubble at the top was displaced away from the side of the hole closest to the threaded rod.

- Greater volumes of entrapped air at the end of the hole produced a void or voids along the length of the hole. Entrapped air with a volume less than or equal to 0.26 cubic inch would remain within the hole as a void. If the entrapped air had a volume greater than 0.26 cubic inch, a portion of the air was normally forced out of the test hole, leaving a void along the side of the anchor.
- Twisting the threaded rod after insertion tended to spread out any voids produced during insertion, thereby increasing the effective area of the void.
- Air trapped in the middle of the hole had the tendency to be forced out of the hole during insertion of the threaded rod.
- The epoxy surrounding the voids adhered both to the threaded nylon rod and to the sides of the acrylic tube. (This adherence was also observed on the accident anchors and in the accident holes.)
- No difference was noted in the void areas produced using the angled nozzle versus the square (flat) nozzle.

Examination of the Effect of an Air Bubble in the Resin or Hardener

The Safety Board performed four experiments simulating the presence of an air bubble at the tip of the container for either the resin or hardener in a dual-cartridge package of Power-Fast Fast Set epoxy. An air bubble in one of the components would result in some amount of epoxy mixed at a ratio different from the 1:1 ratio that was intended. Bubbles of 0.2 and 0.4 cubic inch in the resin or in the hardener were simulated by placing a spacer on the end of one plunger of the injection gun to advance one component ahead of the other. A new mixing nozzle was used for each of the four experiments. As with the void formation experiments described above, the epoxy was injected overhead into clear acrylic tubes simulating anchor holes, and a threaded nylon rod was then inserted.

The epoxy was allowed to set for 24 hours, after which the acrylic end plates from the tops of the tubes were removed. In the two experiments where the resin was extruded ahead of the hardener (an excess of resin), the epoxy had cured to a hard, solid state. In the two experiments where the hardener was extruded ahead of the resin (an excess of hardener), some amount of liquid uncured epoxy remained at the top of the hole. Seven days after installation, the threaded nylon rods were pressed out of the tubes in which the hardener had been extruded ahead of the resin. In both cases, pliable epoxy that was tacky to the touch was found over approximately the top half of the embedded lengths of the threaded nylon rods. Except for the color of the epoxy, these two test anchors appeared similar to the anchors that retained a dark brown pliable epoxy when extracted from the tunnel roof. These results were consistent with the results from the FHWA parametric study, which found that epoxy mixed with an excess of hardener (therefore resulting in some amount of uncured epoxy) decreased the strength of the anchor, while epoxy mixed with an excess of resin increased anchor strength.

Epoxy Testing

Materials Characterization Testing. A variety of materials characterization tests were performed on samples of the anchor adhesive from the D Street portal as well as on samples from newly purchased packages of epoxy. The tests included Fourier transform infrared spectroscopy, differential scanning calorimetry, thermogravimetric analysis, headspace gas chromatography/mass spectroscopy, and X-ray energy dispersive spectroscopy using a scanning electron microscope.

The adhesive samples from the tunnel were taken from the anchors that had been examined in the Safety Board Materials Laboratory and from the adhesive collected from anchor holes during the borescope examination. Some of the samples were selected for examination because they displayed typical adhesive characteristics; others because they displayed an unusual structure.

For reference, samples of new materials were also tested. The anchor adhesive used in the D Street portal tunnel was identified in various construction documents as Power-Fast Epoxy Injection Gel packaged as NRC-1000 Gold Premier Epoxy.[63] New packages of both Standard Set and Fast Set formulations of Power-Fast Epoxy Injection Gel[64] were purchased for testing,[65] along with a manual injection gun. Each package of epoxy consisted of two side-by-side tubes, one containing a white epoxy resin and the other a dark gray hardener. The injection gun simultaneously pushed two plungers that extruded the resin and hardener through a static mixing nozzle (included with the package), which attached to both tubes. The tubes could be resealed for later use (with a new mixing nozzle); additional mixing nozzles were also purchased. For both Standard Set and Fast Set epoxies, the resin and hardener tubes were the same diameter, so the resin and hardener mixed in a 1:1 ratio by volume.

Five samples of adhesive from the D Street portal, along with reference samples of both the Standard Set and Fast Set epoxy formulations, were sent to Trace Laboratories–East in Hunt Valley, Maryland, for preliminary testing. One of the samples from the tunnel had been collected during the borescope examination

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[63] During the early stages of construction of the I-90 connector tunnel ceiling, some of the epoxy used was packaged as Powers Power-Fast epoxy, but this same material at some point began to be packaged as NRC-1000 Gold epoxy.

[64] Sika Corporation, which formulated the epoxies sold by Powers, told the Safety Board that the changes in epoxy formulation that occurred between 1999 and 2006 were not significant. The company also provided the Board with documentation detailing the changes.

[65] The current retail price of a 22-ounce package of Power-Fast Fast Set epoxy is about $2.00 more than the Standard Set version ($46.00 versus $44.00). The cost is the same ($38.20) for the 15-ounce packages. According to Powers' estimates, each 22-ounce package should be sufficient to install about 30 anchors of the type used in the D Street portal.

of holes at the accident site; the other four were from taken from anchors. These included one sample with yellow tint and one sample of pliable dark brown material. The reference samples included samples mixed at 1:1 by volume through the static mixing nozzle and samples mixed with either an excess of white resin or an excess of gray hardener.

Thirty-one adhesive samples from the tunnel were subsequently sent to the Massachusetts Institute of Technology (MIT) for testing. These included samples taken from 17 of the 20 anchors involved in the accident (3 of the failed anchors did not retain sufficient epoxy to allow sampling). The 31 samples included material that had a yellow tint, material that had an appearance typical of fractured epoxy, material that had a pliable texture and a dark brown appearance, and material that showed characteristics of adhesive fracture (at the concrete interface) rather than cohesive fracture (within the epoxy). Also sent for testing were five samples of Power-Fast Fast Set epoxy that had been used during FHWA anchor installation and pull testing. Reference samples of Power-Fast Standard Set and Fast Set epoxy mixed at 1:1 by volume in the Safety Board Materials Laboratory were also submitted for comparison.

Fourier transform infrared spectroscopy at MIT showed that all of the samples from the tunnels, including the samples from the accident site, matched to the Fast Set reference samples. Headspace gas chromatography/mass spectroscopy examination of the Fast Set and Standard Set reference samples at Trace Laboratories showed clear differences in the unreacted components present in the two formulations. All of the epoxy samples from the tunnel that were tested with this technique matched the Fast Set reference samples.

The samples from the failure area were similar to the other samples from the tunnel that were identified as typical. No anomalies were found that would suggest that the epoxy from the anchors in the failure area differed from the epoxy found on anchors in other areas of the tunnels.

Two differential scanning calorimetry thermal scans were performed on each sample. Almost all of the samples demonstrated a difference in the glass transition between the first and second scans, and a number of samples exhibited endothermic peaks or exothermic reactions during the first scan that were not present in the second scan. These results indicate that heating during the first scan induced additional chemical (or structural) reactions, suggesting that the as-installed epoxy was not completely cured. The results of the differential scanning calorimetry tests of the dark brown samples suggest that these materials were consistent with an epoxy mixed with an excess of hardener.

Neither the Fourier transform infrared spectroscopy nor the differential scanning calorimetry testing revealed the cause of the yellow tint on the sample with the yellowed epoxy.

X-ray energy dispersive spectroscopy in the scanning electron microscope was carried out on two epoxy samples from the tunnels and on the reference samples. The spectra for all of the samples appeared similar both in elemental content and in relative peak heights, with peaks for carbon, oxygen, magnesium, silicon, and calcium.

NIST Testing. The Safety Board provided new packages of both Standard Set and Fast Set formulations of Power-Fast Epoxy Injection Gel to researchers in the Building and Fire Research Laboratory at the National Institute of Standards and Technology (NIST) for testing by dynamic mechanical thermal analysis coupled with time-temperature superposition. The testing was intended to predict the long-term behavior of the two epoxy formulations in regard to creep and to estimate the time scale for any changes in creep compliance.[66]

Rearrangement of the long-chain molecules that make up a polymer[67] results in a stiffness that is time-dependent. If a load is applied quickly, the molecules have insufficient time to rearrange and deform, and the polymer reacts as a stiff, glassy material. If the load is then held constant, the molecules will gradually rearrange and deform in a process that is observed as creep. Although, given sufficient time, this deformation could increase by orders of magnitude, with a well-formed polymer network (as in a cross-linked epoxy), the deformation should reach a long-term (rubbery) plateau after which creep is no longer observed.[68]

The molecular rearrangement that occurs over time as the material transitions from glassy to rubbery is similar to the change that occurs in a shorter time when the material is heated. Thus, by combining the results from a series of short-term tests at different temperatures (a procedure known as time-temperature superposition), researchers can predict how a material will respond over a much longer period of time.

NIST researchers tested small thin-film samples of the two epoxy formulations loaded in tension, then combined the results to calculate the creep compliance at room temperature (20° C or 68° F). The results showed that the creep compliance under short-term loading was similar for both the Fast Set and Standard Set epoxies, indicating that the instantaneous response (initial anchor displacement) when a load is applied would be similar for anchors installed with either formulation. For the Fast Set formulation, this initial anchor displacement was predicted to increase rapidly from its initial value—by a factor of 1.8 after 1 day, by a factor of 3.5 after 1 month, by a factor of 6.3 after 1 year, and by a factor

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[66] *Creep compliance* relates the strain (equivalent, in this context, to anchor displacement) at any point in time to the constant applied stress (tensile load). A larger creep compliance translates directly to a larger anchor displacement.

[67] A *polymer* is a natural or synthetic compound that consists of large molecules made up of a linked series of smaller, identical molecules knows as monomers.

[68] The chemical makeup and behavior of epoxy is discussed in more detail in the "Nature of Epoxy" section of this report.

of 14 after 10 years. The best estimate of the Standard Set behavior was that the initial anchor displacement would increase by a factor of 1.2 after 1 day and by a factor of 2 after 10 years.

The NIST testing results indicated that, while the creep compliance will eventually plateau for both epoxies, the long-term creep compliance of the Fast Set epoxy is 11 times that of the Standard Set epoxy. This suggests that the Fast Set epoxy has substantially fewer cross-links than the Standard Set epoxy or possibly a significantly lower filler content. In addition, the testing indicated that the Fast Set epoxy is more complex and inhomogeneous than the Standard Set epoxy.

Additional tests were performed to assess the effects of absorbed water on the two epoxy formulations. Because the testing was performed with thin-film samples, saturation could be achieved fairly quickly by exposing the samples to 100 percent relative humidity at room temperature. Under these conditions, the Fast Set epoxy absorbed almost twice as much water as the Standard Set (4.4 percent compared to 2.3 percent, by mass). The absorbed water softened both materials, causing a lowering of the glass transition temperature (the point at which the material changes from glassy to rubbery) of both as well as a broadening of the transition itself. Tests on samples that were saturated and then dried showed that some of the changes caused by the absorbed water were irreversible.

Nature of Epoxy

Epoxies are used as adhesives in a wide variety of applications. In composite structures (such as aircraft components, printed circuit boards, and sporting equipment), epoxies act as an adhesive holding together the fiber reinforcement. Epoxies have good chemical and electrical resistance, so they are often used in paints and coatings and to make molded parts that act as electrical insulators. In the construction industry, epoxies are used in a number of adhesive and sealant applications and can be used as a matrix with aggregate reinforcement to make highly durable but expensive epoxy concrete. For at least 35 years, epoxies have been used with threaded rods and rebar to form adhesive anchors.

The term “epoxy” covers a broad range of materials formed by the chemical reaction between two components: a resin and a hardener. An epoxy resin contains compounds with one or more epoxide rings (hence the name “epoxy”), which are three-membered rings with two carbon atoms and one oxygen atom. A wide variety of chemical compounds can be used as the hardener, including amines or amides (nitrogen-containing compounds) and mercaptans (sulfur-containing compounds). The Material Safety Data Sheets (MSDS) for Powers Power-Fast epoxies indicate that both the Fast Set and Standard Set hardeners are amine-based.

Once the resin and the hardener are mixed, the amine groups on the hardener molecules begin to link with the epoxide groups on the resin molecules. Typically, the resin molecules have an epoxide ring at each end, and the hardener molecules have an amine group at each end. The resin and hardener molecules can therefore link in an alternating pattern to form long polymer chains. Each amine group can link to more than one epoxide ring, so resin molecules can link to amine groups within different chains, thus forming crosslinks between polymer chains. A well-developed network of crosslinks prevents significant rearrangement of the polymer molecules, so the polymer cannot be melted and reformed. This type of polymer is called a *thermoset.* (Polymers that can be melted and reformed are called *thermoplastics*. In a thermoplastic, the polymer chains are entangled but not crosslinked.) As the epoxy cures, that is, as more and more epoxy molecules link with hardener molecules in long polymer chains, fewer unbonded reactive groups remain available for linking. Also, as the network forms, the viscosity of the material increases, making it more difficult for any free reactive groups to move to an area where a reaction can occur. Eventually, the reaction slows and finally stops. Even at this point, however, some unbonded reactive groups generally remain, and an increase in temperature will cause the network to expand and the viscosity of the material to decrease, which will allow more of the remaining reactive groups to link to one another.

In addition to the epoxy resin and the hardener (or blends of different resins and hardeners), an adhesive formulation can include a number of other components. Epoxy adhesives frequently include inorganic filler particles that reduce cost, reduce shrinkage, increase bulk stiffness and strength, improve gap filling, and increase the viscosity of the components (before curing). The MSDS sheets for the Power-Fast Fast Set and Standard Set epoxies indicate that they both include talc (magnesium silicate) and calcium carbonate, two common inorganic fillers. The formulation can also incorporate organic compounds that alter the viscosity of the resin or hardener, accelerate or slow the curing reaction, and alter the final properties of the adhesive. These organic compounds might have reactive endgroups and be incorporated into the network, or they might remain as unreacted compounds.

