Engineering Design and Human Factors: Insights into Highway Bridge and Tunnel Disasters

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2012 Tulane Engineering Forum
Plenary Session
Friday, March 23, 2012
The NTSB is an independent US federal agency charged with determining the probable cause(s) of transportation accidents, making recommendations to prevent their recurrence, conducting special studies and investigations, and coordinating resources to assist victims and their families after an accident.
Collapse of I-35 Highway Bridge
Minneapolis, MN
Video Sequence of bridge collapse
I-35 “Warren Truss” with Verticals
Figure 3. East elevation of I-35W bridge. The deck truss portion of the bridge extends from just south of pier 5 to just north of pier 8. (Source: Adapted from Mn/DOT graphic)
Probable Cause of Failure

The inadequate load capacity, due to design error of the gusset plates at the “U10” connection points by the engineering consulting firm responsible for the bridge design, which failed under a combination of:

1) Substantial increases in the weight of the bridge, resulting from previous bridge modifications; and

2) Traffic and concentrated construction loads on the bridge the day of the collapse.
Probable Cause of Failure

Contributing to the design error was the failure of the engineering consulting firm’s quality control procedures to ensure appropriate main truss gusset plate calculations were performed; and the inadequate design review by Federal and State transportation officials.

Contributing to the accident was the accepted practice by these officials of giving inadequate attention to gusset plates during inspections and excluding them from load rating analyses.
I-35W Bridge Information

Bridge deck (roadway)

Source: Mn/DOT
Bridge Modifications

• 1977 – modification to increase bridge deck thickness
  - Bridge dead load increase of 13.4%

• 1998 – modifications to the median barrier and outside railings
  – Bridge dead load increase of 6.1%
Figure 17. Reconstruction of estimated positions of construction aggregates and equipment along the two inner southbound lanes of I-35W bridge at time of collapse.
Drawing of Fractures in Node U10E West Gusset Plate

Initial compression failure

Initial tension fracture
Dead Load of Original 1967 Bridge

Orange and red shading: exceeds yield stress
After 1977 and 1998 Modifications

Orange and red shading: exceeds yield stress

Stress

Yield stress

Allowable

Tension diagonal

Compression diagonal
Loads at Time of Accident

Orange and red shading: exceeds yield stress
Loads at Time of Accident

Orange and red shading: exceeds yield stress

Stress

Yield stress

Allowable

Tension diagonal

Compression diagonal
U10 West and U10 East

U10 East

U10 West

Has higher stress at the time of the accident
Accident Loads on 1-Inch-Thick Gusset Plates

Stress

Allowable

Yield stress

0

Compression diagonal

Tension diagonal
Standards, Regulations and Guidance

• AASHO/AASHTO
  – Initial bridge design
  – Inspections
  – Bridge condition evaluations/load evaluations

• MN/DOT
  – Initial bridge design
  – Construction projects

• Federal Highway Administration
  – Inspection requirements (regulations)
  – Construction loading (technical advisories)
Missed Opportunities

- Design, construction, and inspection guidance materials focused on members and other structural elements only.
- Bridge safety inspection engineer – noticed, but made poor assumptions and did not document.
- Evaluations by URS/U. of Minnesota, failed to identify bowing condition, although captured photographic evidence.
- Decision to allow staging of aggregates on bridge deck truss.
Ongoing Issues

• Investigation revealed a number of other instances where questionable bridge designs have been certified and approved for construction.

  – 10 States acknowledged approving designs later found deficient
  
  – At the time, 2008, all but one of these approvals had occurred in the previous 10 years (most within the previous 6 years)
Ceiling Collapse in I-90 Connector Tunnel Boston, MA

Ceiling Collapse in the Interstate 90 Connector Tunnel Boston, Massachusetts July 10, 2006
Probable Cause of Failure

The use of an epoxy anchor adhesive with poor creep that could not sustain long-term loads.

The failure of the project consultants to identify creep as a critical long-term issue, and account for it in the design, specifications, and approval process for an anchoring system.

The failure of the epoxy provider to provide the consultants sufficient information to determine the suitability of the product to sustain long-term tensile loads.
Probable Cause of Failure

Contributing to the accident:

- Failure of the epoxy provider to identify the unsuitability of the epoxy in a previous anchor application.

- Failure of project contractors to continue to monitor the anchors, after the first instance of anchor displacement.

- Failure of the Turnpike authority to implement an inspection program.
Probable Cause of Failure

Contributing to the accident:

1) The failure of the provider of the anchoring system to recognize creep resistance issues with its product, based on knowledge from prior incidents.

2) The failure of the project management consultant and the construction contractor to monitor anchor performance in light of the prior incidents involving the anchor; and

3) The state turnpike authority's failure to implement a timely tunnel inspection program that would have likely identified anchor creep issues in time to correct deficiencies.
Displaced Anchors
Missed Opportunities

• Construction project consultant’s limitations on choice of anchoring system
• Lack of clarity on types of epoxy available/provided
• Insufficient approval review by design consultant – which failed to identify the type of epoxy and note the limits on its use.
• After initially discovering the displacement of anchors, failing to identify the cause.
• After taking some action, failing to follow up to ensure action was appropriate and issue resolved.
Question Assumptions

• Reliance on standards and testing that did not properly assess or account for key characteristics of critical infrastructure components

• Reliance on false assumptions, rather than focusing on actual, visual evidence.