Viscoelasticity and Creep. Like all polymers, the stiffness of an epoxy is time and temperature dependent. If a load is applied suddenly, the epoxy responds like a hard, *glassy* solid. If that load is then held constant, however, the long-chain polymer molecules have time to begin to rearrange and slide past one another, and the stiffness of the epoxy decreases to a range where it can be described as *rubbery*. This increasing deformation under constant load is called *creep*. Materials like epoxy (or any polymer) with an instantaneous elastic response followed by a slowly increasing deformation (like a very viscous fluid) are called *viscoelastic*. The time necessary for the glassy-to-rubbery transition depends on the molecular structure and the lengths of the polymer chains between crosslinks. The temperature is also critically important, because the molecular rearrangements are a result of the constant thermal excitation of the molecules. If the temperature increases, the rate of rearrangement increases, and the glassy-to-rubbery transition occurs more rapidly. Above the glass transition temperature, the molecular rearrangements occur so quickly that the epoxy is always rubbery.

In a thermoplastic (a polymer without crosslinks) under load, the behavior can pass from the glassy regime to the rubbery regime and, given sufficient time, eventually to a fluid regime where the polymer molecules move completely past one another. In a well-formed crosslinked network of a thermoset, the polymer molecules are prevented from moving very far, and once the rubbery state is reached, no further softening occurs.

Because time and temperature are so strongly interrelated in polymers, it is common to try to predict the long-term rubbery behavior by testing at higher temperatures. In fact, the entire glassy-to-rubbery transition can be mapped out by testing over a range of temperatures and then combining all the data. This method, called time-temperature superposition, works well for epoxies that are fully cured. For materials like the Power-Fast Fast Set epoxy, however, the additional reactions that occur as the temperature increases change the molecular structure of the polymer, which interferes with the superposition. Poor time-temperature superposition can be a clue to an incompletely formed network or an inhomogeneous material.

Nonlinear Deformation, Yield, and Damage. The time-temperature superposition method used to predict long-term behavior is generally carried out using relatively small loads and deformations. When the loads are small, the deformations are linearly proportional to the load, and structures are, for the most part, designed so that the loads remain within the range of linear behavior. However, this range depends on the state of the epoxy, because loads that are within the linear range in the glassy state might be outside the linear range in the rubbery state.

Within the linear range, the glassy-to-rubbery transition is assumed to occur independently for each load application. So if two loads are applied at different times, the response in each case is a glassy deformation followed by creep as the molecules rearrange. For loads in the linear range, creep deformation is generally reversible, so that once the load is removed, the epoxy will eventually return to its original shape.

At higher loads, the deformation can become a nonlinear function of the applied load. Depending on their formulation, epoxies can show softening and plastic (unrecoverable) deformation similar to the ductile behavior of metals, suggesting relatively extensive movement of the polymer molecules. The onset of plastic deformation is also time (and temperature) dependent. If the load is applied slowly, plastic deformation begins at a lower load than if the load is applied quickly.

Generally, cured epoxies have been considered to be brittle materials, meaning that they fracture rather than undergo plastic deformation as the load increases. The accumulation of this fracture damage is another possible source of nonlinear creep behavior. In a structure where the loads are not evenly distributed, small cracks in the epoxy can occur where the loads are high, shifting the load to areas where the structure is still intact. The structure therefore behaves as though the epoxy is a softening material even though the epoxy is actually progressively fracturing.

Other Information

Current Guidance for the Use of Power-Fast Epoxy

Powers Guidance. As part of this investigation, the Safety Board reviewed the versions of the Powers *Specification and Design Manual* that were published subsequent to the second edition, which was current at the time the ceiling was installed in the D Street portal. The third edition of the manual was identical to the second edition with respect to the information about adhesive anchors. The fourth edition, dated 2002, had some changes in the ultimate strength values, but, as with previous versions, it did not identify differences in the allowable loads or long-term performance of the Fast Set and Standard Set epoxies.

In 2006, Powers published the fifth edition of its manual. The manual listed the physical properties of the Powers adhesives and showed that the Standard Set epoxy formulation has slightly higher values than Fast Set for compressive, tensile, flexural, and slant shear strengths. All the bond strength capacity tables had a footnote that read (depending on the values in the table): "Reduce the above [allowable/ultimate] bond capacities by 25 percent when calculating [allowable/ultimate] bond capacities for the Fast Set formula." This was the first mention in a Powers manual of a possible difference in the performance of the two epoxy formulations in anchoring applications.

In the front of the manual was a page with sections labeled "Product Description," "General Applications and Uses," "Features and Benefits," and "Approvals and Listings," all having to do with the Power-Fast + Epoxy Adhesive Anchoring System.[69] The "Product Description" section noted that the product is "available in Standard Set and Fast Set formulas." This is the only place on the page that mentioned the two formulations. In the bulleted list of "Features and Benefits" were these two items:

> Listed and approved to resist dead loads, live loads, and short-term loads such as those resulting from wind or earthquake.
>
> Independently tested and qualified to ASTM E1512, AC58 and AC60 criteria, including creep resistance, freeze-thaw cycling and simulated seismic/wind conditions.

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[69] The "+" indicated that a mixing nozzle was included with each cartridge.

The specification and design manual stated

> Safety factors are used to account for field variations which may differ from the testing conditions in the laboratory. Typical minimum safety factors established by industry are as follows [abridged]:
>
> | Product | Typical Safety Factor |
> |---|---|
> | Mechanical Anchors in Concrete | 4 (UBC, IBC, IRC)[a] |
> | Adhesive Anchors in Concrete with Creep Test | 4 (UBC, IBC, IRC) |
> | Adhesive Anchors in Concrete without Creep Test | 5.33 (UBC, IBC, IRC) |
> | Pow[d]er-actuated Fasteners in Steel | 5 (UBC, IBC, IRC) |
>
> [a] UBC – Uniform Building Code; IBC – International Building Code; IRC – International Residential Code.
>
> While the Building Codes utilize the typical safety factors listed above for a minimum recommended allowable design load, higher safety factors (10:1 or higher) may be appropriate for the following conditions:
>
> - Overhead applications
> - Vibratory loads (example, dynamic or shock loads)
> - Safety and life critical applications
> - Questionable base materials
>
> Actual safety factors to be used should be determined by the design professional responsible for the product installation, based on the governing building code and after examining all influencing factors.

In May 2007, Powers updated its Power-Fast epoxy product literature to specifically address the differences in long-term performance of the Fast Set and Standard Set formulations. In the May 2007 revision, tables showing ultimate and allowable bond strengths for threaded-rod anchors are labeled as applying to the "Standard Set Power-Fast+" epoxy. This is a change from previous editions, which had table headings that referred only to "Power-Fast+" epoxy. Additionally, a footnote accompanying the tables states

> **Reduce the above allowable bond capacities by 25 percent when calculating allowable bond capacities for the Fast Set formula. Allowable working load values for Fast Set formula are permitted for short-term loads only; where applicable to code and ICC-ES ESR-1531.** [Emphasis in the original.]

As with all previous editions of the Powers manual, the most recent manual revision recommends the use of seal plugs for overhead applications, but it does not indicate that the presence of a seal plug can reduce the load capacity for a particular anchor and anchor embedment below that published in the tables contained in the manual.

International Code Council Guidance. In February 2003, the four building products evaluation services in the United States—National Evaluation Services, BOCA Evaluation Services, ICBO Evaluation Service, Inc., and SBCCI Public Safety Testing and Evaluation Services—combined to form ICC Evaluation Service, Inc. (ICC ES), as a separately incorporated subsidiary of the International Code Council (ICC).

Evaluation reports of the former services are being revised, reformatted, renumbered, and reissued as ICC ES reports (ICC ESRs). Power-Fast epoxies are now addressed in ICC ESR-1531, which was reissued in December 2006. This report effectively replaces ICBO ER-4514 in regard to the Power-Fast epoxy.[70] ICC ESR-1531 did not carry over the recommendations that were contained in ICBO ER-4514 indicating that Power-Fast Fast Set epoxy should be used for short-term loads only. The "Conditions of Use" section includes the following:

> 5.5 The Power-Fast epoxy adhesive is permitted to be used in normal-weight concrete to resist dead loads, live loads, and short-term loads such as those resulting from wind or earthquake….

The conditions of use do not distinguish Fast Set from Standard Set Power-Fast epoxy. Tables in the report showing allowable tension and shear loads for threaded rods installed in concrete do list separate loads for the Fast Set and Standard Set epoxies. A footnote to the tables states that the allowable loads for the Fast Set epoxy "are calculated using an applied safety factor of 5.33." No text in ICC ESR-1531 restricts the Fast Set formulation to short-term loads.

On May 18, 2007, Powers distributed the (previously discussed) updated version of its *Specification and Design Manual* to the company's branch managers and sales staff. Included with the revised manual was a cover letter from Powers' director of engineering indicating that the changes to the manual reflected clarifications that were needed in ICC ESR-1531. The letter stated that Powers had questioned ICC ES about the fact that the restrictions of ICBO ER-4514 regarding acceptable use of the Fast Set epoxy were not included in ICC ESR-1531. According to the letter, ICC ES had "agreed that a clarification is in order." The letter further stated

> The clarifications for the conditions of use are expected to limit the use of the Fast Set Power-Fast formula in ESR-1531 for the reported allowable loads to short-term loads only, such as those resulting from wind or earthquake.

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[70] ICBO ER-4514 is still available as a legacy report, but in January 2007, all references to Power-Fast epoxy were removed. The report now addresses only the Powers Chem-Stud Capsule adhesive anchoring system.

Quality Control/Quality Assurance

Quality control requirements for highway construction projects are addressed in AASHTO's *Implementation Manual for Quality Assurance* (February 1996) and *Construction Manual for Highway Construction 1990* and in the FHWA's *Quality Assurance Procedures for Construction*, which was published on June 29, 1995, as 23 *Code of Federal Regulations* Part 637.

These documents define quality assurance as "all those planned and systematic actions necessary to provide adequate confidence that a product or service will satisfy given requirements for quality." The guidance goes on to state that

> The term Quality Control and Quality Assurance (QC/QA) has often been used synonymously with Quality Assurance. The above definition considers Quality Assurance to be an all encompassing concept which includes quality control (QC), acceptance, and independent assurance (IA). Therefore, Quality Assurance is the proper term and is used in this manual.

Under the heading "Engineering Personnel," the AASHTO guidance states

> Many Agency engineering personnel have been involved in construction management for many years. They may believe that there is no need to change and that you are trying to 'fix something that isn't broken.' Some may interpret the Quality Assurance program as a form of automation and believe that they are being stripped of responsibilities. They may feel that their only responsibilities are to 'observe and record' test results and when the work is done, just apply the proper pay adjustment. The inspectors must realize that their responsibility has not changed and that inspection is still a critical element of acceptance. If a Contractor is producing unacceptable work, the Contractor must be notified as soon as possible.
>
> It goes on the say that
>
> The Contractors must understand that QC is their responsibility, and 'Acceptance' is the Agency's responsibility. It is important to realize that some of the test results will not be identical; therefore, an Agency must address these instances in their specifications. Contractors should establish correlation factors between their QC tests and the Agencies' acceptance testing.

Under the QC/QA system developed by State departments of transportation, AASHTO, and the FHWA, the contractor produces certifications from suppliers that a material meets the State's specifications. The State's materials testing group then acquires random samples and subjects them to testing by the State's certified laboratory or by a certified private laboratory. This process applies primarily to the structural materials used for a project, such as pavement materials (asphalt, Portland cement, pavement and structural concrete aggregate, structural steel, and admixtures to pavements). In the case of the accident project, the steel anchor rods and the tunnel's Portland cement concrete were tested by the CA/T materials laboratory. The anchor epoxy was tested only for its performance in high temperatures during possible tunnel fires.

This model QC/QA program places responsibility for quality control on the project construction contractor and its materials testing subcontractor. The construction manager (a State or its project management contractor) performs quality assurance by monitoring the quality control of the contractor and the contractor's material testing consultant.

At the request of the Safety Board, AASHTO surveyed its members regarding the testing of critical systems or materials (such as a system or material used to support components suspended over a roadway) that do not have AASHTO or ASTM test methods or specifications associated with them. Appendix B summarizes information obtained from that survey.

CA/T Structural Inspection Program

The accident investigation found no evidence that any inspections had been performed to determine the physical and functional condition of the ceiling system in the D Street portal between the time the tunnel was opened to traffic on January 18, 2003, and the day of the collapse. Nor did records indicate that periodic inspections were performed on any of the ceiling systems in the I-90 connector tunnel.

The scope of services contained in two short-term contracts between MassHighway and B/PB required the management consultant to

> develop a maintenance structural inspection program for the viaducts, tunnels, bridges, buildings and other facilities constructed by [MassHighway] as part of the CA/T Project…. The scope of the program will deal with the structural elements of the tunnels, tunnel finishes, bridges, buildings and facilities as well as the structural components of the electrical, mechanical and control systems and specialty products and materials used in the construction of the CA/T Project. The inspection program will include procedures and protocols for routine and emergency inspections.

In November 2003, B/PB prepared the *Inspection Manual for Tunnels and Boat Structures*, the stated purpose of which was to

> aid the MTA…in the detailed and scheduled inspection of the tunnels, boat sections and the structural elements included within the Central Artery/Tunnel…network. Tailored to this highway tunnel system, the scope encompasses all aspects of a structural inspection.
>
> One component of the inspection manual was the following:
>
> Section 5.0, Classification of Structure Type and Specific Elements, illustrates specific elements encompassed within the CA/T which is comprised of five different tunnel types. This mainly includes special structures, products and testing, concrete and steel components, protective coatings, tunnel finishes and the roadway wearing course.

The manual included a set of condition ratings that applied to the structural elements of the inspection:

> In addition, a set of condition ratings, ranging from 0 to 9, can be applied to the structural elements of the inspection. These techniques assist in providing a straightforward inspection record that is effective for tunnel assessment and maintenance.

The manual indicated that each hanger component used to support the modular concrete ceiling panels in the I-90 and I-93 exhaust duct areas should be inspected visually, by sounding, or by nondestructive testing. Appendix A of the manual included a blank routine hanger inspection field report. The blank field report contained entry fields for hanger number, location, connections for ceiling slab and floor slab, clevis, bolts, turnbuckle, threaded rod, moisture, and comments. The appendix also included a deficiency legend that identified the following deficiencies for exhaust duct hangers (vertical and diagonal) and bolt connections: surface rust, loss of section (percentage), loss of tension, out of plane (horizontal and vertical), broken, and buckled.

Investigators asked MTA officials why the inspection manual was not used from the time it was published in November 2003 until the day of the ceiling collapse. The officials stated that the inspection manual was not used because (1) a tunnel inspection database needed to be developed, (2) the inspection manual was being reviewed by the FHWA and the MTA, and (3) MTA personnel needed time to be trained to use the manual. They said that, in late 2005, the MTA took steps to initiate pilot or trial inspections based on the manual, including engagement of an outside consultant, but these trials were never carried out.

The Metropolitan Highway System Safety Review Team *Stem to Stern Safety Review – Phase I* report[71] recommended that an inspection interval of 6 months be followed for as long as the epoxy anchorage system remains in service in the Ted

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[71] Commonwealth of Massachusetts, Office of the Governor, ***Metropolitan Highway System Stem to Stern Safety Review–Phase I***, November 15, 2006.

Williams Tunnel, the Sumner Tunnel, and the Callahan Tunnel. According to that report, the 6-month inspection interval was necessary until a long-term strategy to address the problems with the ceiling anchorage system could be developed, possibly including replacing all epoxy anchors or maintaining existing anchors and continuing to monitor their performance.

In a summary of the status of tunnel inspections since the accident, the MTA indicated that it had "reinvigorated efforts to develop and implement a comprehensive tunnel inspection program" with the completed, ongoing, and projected actions summarized below.

- The MTA issued a tunnel inspection and testing program policy directive that calls for routine, in-depth inspections of all tunnel elements. The policy requires that all appurtenances suspended over roadways and their hanger systems be inspected annually and that all other structural tunnel components be inspected every 3 years.
- In March 2007, the MTA approved four 3-year general engineering consulting services contracts under which all the MTA tunnels will be continuously inspected in 2007, 2008, and 2009.
- The Metropolitan Highway System engineering and maintenance staff has reorganized and is currently in the process of increasing personnel to allow a greater portion of tunnel inspection and testing to be done by in-house staff. A new senior structural engineer position is being added to organize and oversee the tunnel inspection program, and a new structures maintenance engineer position is being added to coordinate and oversee repairs required in response to the inspection findings. MTA staff is currently inspecting the Sumner and Callahan Tunnels' adhesive ceiling hangers on a continuous basis. Additionally, the MTA will be performing biweekly readings of ceiling hanger instrumentation in the Ted Williams Tunnel.
- Engineering consultants are developing standard tunnel inspection forms based on the *Inspection Manual for Tunnels and Boat Structures* and standard FHWA bridge inspection forms. Data are being collected and organized with respect to providing a report of the preventive maintenance procedures performed on various life safety tunnel systems.
- The MTA is developing a 5-year capital program that will incorporate a tunnel inspection program.

Federal Design and Inspection Standards for Bridges and Tunnels

In the early 1970s, the FHWA, under legislative authority provided under 23 *United States Code* Section 151 and using standards promulgated in 23 *Code of Federal Regulations* Part 650, developed the National Bridge Inspection

Program (NBIP). This program required that each State transportation department inspect all non-federally owned public-road bridges within its jurisdiction.

The NBIP was developed, in part, in response to Safety Recommendation H-71-13, which was issued to the U.S. Secretary of Transportation following the Safety Board's investigation of a December 15, 1967, bridge collapse in Point Pleasant, West Virginia, that killed 46 people.[72]

> H-71-13
>
> Expand existing research programs or institute new research programs to: (a) identify bridge building materials susceptible to slow flaw growth by any of the suspected mechanisms; (b) determine critical flaw size under various stress levels in bridge building materials; (c) develop inspection equipment capable of detecting critical or near critical flaws in standing bridge structures; (d) devise analytical procedures to identify critical locations in bridge structures which require detailed inspection; (e) develop standards which incorporate appropriate safeguards in the design and fabrication of future bridges to ensure protection against failures of material such as occurred in the Point Pleasant bridge; (f) develop standards for the qualification of materials for future bridge structures, using the information disclosed in this investigation; (g) devise techniques for repair, protection, or salvage of bridges damaged by internal flaws; and (h) expand the knowledge of loading history and life expectancy of bridges.

The NBIP consists of *National Bridge Inspection Standards* (NBISs) and a National Bridge Inventory (NBI). The NBISs were first established in 1971 to set national requirements regarding bridge inspection frequency, inspector qualifications, report formats, and inspection and rating procedures. The NBI data include identification of the bridge, structure type and material, age and service, geometric data, navigation data, condition, load rating and posting, proposed improvements, and inspections. The NBISs require that bridges be inspected at regular intervals not to exceed 24 months.

Tunnel inspections are addressed in the FHWA's *Highway and Rail Transit Tunnel Inspection Manual,* 2005 edition, which states that tunnel owners should

> establish the frequency for up-close inspections of the tunnel structure based on the age and condition of the tunnel. For new tunnels, this time period could be as great as five years. For older tunnels, a much more frequent inspection time period may be required, possibly every two years. This up-close inspection is in addition to daily, weekly, or monthly walk-through general inspections.

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[72] National Transportation Safety Board, *Collapse of U.S. Highway Bridge, Point Pleasant, West Virginia, December 15, 1967*, Highway Accident Report NTSB/HAR-71/01 (Washington, DC: NTSB, 1971).

The tunnel inspection manual is a guide for tunnel inspections; the FHWA has not been given legislative authority to mandate compliance with national tunnel inspection standards.

Ceiling Designs in Other U.S. Tunnels

The Safety Board contacted nine tunnel authorities to gather information about various suspended ceiling designs used in tunnels throughout the United States. The Board requested specific information about typical ceiling panel/slab dimensions and weights, the type of ceiling anchorage system used, and whether the ceiling system was continuously supported at the ends of the panel. Appendix C summarizes the information obtained from that survey.

In July 2004, the FHWA developed the *Road Tunnel Design Guidelines* manual that contained guidelines for the design of different categories of tunnels (soft ground tunneling, rock tunnels, mixed-face and difficult-ground tunnels, shafts, shotcrete, immersed tunnels, and cut-and-cover tunnels). The manual did not contain any guidance on the design of tunnel finishes.

Analysis

This analysis begins with a brief description of the July 10, 2006, collapse of the D Street portal ceiling, followed by a discussion of the factors that were considered to be potentially causal or contributory to the accident. The analysis concludes by addressing the safety issues identified during the accident investigation. Those safety issues are as follows:

- Insufficient understanding among designers and builders of the nature of adhesive anchoring systems;
- Lack of standards for the testing of adhesive anchors in sustained tensile-load applications;
- Inadequate regulatory requirements for tunnel inspections; and
- Lack of national standards for the design of tunnel finishes.

Accident Sequence

By July 2006, at least 13 of the ceiling support anchors in the M1 anchor row of the eastbound D Street portal tunnel had likely displaced (pulled out of the tunnel roof) by a significant amount. Although preaccident displacement of the anchors from the accident row could not be measured, 13 of the 20 anchors in that row showed a yellow discoloration found only on displaced anchors. The yellowed epoxy suggests that these anchors, at least, had displaced to some extent before they pulled free during the accident. The yellowed epoxy on one of the anchors indicated that it had displaced by as much as 4 inches from its original 5-inch embedment depth.

About 11:00 p.m. on July 10, 2006, all 20 anchors in the M1 row pulled free. It is likely that the load had been shed from initially displaced anchors to neighboring anchors over time, creating a cascading displacement pattern that continued to worsen until at least several anchors in this row became totally separated from the tunnel roof. The remaining anchors, unable to sustain the additional load, then gave way, allowing the M1 support beam to fall and causing the ends of the concrete panels resting on the beam to rotate downward.

The rotation of the north row of panels was initially somewhat restricted by the channel fittings that attached the tops of the welded studs to the N beam. (Refer to figure 6 for a detail of this type of connection) As the panels continued downward, the concrete began to fracture around these attachments, greatly reducing resistance to additional rotation of the north panels. As the M1 beam continued to drop, the degree of rotation between the concrete panels and the support beams also increased, causing the welded studs at the south end of the center panels to fracture at the welds near their bases. Loss of these connections completely released the south ends of the center panels from beam M2, allowing those ends to move northward and drop off the M2 beam, which remained attached to the roof.

At this point, as the accident passenger car was traveling in the north travel lane, the entire set of 10 large concrete panels, along with support beam M1 and its supporting hardware, swung down and to the north. The south ends of the center panels struck the roadway first, resulting in significant crushing and fracturing of the concrete along the line of contact. (Refer to figure 9.) These center panels were also likely to have been the first to strike the passenger car, with the crushing damage progressing from right to left (from the passenger side toward the driver's side) as the panels continued to fall.

Initial contact of the south panels with the roadway created additional rotation between the panels and beam M1. At some point, as the concrete panels dropped, the loads at most of the 15 attachment positions along support beam N became sufficient to fracture either the welded studs or the rebar in the concrete where the studs were attached. At the easternmost attachment position along the north side of panel N2, the stud remained intact, and the rebar around the fractured portion of the stud kept the panel attached to beam N throughout the accident sequence.

The accident vehicle, after its initial contact with the falling concrete ceiling panels, moved to the north and came to rest against the elevated walkway that paralleled the roadway. Because the south ends of the panels fell first, the north ends of several of the panels came to rest slightly farther to the north than their original positions in the ceiling. The north ends of these panels were partially supported by the 6-foot-high walkway handrail,[73] which slightly reduced the crushing damage to the driver's side of the vehicle and likely made it possible for the driver to survive the accident in which his wife was fatally injured.

After the accident, 161 of the 634 remaining adhesive anchors supporting the D Street portal ceiling were found to have measurable displacement, that is, they showed evidence of having gradually pulled out of the roof under the sustained tension load of the concrete ceiling panels. The Safety Board concludes that by July 2006, a significant portion of the adhesive anchors used to support the D Street portal ceilings had displaced to the extent that, without corrective action, several of the ceiling modules in the three portal tunnels were at imminent risk of failure and collapse.

All of these anchors had been tested after installation and were found capable of supporting, for 2 minutes or less, a minimum of 3,250 pounds. Some portal anchors had been successfully tested to 6,350 pounds. Yet many of these same anchors began to fail under even lesser loads, indicating that—much like

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[73] The railing itself, which was 3 ½ feet high, was affixed to a 2 ½-foot-high raised walkway.

the glue on an adhesive label, which will hold tightly enough to tear the paper if jerked suddenly but will yield to a slow and steady pull—the epoxy anchors in the D Street portal could resist a sudden and brief proof-test load but could not sustain a constant load over time.

Background of the Accident

The July 10, 2006, accident was a sudden, violent event, but the circumstances leading up to it developed over a period of more than 20 years, beginning with the design of the Ted Williams Tunnel in the late 1980s. The specifications for the Ted Williams Tunnel did not require that the tunnel incorporate a provision for attaching a suspended ceiling, even though the owners knew that one would be needed to accommodate the tunnel ventilation system (which had not yet been designed). The D Street portal, which was completed before the Ted Williams Tunnel, was expected to use the same post-installed ceiling as the Ted Williams Tunnel; thus, it also had no embedded ceiling supports.

The lack of embedded anchoring devices led the section design consultant for the Ted Williams Tunnel finishes to devise a ceiling system that relied on adhesive anchors for support. About 24,000 adhesive anchors were installed in the Ted Williams Tunnel, but various installation problems encountered during this process prompted CA/T project authorities to direct that the balance of the I-90 connector tunnel (except for the D Street portal, which was already built) be constructed with embedded steel channels in the roof so that adhesive anchors would not be needed.

Also during construction of the Ted Williams Tunnel, the FHWA, the MTA, MassHighway, and B/PB decided to adopt a simpler and cheaper ceiling system for future tunnels. Instead of the custom-engineered laminated lightweight concrete panels that had proved so costly and time-consuming to install in the Ted Williams Tunnel, they would use cheaper (and more easily installed) precast concrete panels for the I-93 tunnel and the I-90 connector tunnel.

The ceiling system that was adopted by the CA/T owners and B/PB and distributed to other section design consultants consisted of a group of concrete panels supported by a steel framework suspended from rods attached to roof hanger plates. In the I-93 tunnel, these plates would be attached to the roof girders using welded studs. In the I-90 tunnel, they would be attached to the steel channels in the roof. Because the D Street portal roof had neither girders nor embedded channels, section design consultant Gannett Fleming (as discussed later in this analysis) specified the use of adhesive anchors. The anchors that were installed in the D Street portal in response to that specification were the ones that failed on July 10, 2006.[74]

The Safety Board evaluated a number of factors that could have caused or contributed to the failure of the anchors supporting the D Street portal ceiling. These factors included the design of the ceiling and its support system, the procedures used to install the adhesive anchors, and the properties of the epoxy used for the anchors. The Safety Board also evaluated the actions of CA/T project construction and oversight agencies in response to anchor failures that occurred several years before the accident. Those issues, among others, are discussed in the sections that follow.

Design of the D Street Portal Ceiling

Anchor Loading

In making its anchor-loading calculations, Gannett Fleming determined that the greatest load on any anchor in the D Street portal would be 2,600 pounds (1,800 pounds dead load and 800 pounds live load). To increase the margin for safety, however, Gannett Fleming specified that the anchors used in the portal should be capable of supporting a service tensile load of 4,000 pounds, with a safety factor of 4 (16,000 pounds ultimate load capacity).

At the request of the Safety Board, the Turner-Fairbank Highway Research Center, using a finite element model, calculated the loads on the adhesive anchors supporting the ceiling module that collapsed in this accident. The anchor loads were determined for three general conditions: with both vertical and diagonal hanger rods supporting the load, with only the vertical rods supporting the load, and with various combinations of roof hanger plates missing.

This analysis showed that the maximum load on any anchor in the row of anchors that failed was between 2,371 and 2,823 pounds, depending on the load carried by the diagonal hanger rods. While the upper end of this range is slightly higher than the maximum load calculated by Gannett Fleming (2,600 pounds), it is less than the service load capacity of 4,000 pounds specified by Gannett Fleming for the D Street portal anchors. The Safety Board therefore concludes that the anchor loading calculations developed by Gannett Fleming for the ceiling in the D Street portal tunnel were consistent with the actual maximum loads sustained in service.

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[74] After the accident, all the ceiling modules in the D Street portal were permanently removed. CA/T authorities determined that, because of the short span of the tunnel and its proximity to the tunnel opening, the suspended ceiling was not needed.

Decision to Use Adhesive Anchors

The Safety Board considered whether adhesive anchors were appropriate for use in the D Street portal. Gannett Fleming initially planned to use undercut anchors in the D Street portal. In January 1997, however, B/PB informed the design consultant that, because of problems encountered when another contractor had used undercut anchors, these anchors were not to be used in the D Street portal. Gannett Fleming continued to make the case for the undercut anchors, researching the various alternatives available and suggesting to B/PB, in an August 1997 letter, that undercut anchors still appeared to be the best choice for this application. B/PB was not persuaded and sustained its directive not to use these anchors. Gannett Fleming accepted this direction and specified the use of adhesive anchors rather than undercut anchors.

The Safety Board notes that, while B/PB cited previous installation problems in rejecting undercut anchors, it apparently did not consider or give significant weight to the problems with adhesive anchors that were encountered by the contractor who installed the ceiling in the Ted Williams Tunnel. That experience was at least partly responsible for the fact that the tunnels that were yet to be built would have ceiling supports embedded in the tunnel roofs, obviating the need for adhesive anchors. Too many variables exist to assume that had undercut anchors been used in the D Street portal, this accident would not have occurred; however, the Safety Board notes that, after the accident, all of the adhesive anchors in the I-90 connector tunnel were replaced with undercut anchors.

According to test data provided by the anchor epoxy supplier (Powers) and forwarded to Gannett Fleming during the anchor approval process, assuming the particular combination of concrete type, anchor size, and embedment depth proposed for the D Street portal project, each epoxy anchor, using a safety factor of 4, could support up to 6,350 pounds. A safety factor of 4 means that an average anchor is expected to support four times this weight, or 25,400 pounds, before failure of the adhesive or the concrete surrounding the anchor. The safety factor incorporated into the design was intended to provide a margin of safety to account for imperfect installation, weaker-than-normal concrete, unexpected operating conditions, or other uncertainties. Thus, even in less-than-ideal conditions, the anchors were expected to safely support loads of up to 6,350 pounds. The finite element analysis conducted for the Safety Board by the FHWA showed that the expected anchor loads, even with the diagonal hanger rods excluded, were well below the load capacities of the adhesive anchors shown in the then-current Powers manual.

The FHWA analysis also showed that, even with any one ceiling hanger plate completely missing, the anchor loads in the remaining plates remained below 6,350 pounds. Only when two adjacent ceiling hanger plates were removed from the model did the calculated load on anchors in the adjacent plates exceed 6,350 pounds. Even then, the loads were well below the expected average ultimate load capacity published by the anchor supplier.

The Safety Board therefore concludes that, based on published anchor strength test data, the calculated anchor loading for the D Street portal ceiling system, and the limited number of available alternatives, Gannett Fleming's specification of an adhesive anchoring system to support the ceiling system was not inappropriate.

But while the specification of adhesive anchors to support the D Street portal ceiling was not necessarily inappropriate, the use of these anchors in the D Street portal—supporting significant loads in pure tension—was an atypical application that placed additional responsibility on the designers to ensure the safety of the system. Gannett Fleming engineers should have been aware that polymeric adhesives have significantly different properties than the steel and concrete that is typically used in construction. That fact, plus the somewhat innovative use of such adhesives as a primary structural element, should have led Gannett Fleming to perform careful measurements and calculations to ensure that the structure would remain sound. Despite the fact that all polymers have the potential to deform under sustained load, the designers included in the contract no specifications regarding the long-term mechanical properties of the adhesive, no requirement for testing of the adhesive for long-term performance, no consideration of the service life of the adhesive anchors in relation to the expected life of the tunnel, and no provision for periodic inspections of the installed anchors. The Safety Board therefore concludes that Gannett Fleming and B/PB failed to account for the fact that polymer adhesives are susceptible to deformation (creep) under sustained load, with the result that they made no provision for ensuring the long-term, safe performance of the ceiling support anchoring system.

Anchor Installation Procedures

The investigation determined that the adhesive anchor installation procedures provided by Modern Continental, the installation instructions provided by the epoxy manufacturer, and the installation procedures described by the workers themselves were generally consistent. However, notations from the B/PB field engineer daily report indicated that workers installed at least some anchors without first blowing out the holes with compressed air.

The Safety Board evaluated multiple parameters having to do with anchor installation to determine whether they might have caused or contributed to the anchor failures in this accident. These parameters included the cleaning of the anchor holes, the presence of damp concrete during installation of the anchors, the drilling of an anchor hole through rebar, the improper mixing of the epoxy components, and the presence of voids in the epoxy between the anchor threads and surface of the anchor hole.

Epoxy installation procedures typically emphasize that the hole must be clean and suggest that the holes be brushed, blown out with compressed air, and brushed again. But in FHWA tests conducted for the Safety Board, the cleanliness or dampness of an anchor hole reduced the short-term load capacity by less than 20 percent. These results suggest that overhead drilling with water lubrication might itself remove most dirt and debris from the hole. Of the 188 anchors FHWA personnel pulled out of the eastbound D Street portal tunnel roof, few gave way at the epoxy-to-concrete interface, indicating that, however well the hole had been cleaned, the hole surface was prepared well enough to bond with the epoxy.

Many, if not most, of the anchors holes in the D Street portal intersected segments of rebar, but FHWA testing revealed that installing anchors in holes cored through rebar had little or no effect on short-term load capacity of the anchors. Poorly mixed epoxy (such as might result from shortening the mixing nozzle from 7 to 5 inches to speed installation) similarly had little effect on the capacity of the anchor to sustain a load. An improper ratio of the two constituents did have an effect, but the effect depended on the balance of the constituents, with an excess of hardener decreasing the anchor maximum strength and an excess of resin increasing it.

Storage of a Fast Set epoxy cartridge at 140° F for 56 hours before installation resulted in a phase separation within the material, but this generally affected only the first anchor to be installed, after which the epoxy returned to its normal consistency and its normal load capacity. Use of a diamond core drill bit instead of the recommended carbide-tipped bit had no effect on anchor load capacity. Also, the anchors performed similarly whether the attaching nuts were torqued at 50, 90, or 125 foot-pounds.

The epoxy found on some anchors outside the failure area was dark brown and pliable when the anchor was removed, consistent with a mixture with an excess of hardener. The Safety Board identified two mechanisms that could lead to mixing of the epoxy at ratios other than the intended 1:1 by volume. The first mechanism was phase separation during storage. Settling of the filler particles would increase the concentration of the fluid resin or hardener compounds at the top of the cartridge. This process was accelerated by storing a Fast Set epoxy cartridge at 140° F for 56 hours before installation. The hardener component appeared to be more susceptible to phase separation than the resin, making a mixture with an excess of hardener (the worst case) more likely.

A second mechanism that could cause an excess of resin or hardener is the presence of an air bubble at the tip of one of the tubes in the dual cartridge. Only the component without the air bubble would be extruded initially, which would coat all of the surfaces of the mixing nozzle and be entrained into the subsequent mixed epoxy. A relatively small air bubble in either tube could therefore affect the ratio of resin to hardener in a relatively large volume of epoxy, even if some of the first epoxy extruded is discarded, as recommended in the installation instructions. Except for the color of the epoxy, the test anchors where the hardener was extruded ahead of the resin appeared remarkably similar to anchors that retained a dark brown pliable epoxy when they were extracted from the tunnel roof.

Examination of the anchor holes from the failure area showed that several had adhesive failure regions, with two anchor holes having adhesive failure area fractions between 40 and 50 percent, and four additional anchor holes having adhesive failure area fractions from 18 to 31 percent. The examination did not reveal the presence, in any of the anchor holes or on any of the anchors from the failure area, of significant uncured epoxy, which can result from excessive amounts of hardener.

The Safety Board therefore concludes that, although it is unlikely that all the D Street portal adhesive anchors were installed in a manner that would ensure maximum anchor performance, improper or deficient anchor installation procedures or practices alone would not account for all of the anchor failures that were observed before and after the accident.

One installation factor that almost certainly has an impact on anchor load capacity is the amount of epoxy surrounding the anchor. If insufficient epoxy is inserted into the hole, or if it is injected in such a way that significant voids are created, the epoxy bond area is decreased, which increases the load stresses on the remaining epoxy and compromises the ultimate load capacity of the anchor.

The Safety Board found measurable void areas associated with almost all of the anchors and anchor holes that were examined after the accident. For example, the anchor holes from the failure area showed void area fractions as high as 38 percent, with 11 of the 20 holes having void area fractions of 20 percent or more.[75] These voids significantly reduced the load transfer area of the epoxy, which increased the average stress on the remaining epoxy and accelerated the rate of displacement of the anchors after installation.

As shown by Safety Board simulations, the size and location of voids can be influenced in a variety of ways during epoxy injection or anchor insertion. More significant, however, was the finding that voids were frequently introduced during the installation tests conducted by the FHWA, even when the proper procedures were followed precisely and every effort was made to eliminate voids. This suggests that, in overhead applications, voids are introduced into the adhesive by the nature of the task itself. The Safety Board therefore concludes that installing adhesive anchors in overhead applications appears, by the nature of the task, to introduce voids into the adhesive that can reduce the ultimate load capacity of the anchor and thus the overall reliability of the anchoring system.

Because it is unlikely that independent epoxy qualification testing evaluates products in an overhead application, the load values from those tests may not reflect the reductions in load capacity that would result from the voids that would likely be introduced by such installations. In addition, overhead applications typically require use of seal plugs to contain the epoxy until it sets. If the seal plug

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[75] The measured void area fractions were considered minimums because some evidence of the presence of voids could have been lost during the failure process.

prevents bonding between the epoxy and the concrete (as did the polyethylene plugs used for the anchors in this accident), the effective anchor embedment depth may be reduced,[76] causing a further reduction in anchor load capacity. The Safety Board therefore believes that the International Code Council should use its building codes, qualified materials listings, test criteria, or other mechanisms to make end users aware of the strong potential for creating voids in the adhesive during the overhead installation of adhesive anchors and of the need to account for the reduction in effective embedment depth associated with the use of seal plugs in such applications.

Epoxy Used in the D Street Portal

Epoxy is a polymer and, like all polymers, its stiffness is time and temperature dependent. If a load is applied suddenly, the epoxy responds like a hard solid. But if that load is then held constant, the molecules within the polymer may begin to rearrange and slide past one another, causing the epoxy to gradually deform in a process called *creep*. As the deformation increases, it becomes irreversible and eventually leads to damage accumulation and failure. This process can also be affected by other aspects of the operating environment, such as the presence of moisture or chemicals.

For the D Street portal adhesive anchors, Modern Continental (the construction contractor) chose an epoxy anchoring system provided by Newman Renner Colony. The epoxy was Powers Power-Fast Epoxy Injection Gel, which was packaged by Powers for Newman Renner Colony and supplied to the CA/T project as NRC-1000 Gold epoxy. Although the Powers Power-Fast epoxy was available in either Standard Set or Fast Set versions, at the time of the original purchase agreement between Modern Continental and Newman Renner Colony, the Fast Set formulation was the only one that was being packaged as NRC-1000 Gold epoxy.

Fourier transform infrared spectroscopy and headspace gas chromatography/mass spectroscopy testing of epoxy samples from most of the anchors that failed in this accident and other randomly selected anchors revealed that their chemical composition was consistent with the Fast Set epoxy. None of the anchors tested showed a chemical composition consistent with the Standard Set epoxy. Project invoices indicated that Modern Continental purchased Power-Fast Fast Set/NRC-1000 Gold epoxy during the period when the D Street portal ceiling was being installed, and no record was found of the purchase of Standard Set epoxy during this period. Based on these tests and observations, the Safety Board concludes that Modern Continental was supplied with and used the Fast Set formulation of Power-Fast Epoxy Injection Gel when the company was

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[76] The seal plugs used in the D Street portal reduced the effective anchor embedment by more than ½ inch.

installing the anchors in the D Street portal, including the anchors that failed in this accident.

Postaccident testing conducted by the Turner-Fairbank Highway Research Center at the request of the Safety Board revealed that, while both the Fast Set and Standard Set formulations of the Powers epoxy performed similarly in short-term load tests, they differed dramatically under long-term load. The testing showed that anchors installed with the Powers Fast Set epoxy, using best practices, exhibited significant and continued displacement (creep) when subjected to loads as low as 1,000 pounds. Anchors loaded to 4,000 pounds completely separated from their anchor holes before the end of the 82-day test period. Given that the expected maximum anchor load was 2,600 pounds, the FHWA testing showed that the Fast Set epoxy, because of its susceptibility to creep, was not suitable for use in any long-term tension load application—such as supporting the D Street portal ceiling. The Safety Board concludes that the source of the anchor displacement that was found in the D Street portal tunnels and that precipitated the ceiling collapse was the poor creep resistance of the Power-Fast Fast Set epoxy used to install the anchors.

The Safety Board notes the likelihood that, between the time the ceiling was installed and the tunnel ventilation system began operation, the load on the anchors would have been primarily from the dead load, and not all of the anchors would have been expected to support the maximum load. Gannett Fleming calculated the maximum anchor dead load to be 1,800 pounds. Based on the FHWA sustained load testing, even this load would have been enough to cause significant and fairly rapid anchor displacement. Once the ventilation system was placed in operation, the resulting suction load generated by the fans could have significantly reduced the tension load on the anchors and slowed their displacement. This might explain why the D Street portal ceiling system did not fail sooner than it did.

Use of Fast Set Versus Standard Set Epoxy

As the investigation revealed, the use of Power-Fast Fast Set epoxy virtually assured future problems with the D Street portal ceilings. The obvious question, then, is how did Modern Continental come to use an epoxy formulation that had been shown to be inappropriate for this application.

The investigation found no evidence that Modern Continental was offered a choice or made a conscious decision to use one epoxy formulation over another. When Modern Continental contracted with Newman Renner Colony to provide the Powers epoxy, the Fast Set epoxy formulation was the only one being offered by Powers under the Newman Renner Colony label. Powers was beginning the process of also providing its Standard Set epoxy for distribution by Newman Renner Colony, but this was in response to a potential requirement for other projects and was unrelated to the work in the D Street portal. Evidence was found that some of the epoxy Newman Renner Colony provided for the D Street portal contract was packaged as Power-Fast epoxy, but this was the same Fast Set product that the company was supplying under its own NRC-1000 Gold label.

Installation of the anchors in the D Street portal began in July 1999, using epoxy purchased from Newman Renner Colony. No evidence was found that Modern Continental had any information at that time to suggest that the epoxy it was using was susceptible to creep. The Safety Board therefore concludes that Modern Continental was not aware, when its employees installed the adhesive anchors in the D Street portal, that the epoxy being used was susceptible to creep and was therefore unsuitable for this application.

The draft reissue of ICBO ER-4514, which Modern Continental submitted to Gannett Fleming in December 1999 in its fourth attempt to have the anchors approved by the design consultant, did refer to two epoxy formulations and did state that the Fast Set version was approved for short-term loads only. But this documentation, as well as the ultimate load figures submitted to show that the anchor capacities were sufficient to support the calculated design loads, was supplied by Powers, and none of the documentation specified which epoxy formulation had been supplied for use in the D Street portal. Modern Continental apparently assumed, based on information provided by Powers, that the epoxy it was using was suitable.

As noted previously, Gannett Fleming did not include a contract specification identifying long-term performance (creep resistance) of the anchor adhesive as an issue that should be addressed by contractors. In the specification for ceiling support anchors, Gannett Fleming indicated that the selected adhesive material should “remain unaffected by continuous humidity and by chemicals present in a vehicle exhaust type of air duct environment,” but the design consultant said nothing about the potential for creep in such materials and thus of the necessity of verifying that the selected material could support substantial tension loads indefinitely. Had it done so, the construction contractor would have at least been made aware of the potential for anchor creep[77] so that it could have specifically considered this factor when selecting the anchor adhesive. The Safety Board concludes that had Gannett Fleming, in the construction contract for the D Street portal finishes, specified the use of adhesive anchors with adequate creep resistance, a different anchor adhesive could have been chosen, and the accident might have been prevented.

Even though Gannett Fleming made no provisions in the initial design specifications regarding the long-term performance of the adhesive anchors, the company could have addressed that issue during the approval process for the anchoring system selected by Modern Continental. Gannett Fleming engineers reviewed all of the documentation relating to the contractor’s proposed anchoring

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[77] As used in this report, *anchor creep* refers to continuous anchor displacement under an applied load as a result of creep or damage accumulation, or both, in the epoxy adhesive.

system and even rejected the first three submittals, each time requesting more information. With its fourth anchor adequacy submittal, Modern Continental included the draft revision of ICBO ER-4514, which stated that the Power-Fast Fast Set epoxy formulation was approved for short-term loads only. Although the guidance in the report was somewhat ambiguous (as will be discussed later in this analysis), Gannett Fleming had the responsibility to carefully review all of the anchor adequacy documentation. Such a review of the draft ICBO ER-4514 should have prompted Gannett Fleming to inquire as to which epoxy formulation Modern Continental was using. A query from Modern Continental to Newman Renner Colony or Powers would likely have revealed that the Fast Set version was being provided to the job, and work could have been stopped and corrective measures taken. Instead, the Gannett Fleming reviewer authorized Modern Continental to proceed with work installing the anchors (by this time, the anchors that would be involved in the accident had already been installed). The Gannett Fleming reviewer apparently evaluated Power-Fast/NRC-1000 Gold epoxy as a single product and focused only on the bond strength as shown in the tables. The Safety Board concludes that Gannett Fleming approved the D Street portal anchors without identifying which epoxy formulation was being used, even though the company was provided with information indicating that one version of the Power-Fast epoxy should be used for short-term loading only.

Guidance for Using Fast Set Versus Standard Set Epoxy

ICBO ER-4514

Powers was updating its ICBO listing for Power-Fast epoxies in 1997, which required that the epoxies be independently tested in accordance with ICBO guidelines. As part of the qualification testing, an optional 120-day creep test was performed on the Standard Set epoxy. In response to a change in ICBO guidance (AC58), the results of the 120-day test of Power-Fast were extrapolated to 600 days. The Standard Set epoxy met the standards for creep in both the 120- and extrapolated 600-day tests. No creep tests were reported for the Fast Set formulation (although such tests had been performed, as will be discussed below).

The ICBO evaluation report (ER-4514) on Power-Fast epoxy reissued in February 2000 had few references to Fast Set epoxy, and those could easily have been overlooked without a careful reading. In the product description, the report noted that the epoxy was available in two formulations and that the Fast Set version had additives to speed curing. (A table of relative curing times was also included.) The most significant mention of Fast Set epoxy was in the "Findings" section where, in a long paragraph presenting the 10th finding, the use of the Fast Set formulation with threaded rods was "permitted for short-term loads, such as those resulting from wind or earthquake forces only."

Another mention was in a footnote to the table of allowable tension loads for threaded rods in concrete. According to the footnote, when using Fast Set, the allowable loads from the table should be reduced "by 25 percent based on a safety factor of 5.33." The footnote made no reference to any difference in long-term performance under load between Fast Set and Standard Set epoxy. In total, the report said very little about Power-Fast Fast Set epoxy except in its finding that this formulation should only be used for short-term loads.

At the time the anchors were installed in the D Street portal, the ICBO (or its umbrella organization, the ICC) required, in acceptance criteria AC58, that a design safety factor of 5.33 be used for anchors in concrete when the epoxy formulation had not passed the optional creep test (either because it was not tested or because it failed the test). Thus, the footnote specifying a safety factor of 5.33 for Power-Fast Fast Set epoxy indicated that this material had not passed the optional creep test. There was no requirement to report that a material had failed the optional creep test.

Tables contained in ICBO ER-4514 showed that the allowable load for Power-Fast Standard Set epoxy, with the anchor size and embedment used in the D Street portal and with a safety factor of 4, was 5,150 pounds. Based on this load and the recommended 25-percent reduction, the allowable load for Fast Set epoxy would be about 3,860 pounds. This was about 1,200 pounds more than the design load of 2,600 pounds calculated by Gannett Fleming for the D Street portal anchors and only about 600 pounds more than the initial 3,250-pound proof-test loads (and considerably less than the 6,350-pound proof-test load applied to some of the anchors).

Every anchor in the D Street portal was thus tested to within a few hundred pounds of the catalog allowable load for that anchor, using guidelines in the ICBO report, and some of these were tested to the 6,350-pound allowable load listed in the Powers literature. Yet many of the anchors began to pull away from the tunnel roof after being under constant load for 2 months or less. The Safety Board therefore concludes that, as shown by the displaced anchors in the D Street portal, the maximum load capacity of an adhesive anchor, which relates to short-term loading, does not indicate that the anchor will be able to support even lighter loads over time, and thus a larger design safety factor cannot compensate for an adhesive material that is susceptible to creep.

The Safety Board learned during this investigation that the Power-Fast Fast Set epoxy had been tested for creep performance in 1995 and 1996 and had failed to meet the standard. That alone would explain the ER-4514 recommendation that the Fast Set epoxy be used to resist short-term loads only. But this load restriction was only shown in the report recommendations. In the bond strength tables, footnotes indicated only that the allowable loads shown should be reduced sufficiently to allow a safety factor of 5.33 (rather than 4) if the Fast Set material was to be used. Nothing in the tables or the footnotes indicated that the Fast Set epoxy should limited to use with short-term loads regardless of the safety factor employed.

Given that the ability to sustain a load over a period of time is a typical requirement for almost any type of fastener, the Safety Board is concerned that the ICC has previously allowed creep testing of epoxy adhesives to be optional. A design engineer or contractor should be provided with all of the relevant information about a product before it is used in a safety-critical application; therefore, the Safety Board believes that the ICC should require creep testing for the qualification of anchor adhesives and disqualify for use in sustained tensile loading any adhesive that has not been tested for creep or that has failed such tests. The capabilities of Powers Power-Fast epoxy anchor systems are now covered in ICC ESR-1531. Although the bond strength tables in the report have separate listings for the Fast Set and Standard Set epoxies, the report does not address the difference in long-term performance between the two formulations or indicate that Fast Set should be used only for short-term loads. Because of the possibility that the critical difference in the two epoxies could still be overlooked, the Safety Board believes that ICC Evaluation Service, Inc., should revise evaluation report ICC ESR-1531 to state explicitly in the text and in the bond strength tables that the Fast Set formulation of the epoxy is approved for short-term loads only.

Powers Design Manual

According to Powers, in the second edition of its *Fastening Systems Design Manual,* the only difference in anchor performance between the Power-Fast Standard Set and Fast Set epoxies was their respective gel and curing times. Except for the ICBO report itself (which, as noted earlier, was somewhat ambiguous), none of the documentation submitted by Powers to support the qualification of the NRC-1000 Gold epoxy suggested a possible difference in long-term performance between the Standard Set and Fast Set formulations.

Powers should have made a clear distinction in all of its literature between the relative capabilities of its Standard Set and Fast Set formulations. It did not do so, even though, before the epoxy was provided to the D Street portal project, the company had conclusive evidence that its Fast Set epoxy was susceptible to creep and that it was therefore inappropriate for long-term tension loading in a safety-critical application.

Powers was aware that Modern Continental was using the Power-Fast product for long-term tension loads; it was also aware that the NRC-1000 Gold formulation being used was the Fast Set material. But there is no evidence that the company ever communicated with the contractor in regard to which formula should be or was being used in the D Street portal.

Only in May 2007, more than 10 months after this accident, did Powers revise its product literature to indicate that the Power-Fast Fast Set epoxy should be used for short-term loads only. The Safety Board notes that this is the only Powers product literature obtained during this investigation that explicitly alerts designers or contractors of a difference in creep resistance between the company's two epoxy formulations. The Safety Board therefore concludes that the information that was provided by Powers regarding its Power-Fast epoxy was inadequate and misleading, with the result that Modern Continental used the Fast Set formulation of the epoxy for the adhesive anchors in the D Street portal even though that formulation had been shown through testing to be susceptible to creep under sustained tension loading.

As a follow-on to the revised product literature and as an additional safety measure, the Safety Board believes that Powers should revise the packaging, for all distributors, of its Power-Fast Epoxy Injection Gel Fast Set formulation to state explicitly that this formulation is approved for short-term loads only. Also, because Sika Corporation, the epoxy manufacturer, markets the fast-setting version of this epoxy as Sikadur Injection Gel AnchorFix-3, the Safety Board believes that Sika Corporation should revise its product literature and packaging to state explicitly that Sikadur Injection Gel AnchorFix-3 is approved for short-term loads only. To address the issue of epoxy creep more globally, the Safety Board believes that the ICC should revise its building codes, qualified materials listings, and product labeling guidelines to clearly address the possibility for creep in polymeric anchor adhesives and to make end users aware of the potential lack of correlation between short- and long-term performance of these adhesives.

Response to Preaccident Anchor Failures

B/PB and Modern Continental

As noted previously, no evidence was found to indicate that Modern Continental, Gannett Fleming, or B/PB was aware that the adhesive the contractor had used in the D Street portal was susceptible to creep and was therefore inappropriate for this use. But Modern Continental and B/PB had opportunities, long before the tunnel was opened, to correct the mistake. Unfortunately, those opportunities were missed.

On September 9, 1999, a Modern Continental employee installing ventilation ductwork above the HOV tunnel ceiling noticed that several of the anchors in the tunnel had begun to pull out. When subsequent checks over the next few weeks revealed that the displacement was increasing, Modern Continental notified B/PB of the problem. This was the first evidence that at least some of the 3,250-pound proof-tested anchors were yielding to even lesser loads over a period of time—which, in this case, was only about 2 months.

B/PB initially suspected that the anchor displacement was the result of improper anchor installation or improper erection of the ceiling panels by Modern Continental. Powers sent representatives to the site in October 1999 to help identify the source of the displacement, but in the end, as cited by Modern Continental, "based on information gathered on site, which included a visual inspection [by Powers] of the anchors in question, a determination of failure could not be made."

The "fix" for the problem that was ultimately agreed to by B/PB and the contractor was that the contractor would remove and replace all the failed anchors and proof test them to a higher load of 6,350 pounds. Additionally, all previously installed anchors in the HOV tunnel would be retested to the higher load, and subsequent new anchor installations in the I-90 tunnel would also be tested to 6,350 pounds. As shown by the investigation, the higher proof test loads could not confirm that the anchors would be able to sustain long-term loads, and replacing the anchors using the same formulation of epoxy did nothing to prevent future displacement.

B/PB and Modern Continental had no basis for assuming that replacing the failed anchors and testing them to a higher load would solve the problem. As indicated by Modern Continental and B/PB correspondence that discussed various proposed remedies for the failed anchors, both the contractor (who was responsible for quality control) and the management consultant (who was responsible for quality assurance) were fully aware that the specific cause of the anchor displacement had not been identified. Some engineering officials within B/PB expressed particular concern that, because the source of the anchor displacement had not been determined, the proposed remedy might not work. At a minimum, the prudent course would have been for the contractor or B/PB personnel, or both, to continue to monitor the performance of all the anchors in the D Street portal until they could be sure the problem had been solved. Had this occurred, the contractor or B/PB personnel would no doubt have discovered that anchors were continuing to pull out, even those that had successfully passed a higher proof test. At that point, a thorough review of the ceiling installation would likely have been undertaken. Such a review could have resulted in a change in anchor type or a change in the epoxy, either of which might have prevented this accident.

About 2 years later, in 2001, a B/PB field engineer noted anchor "slippage" in the Unistrut portion of the I-90 connector tunnel. In December of that year, a Modern Continental quality control inspector working in the Unistrut portion of the eastbound I-90 connector tunnel found additional anchors that had begun to pull out. These anchors had been tested, only a few months before, to 6,350 pounds, and all had passed. The nonconformance report that was issued regarding the anchors noted that the "reason for failure is unknown." The failed anchors were replaced and retested.

At this point, it should have been obvious to B/PB and to Modern Continental that the remedy that had been developed in response to the anchor displacement in the HOV tunnel in 1999 had not been effective, as anchors that had passed proof tests at higher values were still displacing. This was another opportunity for the management consultant and the contractor to inspect all the installed anchors to determine the extent and, more importantly, the cause of the anchor displacement. Instead, the companies apparently considered the continuing failures as isolated instances and took no action to address the problem in a systemic way. The Safety Board therefore concludes that, after unexplained anchor displacement was found in the I-90 connector tunnel in 1999 and 2001, B/PB and Modern Continental should have instituted a program to monitor anchor performance to ensure that the actions taken in response to the displacement were effective. Had these organizations taken such action, they likely would have found that anchor creep was occurring and they might have taken measures that would have prevented this accident.

Powers

Although neither Modern Continental nor B/PB responded appropriately to preaccident anchor displacement, they received very little help from Powers in devising an effective solution. When Powers was called to examine the anchor displacements in the HOV tunnel in 1999, the company seemed surprised that anchors that had been successfully proof tested only a few months before could be failing. The company's summary of its anchor examination suggested that the displacement could have resulted from deficiencies in anchor installation that had been masked by the high safety factors (which allowed the anchors to pass the proof test). Again, the company was equating an adhesive anchor's short-term load capacity with its ability to resist long-term deformation.

The only potential source of the anchor displacement that was specifically identified by the Powers representative was overtorquing of the nuts that were threaded onto the anchors, which might have overstressed them. According to the Powers report, some of the anchors in the HOV tunnel—those that had displaced and those that had not—were checked and found to have been installed with 120 foot-pounds of torque, which was more than the recommended 50 to 90 foot-pounds.

Leaving aside the question of how it was possible to check the installation torque of a nut after the anchor had pulled away from the roof, these torque readings appear not to have been typical within the D Street portal. Of the 130 randomly selected anchors in the eastbound and westbound tunnels that were subsequently checked by B/PB and Modern Continental engineers, all were reported to have been installed with slightly less than 75 foot-pounds of torque, which was well within the recommended range. Furthermore, testing of anchors installed with 125 foot-pounds of torque showed no reduction in load capacity. These findings combine to indicate that application of excess torque did not cause or contribute to the failure.

No evidence was found that Powers took any followup action in regard to the anchor displacement in CA/T tunnels after the 1999 anchor examination and submission of findings. Even though the company was aware that its product was not performing as expected in the HOV tunnel and that a definitive reason for the failures had not been determined, it did not recommend that B/PB or Modern Continental continue to monitor anchor performance, and it did not offer to provide or arrange for such inspections itself.

Nor was evidence found that Powers performed subsequent testing or conducted further research as a result of the anchor failures. At least some officials within Powers were aware that the Power-Fast Fast Set epoxy was subject to creep, but this information was apparently not considered (or was not known) by the Powers representatives and engineers who evaluated the failed anchors in the HOV tunnel. Even if the information about the poor creep resistance of the Fast Set epoxy was not common knowledge within the company, a reasonable amount of research would likely have revealed it, and corrective action could have been taken. The Safety Board would have expected the supplier of a safety-critical construction component to have been more proactive in determining why its product was failing to perform as expected. The Safety Board therefore concludes that Powers' response to the anchor displacements that occurred in 1999 in the HOV tunnel of the D Street portal was deficient in that the company did not identify the source of the failures as creep in the Fast Set anchor adhesive and took no followup action to ascertain why its product had not performed in accordance with the users' expectations.

Standards and Protocols for the Testing of Adhesive Anchors

In hindsight, the installation and test procedures used for the adhesive anchors in the CA/T I-90 tunnels were clearly inadequate to ensure that the anchors would perform as required over the life of the tunnels. The proof-test procedure used, while it may have been appropriate for mechanical anchors, provided no information about the long-term strength of adhesive anchors under sustained load, or even about the anchors' ultimate short-term load strength. Also, as noted previously, the voids that appear to have been unavoidably introduced during the overhead installation of the adhesive anchors would have reduced the anchor load capacity irrespective of the creep resistance of the epoxy.

In its *2002 Standard Specifications for Highway Bridges,* 17th Edition, AASHTO recommended that embedment anchors (defined as cast-in-place, grouted, adhesive-bonded, expansion, and undercut steel anchors) be subjected to sacrificial tests at the job site to document the capability of the anchor to achieve the full tension value as shown in the manufacturer's literature. Instead of conducting such sacrificial tests, CA/T managers and owners apparently accepted at face value the catalog load capacities provided by Powers and performed no independent testing to verify that the numbers were valid or that the anchors would perform similarly in this particular application.

Although the lack of maximum-load verification testing using overhead installations cannot be definitively shown to have contributed to this accident, testing a sample of the anchors to their ultimate loads would have been prudent given the safety-critical nature of the system. The Safety Board concludes that, because of the potential catastrophic effects of a failure of the D Street portal ceiling system, B/PB and Gannett Fleming should have required that ultimate load tests be conducted on the adhesive anchors used to support the ceiling before allowing any of the anchors to be installed.

The Safety Board recognizes that ultimate load tests alone would not have revealed the property of the epoxy that eventually led to this accident, which highlights the need for more refined and specific testing of any adhesive anchor system that is being considered for use in a sustained tensile-load application. Because no protocols or standards currently exist for such testing, public agencies and their contractors are left to devise their own tests or to conduct no tests at all. The Safety Board concludes that protocols or standards for the testing of adhesive anchors in sustained tensile-load applications will provide designers and builders with test methods designed specifically to accurately assess the long-term safety of those anchors.

A creep testing protocol is specified in ICBO-AC58, but this is a pass/fail test that is conducted using one load at a single temperature for a specified time. Such a test may be appropriate as a screening tool to identify adhesives that should never be used for long-term tensile loads (such as the Power-Fast Fast Set epoxy, which failed the test), but it does not provide any data that could be used to predict the operational lifetime of an adhesive. Nor does it provide information to assist users in establishing appropriate inspection intervals for adhesive anchors under different loads or at different temperatures.

ASTM Standard D 2990-01, *Standard Test Method for Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics* (first adopted in 1971 and most recently reapproved in 2001), includes standardized testing guidelines and information in a series of appendixes. The appendixes describe a number of well-established and complementary methods for predicting the long-term properties of polymers and for ensuring their safe use under creep conditions. The introduction to the appendixes notes that

> Since the properties of viscoelastic materials are dependent on time, temperature, and rate of loading, an instantaneous test result cannot be expected to show how a material will behave when subjected to stress or deformation for an extended period of time.

The standard itself discusses various methods for testing plastics (polymers) to assess their behavior (creep) under sustained loads; it does not address adhesive anchors. The test methods described in the standard could, however, be adapted, through specific testing protocols, to generate data that would aid designers and others in evaluating the suitability of adhesive anchors for a particular application.

For example, one method for predicting long-term properties discussed in ASTM D 2990-01 involves conducting a number of tests over a range of applied loads (similar to the sustained load tests performed at several load levels by the FHWA as part of this investigation) to determine the time to failure as a function of load. These data can then be extrapolated to estimate the load at which failure will occur for times beyond the range of the tests.

A second method outlined in an appendix to ASTM D 2990-01 employs laboratory testing coupled with time-temperature superposition to calculate creep compliance over a wide range of time. Because creep compliance is directly related to the displacement of an anchor under a constant load, this method could be used with a maximum displacement criterion to predict the expected useful life of an adhesive anchor. The results of this testing could also be used to assess the effect of variations in temperature over the life of the installation. The time- temperature superposition tests performed for the Safety Board at NIST predicted that the room temperature displacement of an anchor installed with Power-Fast Fast Set epoxy would increase by a factor of 3.5 after 1 month and by a factor of 14 after 10 years.

The results of the FHWA creep tests and the NIST material evaluations appear comparable (except for the Fast Set anchors loaded at 4,000 pounds, which in the FHWA tests demonstrated a nonlinear behavior suggesting yield or damage accumulation in the adhesive), although a rigorous comparison has not yet been attempted. In any event, use of either of these methods as a part of the preparations for construction in the D Street portal would have demonstrated that the Fast Set epoxy was not suited to this application.

NIST also performed experiments suggesting that moisture absorption could have a significant effect on the material properties of the Fast Set and Standard Set epoxies. These experiments were performed on small samples that allowed for rapid saturation and therefore might not reflect actual-use conditions; however, they indicate that a testing plan to assess the long-term durability of polymeric materials must consider environmental effects in addition to temperature.

The Safety Board therefore believes that, building on current test standards from ASTM or other sources, the FHWA and AASHTO should work jointly to develop standards and protocols for the testing of adhesive anchors to be used in sustained tensile-load overhead highway applications. These standards and protocols should consider site-specific ultimate strength values as well as the creep characteristics of the adhesive over the expected life of the structure. Once these standards and protocols are developed, the Safety Board believes that AASHTO should incorporate them into the *AASHTO Construction Quality Assurance Guidelines*.

Until these standards and protocols have been developed and implemented, the Safety Board believes that the FHWA and the transportation departments of the 50 States and the District of Columbia should prohibit the use of adhesive anchors in sustained tensile-load overhead highway applications where failure of the adhesive would result in a risk to the public. Concurrently, the Safety Board believes that AASHTO should use the circumstances of this accident to emphasize to its members through its publications, Web site, and conferences, as appropriate, the risks associated with using adhesive anchors in sustained tensile-load applications where failure of the adhesive would result in a risk to the public.

These recommendations will affect future installations of adhesive anchors, but they do not address adhesive anchors that may already have been used to support overhead signs or traffic control devices where a failure could result in injury or death. The Safety Board is concerned that some of these anchors may be susceptible to creep and that, without monitoring and corrective action, these anchors may fail. The Safety Board therefore believes that the transportation departments of the 50 States and the District of Columbia should review the use of adhesive anchors in highway construction within their jurisdictions and identify those sites where failure of the adhesive under sustained load could result in a risk to the public. Once those sites have been identified, a repair and inspection program should be implemented to ensure that such failures do not occur.

Lack of Awareness of the Potential for Adhesive Anchor Creep Under Sustained Load

This accident investigation revealed a striking lack of knowledge among the designers, contractors, managers, and overseers of the CA/T project 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 risk to the public. No one involved with the CA/T project appeared to be aware of the potential of a polymer such as the anchor epoxy to gradually deform under sustained load. Even after being presented with evidence of anchor creep, project managers and overseers failed to recognize the inherent weakness in the epoxy adhesive—a weakness that could not be overcome even with the best installation practices or the most rigorous short-term proof testing.

The Safety Board does not believe that those associated with the CA/T project were unique in their lack of understanding of the nature of adhesive anchors. While the anchors have been in use for a number of years, they have rarely, perhaps never, been used in such numbers and in such a challenging environment as in the I-90 tunnels. In civil projects, adhesive anchors are typically used in short-term or shear load applications. Under these conditions, even if the adhesive is susceptible to creep, the displacement will likely never reveal itself, and those responsible for specifying, approving, installing, and testing the anchors will not be aware of it. Unfortunately, the lack of knowledge of the nature of epoxy anchors could lead to the use of these anchors in highway, tunnel, and bridge applications where susceptibility to creep could be a threat to public safety. The Safety Board therefore concludes that the circumstances of this accident demonstrate a general lack of knowledge and understanding among design and construction engineers and builders of the complex nature of epoxies and similar polymer adhesives, and in particular, the potential for those materials to deform (creep) under sustained tension loads.

The Safety Board expects that the implementation of its safety recommendations to the FHWA and AASHTO will serve to inform those involved in public works projects of the potential for creep in adhesive anchors. But the use of adhesive anchors is not limited to civil projects; such anchors are sometimes used in commercial construction. The Safety Board therefore believes that the American Concrete Institute[78] should use its building codes, forums, educational materials, and publications to inform design and construction agencies of the potential for gradual deformation (creep) in anchor adhesives and to make them aware of the possible risks associated with using adhesive anchors in concrete under sustained tensile-load applications.

Finally, because civil engineers and general contractors involved in civil and commercial construction are generally not expected to be familiar with the complex chemistry of epoxies or similar adhesives and yet may specify or use adhesive anchors in their projects, the Safety Board believes that the American Society of Civil Engineers[79] and the Associated General Contractors of America[80] should use the circumstances of this accident to emphasize to their members through their publications, Web sites, and conferences, as appropriate, the need to assess the creep characteristics of adhesive anchors before those anchors are used in sustained tensile-load applications.

Tunnel Inspections

No tunnel inspections were performed to determine the physical and functional condition of the ceiling system from the time the I-90 eastbound connector tunnel was opened to traffic on January 18, 2003, until the day of the fatal accident.

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[78] The *American Concrete Institute* is a nonprofit technical and educational society representing public agencies, engineers, architects, owners, contractors, educators, or others interested in the design, construction, or maintenance of concrete structures.

[79] The *American Society of Civil Engineers* (ASCE) has the stated mission of advancing professional knowledge and improving the practice of civil engineering. In support of this mission, the society develops and transfers to its members research results and technical policy and managerial information.

[80] The Associated General Contractors (AGC) of America is the Nation's largest and oldest construction trade association. A stated goal of the organization is to improve the construction industry through education and technology. AGC of America members represent all areas of construction, public and private, except for residential construction.

In response to the contract scope of services, B/PB, in November 2003, published an inspection manual entitled *Inspection Manual for Tunnels and Boat Structures*. Although the manual was a comprehensive and detailed guide for inspecting CA/T tunnels, the MTA did not use it between November 2003 and July 2006, and the tunnels were not inspected.

Postaccident inspection of the area above the suspended ceilings in the D Street portal revealed the large number of anchors that had become displaced from the tunnel roof. The displaced roof hanger plates were so obvious that even a cursory examination of this area before the accident would have revealed that the structural integrity of the ceiling system was threatened. At the time the inspection manual was published in November 2003, the ceiling module that collapsed in this accident had already been in place for 4 years, and at that time at least some of its anchors had probably begun to yield to the load.

The Safety Board concludes that had the MTA, at regular intervals between November 2003 and July 2006, inspected the area above the suspended ceilings in the D Street portal tunnels, the anchor creep that led to this accident would likely have been detected, and action could have been taken that would have prevented this accident.

According to guidance in the FHWA's *Highway and Rail Transit Tunnel Inspection Manual,* 2005 edition, the frequency of tunnel inspections could be as great as 5 years for new tunnels and 2 years for older tunnels. The FHWA requires that bridges, in contrast to tunnels, be inspected at least every 2 years, regardless of age. In this accident, problems with some of the anchors in the HOV tunnel were identified within weeks or months of their installation, indicating that even recently built structures are not immune to potentially hazardous defects. In the view of the Safety Board, the inspection interval for tunnels, whether new or old, should be consistent with the interval for inspection of bridges. Recognizing that the FHWA lacks the authority to establish and mandate a nationwide tunnel inspection program, the Safety Board believes that the FHWA should seek legislation authorizing it to establish a mandatory tunnel inspection program similar to the NBIP. Once such legislation has been obtained, the Safety Board believes that the FHWA should develop and implement a tunnel inspection program that will identity critical inspection elements and specify an appropriate inspection frequency.

National Standards for Design of Tunnel Finishes

The FHWA's 2004 manual *Road Tunnel Design Guidelines* did not address the design of tunnel finishes, despite the fact that tunnel authorities throughout the country use a wide variety of tunnel finish designs and anchorage systems with different redundant support systems and different installation requirements. The Safety Board's survey of tunnel finishes (refer to appendix C) revealed that adhesive anchors are seldom used as an anchorage system to support suspended ceiling panels. When adhesive anchors are used, they rarely are required to act in pure tension, and they typically support lightweight panels. The most common anchorage systems used to support suspended ceiling panels are mechanical expansion anchors.

The survey also revealed that a majority of U.S. tunnels have continuous ceiling panels/slabs that extend into the concrete tunnel walls. This continuous support provides significant redundancy in that, if the hangers fail, the suspended ceiling panels are self-supported. The I-90 connector tunnel had no continuous supports that extended from the ends of the ceiling panels into the concrete tunnel walls. The struts on either side of each ceiling module prevented movement of the ceiling system in the transverse direction; they provided no support for the ceiling panels in the event of anchor or hanger failure.

In the Safety Board's opinion, national standards for the design of tunnel finishes would be useful to government entities or other organizations that are designing new tunnels or retrofitting existing ones. As more tunnels are built and retrofitted in the future, the need will only increase for national standards that will help tunnel owners ensure uniformity and safety in their tunnel finish designs.

The Safety Board therefore concludes that national standards for the design of tunnel finishes, including tunnel suspended ceilings, will provide government entities or other organizations with ready access to information that could be useful in designing tunnel finishes that minimize potential risks to public safety. The Safety Board therefore believes that the FHWA should, in cooperation with AASHTO, develop specific design, construction, and inspection guidance for tunnel finishes and incorporate that guidance into a tunnel design manual.

CONCLUSIONS

Findings

1. By July 2006, a significant portion of the adhesive anchors used to support the D Street portal ceilings had displaced to the extent that, without corrective action, several of the ceiling modules in the three portal tunnels were at imminent risk of failure and collapse.

2. Although it is unlikely that all the D Street portal adhesive anchors were installed in a manner that would ensure maximum anchor performance, improper or deficient anchor installation procedures or practices alone would not account for all of the anchor failures that were observed before and after the accident.

3. The anchor loading calculations developed by Gannett Fleming, Inc., for the ceiling in the D Street portal tunnel were consistent with the actual maximum loads sustained in service.

4. Based on published anchor strength test data, the calculated anchor loading for the D Street portal ceiling system, and the limited number of available alternatives, Gannett Fleming, Inc.'s, specification of an adhesive anchoring system to support the ceiling system was not inappropriate.

5. Gannett Fleming, Inc., and Bechtel/Parsons Brinckerhoff failed to account for the fact that polymer adhesives are susceptible to deformation (creep) under sustained load, with the result that they made no provision for ensuring the long-term, safe performance of the ceiling support anchoring system.

6. Modern Continental Construction Company, Inc., was supplied with and used the Fast Set formulation of Power-Fast Epoxy Injection Gel when the company was installing the anchors in the D Street portal, including the anchors that failed in this accident.

7. The source of the anchor displacement that was found in the D Street portal tunnels and that precipitated the ceiling collapse was the poor creep resistance of the Power-Fast Fast Set epoxy used to install the anchors.

8. Modern Continental Construction Company, Inc., was not aware, when its employees installed the adhesive anchors in the D Street portal, that the epoxy being used was susceptible to creep and was therefore unsuitable for this application.

9. Had Gannett Fleming, Inc., in the construction contract for the D Street portal finishes, specified the use of adhesive anchors with adequate creep resistance, a different anchor adhesive could have been chosen, and the accident might have been prevented.

10. Gannett Fleming, Inc., approved the D Street portal anchors without identifying which epoxy formulation was being used, even though the company was provided with information indicating that one version of the Power-Fast epoxy should be used for short-term loading only.

11. The information that was provided by Powers Fasteners, Inc., regarding its Power-Fast epoxy was inadequate and misleading, with the result that Modern Continental Construction Company, Inc., used the Fast Set formulation of the epoxy for the adhesive anchors in the D Street portal even though that formulation had been shown through testing to be subject to creep under sustained tension loading.

12. As shown by the displaced anchors in the D Street portal, the maximum load capacity of an adhesive anchor, which relates to short-term loading, does not indicate that the anchor will be able to support even lighter loads over time, and thus a larger design safety factor cannot compensate for an adhesive material that is susceptible to creep.

13. After unexplained anchor displacement was found in the Interstate 90 connector tunnel in 1999 and 2001, Bechtel/Parsons Brinckerhoff and Modern Continental Construction Company, Inc., should have instituted a program to monitor anchor performance to ensure that the actions taken in response to the displacement were effective. Had these organizations taken such action, they likely would have found that anchor creep was occurring, and they might have taken measures that would have prevented this accident.

14. Powers Fasteners, Inc.'s, response to the anchor displacements that occurred in 1999 in the high-occupancy tunnel of the D Street portal was deficient in that the company did not identify the source of the failures as creep in the Fast Set epoxy adhesive and took no followup action to ascertain why its product had not performed in accordance with the users' expectations.

15. Had the Massachusetts Turnpike Authority, at regular intervals between November 2003 and July 2006, inspected the area above the suspended ceilings in the D Street portal tunnels, the anchor creep that led to this accident would likely have been detected, and action could have been taken that would have prevented this accident.

16. Because of the potential catastrophic effects of a failure of the D Street portal ceiling system, Bechtel/Parsons Brinckerhoff and Gannett Fleming, Inc., should have required that ultimate load tests be conducted on the adhesive

anchors used to support the ceiling before allowing any of the anchors to be installed.

17. Installing adhesive anchors in overhead applications appears, by the nature of the task, to introduce voids into the adhesive that can reduce the ultimate load capacity of the anchor and thus the overall reliability of the anchoring system.

18. The circumstances of this accident demonstrate a general lack of knowledge and understanding among design and construction engineers and builders of the complex nature of epoxies and similar polymer adhesives, and in particular, the potential for those materials to deform (creep) under sustained tension loads.

19. Protocols or standards for the testing of adhesive anchors in sustained tensile-load applications will provide designers and builders with test methods designed specifically to accurately assess the long-term safety of those anchors.

20. National standards for the design of tunnel finishes, including tunnel suspended ceilings, will provide government entities or other organizations with ready access to information that could be useful in designing tunnel finishes that minimize potential risks to public safety.

Probable Cause

The National Transportation Safety Board determines that the probable cause of the July 10, 2006, ceiling collapse in the D Street portal of the Interstate 90 connector tunnel in Boston, Massachusetts, was the use of an epoxy anchor adhesive with poor creep resistance, that is, an epoxy formulation that was not capable of sustaining long-term loads. Over time, the epoxy deformed and fractured until several ceiling support anchors pulled free and allowed a portion of the ceiling to collapse. Use of an inappropriate epoxy formulation resulted from the failure of Gannett Fleming, Inc., and Bechtel/Parsons Brinckerhoff to identify potential creep in the anchor adhesive as a critical long-term failure mode and to account for possible anchor creep in the design, specifications, and approval process for the epoxy anchors used in the tunnel. The use of an inappropriate epoxy formulation also resulted from a general lack of understanding and knowledge in the construction community about creep in adhesive anchoring systems. In addition, Powers Fasteners, Inc., failed to provide the Central Artery/Tunnel project with sufficiently complete, accurate, and detailed information about the suitability of the company's Fast Set epoxy for sustaining long-term tensile loads. Contributing to the accident was the failure of Powers Fasteners, Inc., to determine that the anchor displacement that was found in the high-occupancy vehicle tunnel in 1999 was a result of anchor creep due to the use of the company's Power-Fast Fast Set epoxy, which was known by the company to have poor long-term load characteristics. Also contributing to the accident was the failure of Modern Continental Construction Company, Inc., and Bechtel/Parsons Brinckerhoff, subsequent to the 1999 anchor displacement, to continue to monitor anchor performance in light of the uncertainty as to the cause of the failures. The Massachusetts Turnpike Authority also contributed to the accident by failing to implement a timely tunnel inspection program that would likely have revealed the ongoing anchor creep in time to correct the deficiencies before an accident occurred.

RECOMMENDATIONS

As a result of its investigation of the July 10, 2006, ceiling collapse in the I-90 connector tunnel in Boston, Massachusetts, the National Transportation Safety Board makes the following safety recommendations:

To the Federal Highway Administration:

> In cooperation with the American Association of State Highway and Transportation Officials, develop standards and protocols for the testing of adhesive anchors to be used in sustained tensile-load overhead highway applications. These standards and protocols should consider site-specific ultimate strength values as well as the creep characteristics of the adhesive over the expected life of the structure. (H-07-15)
>
> Prohibit the use of adhesive anchors in sustained tensile-load overhead highway applications where failure of the adhesive would result in a risk to the public until testing standards and protocols have been developed and implemented that ensure the safety of these applications. (H-07-16)
>
> Seek legislation authorizing the Federal Highway Administration to establish a mandatory tunnel inspection program similar to the National Bridge Inspection Program. (H-07-17)
>
> Once provided with legislative authority to establish a mandatory tunnel inspection program as indicated in Safety Recommendation H-07-17, develop and implement a tunnel inspection program that will identity critical inspection elements and specify an appropriate inspection frequency. (H-07-18)
>
> In cooperation with the American Association of State Highway and Transportation Officials, develop specific design, construction, and inspection guidance for tunnel finishes and incorporate that guidance into a tunnel design manual. (H-07-19)

To the American Association of State Highway and Transportation Officials:

> Work with the Federal Highway Administration to develop standards and protocols for the testing of adhesive anchors to be used in sustained tensile-load overhead highway applications, and incorporate those standards and protocols into the *AASHTO Construction Quality Assurance Guidelines.* These standards and

protocols should consider site-specific ultimate strength values as well as the creep characteristics of the adhesive over the expected life of the structure. (H-07-20)

Use the circumstances of the July 10, 2006, accident in Boston, Massachusetts, to emphasize to your members through your publications, Web site, and conferences, as appropriate, the risks associated with using adhesive anchors in sustained tensile-load applications where failure of the adhesive would result in a risk to the public. (H-07-21)

In cooperation with the Federal Highway Administration, develop specific design, construction, and inspection guidance for tunnel finishes and incorporate that guidance into a tunnel design manual. (H-07-22)

To the Departments of Transportation of the 50 States and the District of Columbia:

Prohibit the use of adhesive anchors in sustained tensile-load overhead highway applications where failure of the adhesive would result in a risk to the public until testing standards and protocols have been developed and implemented that ensure the safety of these applications. (H-07-23)

Review the use of adhesive anchors in highway construction within your jurisdiction and identify those sites where failure of the adhesive under sustained load could result in a risk to the public. Once those sites have been identified, implement an inspection and repair program to ensure that such failures do not occur. (H-07-24)

To the International Code Council:

Require creep testing for the qualification of all anchor adhesives. (H-07-25)

Disqualify for use in sustained tensile loading any adhesive that has not been tested for creep or that has failed such tests. (H-07-26)

Revise your building codes, qualified materials listings, and product labeling guidelines to clearly address the possibility for creep in polymeric anchor adhesives and to make end users aware of the potential lack of correlation between short- and long-term performance of these adhesives. (H-07-27)

Use your building codes, qualified materials listings, test criteria, or other mechanisms to make end users aware of the strong potential for creating voids in the adhesive during the overhead installation of adhesive anchors and of the need to account for the reduction in effective embedment depth associated with the use of seal plugs in such applications. (H-07-28)

To ICC Evaluation Service, Inc.:

Revise evaluation report ICC ESR-1531 to state explicitly in the text and in the bond strength tables that the Fast Set formulation of Powers Power-Fast epoxy is approved for short-term loads only. (H-07-29)

To Powers Fasteners, Inc.:

Revise the packaging, for all distributors, of your Power-Fast Epoxy Injection Gel Fast Set formulation to state explicitly that this formulation is approved for short-term loads only. (H-07-30)

To Sika Corporation:

Revise your product literature and packaging to state explicitly that Sikadur Injection Gel AnchorFix-3 epoxy is approved for short-term loads only. (H-07-31)

To the American Concrete Institute:

Use your building codes, forums, educational materials, and publications to inform design and construction agencies of the potential for gradual deformation (creep) in anchor adhesives and to make them aware of the possible risks associated with using adhesive anchors in concrete under sustained tensile-load applications. (H-07-32)

To the American Society of Civil Engineers:

Use the circumstances of the July 10, 2006, accident in Boston, Massachusetts, to emphasize to your members through your publications, Web site, and conferences, as appropriate, the need to assess the creep characteristics of adhesive anchors before those anchors are used in sustained tensile-load applications. (H-07-33)

To the Associated General Contractors of America:

> Use the circumstances of the July 10, 2006, accident in Boston, Massachusetts, to emphasize to your members through your publications, Web site, and conferences, as appropriate, the need to assess the creep characteristics of adhesive anchors before those anchors are used in sustained tensile-load applications. (H-07-33)

BY THE NATIONAL TRANSPORTATION SAFETY BOARD

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Adopted: July 10, 2007

APPENDIX A

Hearing and Investigation

The National Transportation Safety Board was notified of the Boston, Massachusetts, accident on July 10, 2006. An investigative team was initially dispatched from the Safety Board's Arlington, Texas, office. As the investigation progressed, additional investigators responded from the Washington, D.C., and Atlanta, Georgia, offices. Separate groups were established to investigate issues related to human performance, structural engineering, and construction oversight. No Board Member was on scene.

Participating in the investigation were representatives of the Federal Highway Administration, the DOT's Office of the Inspector General, and the Massachusetts State Police.

One deposition was conducted in which an employee of Powers Fasteners, Inc., was interviewed on March 21, 2007.

APPENDIX B

AASHTO Testing Survey

The bracketed numbers reflect the percentage of the 30 States that responded to survey options A through E below. Percentages total more than 100 because of the selection of multiple options.

How does your State ensure that these critical systems or materials will work properly? Please [select] one or more of the [options] below:

> A. The state evaluates the material in-house (or hires a lab to evaluate it) based on a non-AASHTO protocol [32.3 percent]
>
> B. The state asks the contractor to evaluate the material (or hire a lab to evaluate it) based on a non-AASHTO protocol [12.9 percent]
>
> C. The state uses/trusts the manufacturers' specs or certifications [25.8 percent]
>
> D. The state delegates responsibility to the contractor to ensure that these critical systems will work properly (the contractor, in turn, may simply use the manufacturers' specs or certifications) [19.4 percent]
>
> E. Other (please explain) [67.7 percent]

Responses to the "Other" category from various States included the following observations:

> A qualified products list (QPL) is developed based on a corresponding procedure that includes independent lab testing from the supplier and our lab testing for verification. Contractor performs witnessed proof testing in the field to confirm personnel ability and procedures. Quality control (QC) testing is done on the first day of production installation. Quality assurance (QA) testing is done on a random basis. Criteria and requirements for QC and QA testing are cited in the specifications.
>
> The Professional Engineer will have to verify the design and testing to assure the system will meet the critical application.

How handled varies. If proposed on a working contract an ad-hoc group is formed to evaluate/test. Often, we ask for independent lab results from the contractor/vendor, but attempt to reconfirm testing in our own lab. If a vender submitted item and not time critical, it goes to our Products Evaluation Unit and may be accepted or rejected by the Highway Developmental Council (standing group to evaluate non-standard materials). In both cases we research what would be the most appropriate testing protocols.

When material can not be tested in-house we require notarized test results and certifications from the manufacturer.

We recently completed a Materials Risk Analysis, evaluating all common materials for two kinds of risk: failure to meet specification and consequences if specifications are not met. This analysis provides a basis for how we accept materials: based on testing, fabrication inspection, manufacturer's cert of compliance, visual, etc.

We'd try and perform ourselves or use a consultant services provider to ensure compliance.

[We use] a standard form to get all pertinent information on the material in question. We would ask the manufacturer of that material to provide contacts, preferably [department of transportation], where the material had been used if possible and provide any test data that they have on the material for our review. Based on this information we would make a decision to proceed with evaluating the material for use on a project specific basis or on a statewide basis.

Additional methods for critical systems or materials that have been utilized include a mandatory system operation, or materials function, failure free time period. During this time the contractor must maintain, rectify, correct any and all operational issues at their cost. The time cannot conclude nor final payment [be] made until the specified time period has passed continuously without issues.

If we could develop our own test method or specifications to include in the contract we would. If no specifications exist, we may require the supplier to provide specifications, test results, and certifications on the product. In some instances we may accept the product based only on the suppliers certification.

We use [established] test procedures, Certificates of Compliance, Analysis, and Delivery. We use a great deal of in-house testing and use some contractor results in the acceptance process.

For critical items as described above, [we require] the manufacturer/contractor to provide engineering calculations to support the use of the material/system in question. We may also test some of the materials to verify the properties supplied by the manufacturer/contractor.

We would in some situations evaluate the component itself to determine the appropriate action. It could be a combination of the items in question 3. If at all possible we would try to find an AASHTO or ASTM reference that would at least support the direction of our action.

In some cases we maintain an approved products list that “qualifies” certain materials where we review and test the material or system and then it is available for any project.

[I]f we do not have the equipment or expertise to test the material in house we would identify outside testing expertise and, dependent on how critical the element is, we may even witness the testing.

We do not ‘ask’ contractor to evaluate critical systems or materials that do not have AASHTO or ASTM specification, but we have ‘required’ the contractor to test items and we witness the testing.

Most structure critical components are tested in our Central Materials Laboratory. Generally, if there is not an accepted AASHTO or ASTM test method, there is a state test method outlining the procedure to be used. Certain components are taken on manufacturers’ certification and/or a certified test report.

Require that a registered professional engineer, registered in any state, evaluate and certify that the item design complies with the plans and specifications and meets and exceeds the appropriate national standard and that the materials meet or exceed the specification requirements. In addition, require the Contractor to furnish a certification that the item is fabricated in compliance with the certified design and complies with the specification requirements. For devices that require crash testing, the manufacturer is required to supply a certification that the device has been crashed tested and meets requirements per the appropriate crash test specified.

APPENDIX C

Tunnel Ceiling Survey

Tunnel authority	Typical ceiling panel or slab dimension			Typical ceiling panel or slab weight		Ceiling anchorage system	Continuous support at end of panels or slabs
	Length	Width	Thickness	Weight (lbs)	psf		
Massachusetts Turnpike Authority							
Sumner Tunnel	11’ 3”	3’ 3”	2”	550	15	Adhesive anchors	No
Callahan Tunnel	11’ 3”	3’ 3”	2 ¼”	550	15	Adhesive anchors	No
I-90 Ted Williams Tunnel	11’ 0”	4’ 0”	2”	1,200	28	Adhesive anchors	No
I-90 Connector Tunnel	12’ 0”	8’ 0”	4”	4,800	50	Bolts in embedded steel channels, adhesive anchors at east portal and isolated locations	No
I-93 Central Artery Tunnel	12’ 0”	8’ 0”	4”	4,800	50	Hanger plates typically attached to steel roof girders	No
MTA Bridges and Tunnels in New York							
Brooklyn Battery Tunnel	10’ 8”	20’ 5”	5”	12,380	57	Centerline cast-ring bolted hanger plus expansion anchors mechanically engaged in concrete lining	Yes, plus continuous steel I-beam
Queens Midtown Tunnel	10’ 8”	20’ 6”	5”	12,479	57	Centerline cast-ring bolted hanger plus acrylic resin expansion anchors mostly in shear and partially in pullout	Yes, plus continuous steel I-beam

Tunnel authority	Typical ceiling panel or slab dimension			Typical ceiling panel or slab weight		Ceiling anchorage system	Continuous support at end of panels or slabs
	Length	Width	Thickness	Weight (lbs)	psf		
Port Authority of New York and New Jersey Tunnels							
Lincoln Tunnel	22' 0"	5' 0"	4 ¾"	8,000	73	Original cast-in-place slab supported at ends by concrete tunnel liner and by center support assembly bolted to cast-iron ring	Yes
Holland Tunnel	23' 0"	5' 0"	4 ½"	8,000	70	Precast replacement panels supported at ends by concrete liner, by inserts secured to concrete liner near each end of panel, and by center assembly bolted to the cast iron ring	Yes
Detroit–Windsor Tunnel Authority in Michigan							
Detroit–Windsor Tunnel	10' 0"	20' 0"	5"	11,000	55	Slab supported at mid-span by manganese bronze metal ceiling hangers	Yes
South Jersey Transportation Authority							
Atlantic City Expressway Tunnel	n/a	n/a	n/a	n/a	n/a	No suspended ceiling panels used in tunnel; ventilation is accomplished through jet fans	n/a
Maryland Transportation Authority							
Fort McHenry Tunnel	6' 10"	2' 4"	2"	353	22	Panel supported by pipe hangers extended into concrete ceiling with expansion anchors	Yes

Tunnel authority	Typical ceiling panel or slab dimension			Typical ceiling panel or slab weight		Ceiling anchorage system	Continuous support at end of panels or slabs
	Length	Width	Thickness	Weight (lbs)	psf		
Chesapeake Bay Bridge and Tunnel District in Maryland							
Chesapeake Bay Tunnel	12’ 0”	12’ 0”	5”	8,640	60	Cast-in-place concrete slab supported by stainless steel hangers that extend into upper socket embedded into concrete ring ceiling that contains stainless steel strap anchors	Yes
Pennsylvania Turnpike Commission							
Allegheny and Tuscarora Tunnels	30’ 0”	28’ 6”	5”	47,500	56	Slab corbelled into tunnel walls with redundant support system at mid-span consisting of 3 hanger rods; hanger rods are attached to separate threaded insert cast in place at top of arch	Yes, at side walls, but not between slabs
Virginia Department of Transportation							
Midtown Tunnel	6’ 6”	2’ 6”	2”	407	25	Cast-in concrete anchors	No
Hampton Roads Bridge Tunnel							
eastbound tube	7’ 7”	2’ 0”	2”	474	31	Mechanical expansion anchors	No
westbound tube	12’ 9”	1’ 0”	2”	318	25	Cast-in concrete anchors	No
Big Walker Mountain Tunnel	38’ 6”	31’ 0”	6”	89,500	75	Steel anchorage assemblies cast into concrete tunnel lining	Yes

Tunnel authority	Typical ceiling panel or slab dimension			Typical ceiling panel or slab weight		Ceiling anchorage system	Continuous support at end of panels or slabs
	Length	Width	Thickness	Weight (lbs)	psf		
East River Mountain Tunnel	38' 6"	31' 0"	6"	89,500	75	Steel anchorage assemblies cast into concrete tunnel lining	Yes
Downtown Tunnel							
eastbound tube	7' 6"	2' 6"	2"	474	25	Mechanical expansion anchors	No
westbound tube	7' 6"	2' 6"	3"	703	37	Cast-in concrete anchors	No
Monitor–Merrimac Memorial Bridge Tunnel	7' 3"	3' 0"	2"	544	25	Mechanical expansion anchors for both tubes	No