National Aeronautics and Space Administration

SYSTEM FAILURE CASE STUDIES

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A Half-Inch to Failure

At 6:05 pm, on Wednesday, August 1, 2007, the Interstate-35 West (I-35W) bridge over the Mississippi River in Minneapolis collapsed. On the day of the collapse, four of the bridge's eight lanes were closed for planned construction. Four weak connector plates fractured under the combined burden of rush hour traffic, concentrated construction equipment, and previous heavy renovations. The bridge fell 108 feet into the Mississippi River. The police, fire department, and U.S. Coast Guard immediately initiated rescue operations. Of the 190 people on or near the bridge, thirteen died and 145 were injured.

BACKGROUND

The I-35W bridge supported a 1,907 foot long, 8-lane wide roadway that served Minneapolis for forty years. The state inspected the bridge annually using the *National Bridge Inspection Standards* set by the Federal Highway Administration (FHWA). Inspectors had been labeling the bridge "structurally deficient" since 1991. This label indicated that the bridge required significant maintenance and repair to remain in service, but not that it was unsafe (inspectors would have closed the bridge if they believed it was unsafe). A structurally deficient rating is not uncommon; approximately 12% of U.S. bridges are rated structurally deficient.

Steel truss bridges, like I-35W, were more frequently labeled structurally deficient; approximately 31% of the 465 steel truss bridges in the U.S. were listed as structurally deficient at the time of the collapse. Such bridges consist of straight beams of steel formed into triangular units (Figure 1). In large steel truss bridges, the ends of the beams are connected with riveted metal plates called gusset plates. I-35W's gusset plates connected three beams at each node: two diagonal beams and one vertical beam (Figure 2).

Over the course of forty years, the state of Minnesota conducted significant renovations on the bridge three times. In 1977, the State increased the bridge deck thickness about two inches. This renovation increased the dead load (weight of the structure itself) by 13.4%. In 1998, the State increased the dead load another 6.1% when it installed a median barrier. Together, these two renovations increased the weight of the bridge 19.5% over the original design.

Figure 1: The I-35W Bridge

A third set of renovations began in June 2007, two months before the collapse. The Minnesota Department of Transportation (MnDOT) hired a construction contractor, Progressive Contractors, Inc. (PCI), to resurface the bridge. The renovations involved removing two inches of concrete on the roadway and replacing it with fresh concrete.

Resurfacing required heavy construction equipment to mix and pour concrete. In the weeks leading up to the collapse, the construction contractor had poured concrete on seven bridge deck sections. The contractor placed heavy construction equipment on bridge ramps for five concrete pours; one pour stationed some equipment on the bridge

August 1, 2007: The I-35W Bridge that spanned the Mississippi River in Minneapolis collapsed, killing 13 and injuring 145.

Proximate Cause:

- Weak gusset plates fractured under the weight of rush hour traffic, previous bridge renovations and concentrated construction materials.

Underlying Issues:

- Inadequate gusset plate design and insufficient review process.
- Added weight from renovations, traffic, and construction materials.
- Lack of attention to gusset plates in inspections and load ratings.
- Communication issues between the construction contractor and the State.

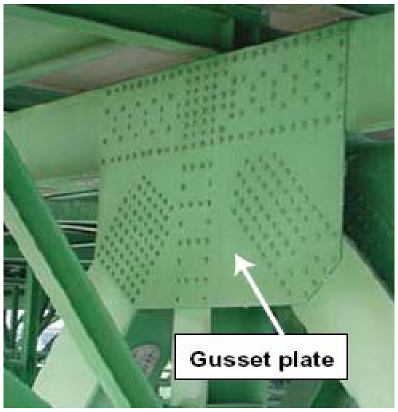

Figure 2: I-35W Gusset Plate

deck and some on the ramps, and another positioned the equipment and materials on the bridge deck itself.

About a week before the collapse, the contractor was preparing for one of the concrete pours, and the foreman asked the state bridge construction inspector if equipment and materials could be placed on the bridge. The foreman (worried about post-task cleanup rather than structural loading) interpreted the inspector's expressed lack of concern as permission. However, the bridge construction inspector was not an engineer, and he lacked the authority to grant such permission. He was present to ensure that the construction crew used the correct materials and fulfilled contract terms. Work proceeded and by August 1, the contractor had finished resurfacing the two outside lanes on both sides of the bridge, leaving the four inner lanes to be resurfaced.

What Happened?

On August 1, the day of the collapse, the contractor set up equipment to mix and pour the eighth section of concrete. Two cement tankers weighed more than the bridge's posted legal limit for trucks (80,000 lbs.), so the contractor did not bring them onto the bridge. One cement tanker weighed less than the legal limit, and the contractor brought it on the bridge along with four piles of sand and four piles of gravel, a water tanker truck, a small excavator, and four self-propelled buggies. The material and vehicles were concentrated in a section of two closed lanes. By 2:30 pm, all the equipment was set up, ready for the concrete pour, which was scheduled to begin at 7 pm.

The bridge collapsed at 6:05 pm, when the gusset plates at a set of the nodes on the south side of the bridge fractured. Once the gusset plates broke, the rest of the bridge could not support the extra weight; within seconds, it fell into the Mississippi river.

Observers immediately notified 9-1-1. Approximately 100 people nearby began rescue efforts; over thirty plunged into the river to help those in submerged vehicles. Just five minutes after the collapse, the Minneapolis Police arrived, followed by area Fire and Sherriff's Departments. At 7:27 pm, the Sherriff's Department officially switched from rescue to recovery operations. Recovery continued until August 6, when the last victim was found. Of the 190 people on or near the bridge at collapse, 111 had minor injuries, 34 suffered serious injuries, and 13 did not survive.

Proximate Cause

According to the National Transportation Safety Board, the gusset plates at the nodes that failed were only half as thick as they should have been. In addition to being too thin, some of the gusset plates were bowed, a distortion that further decreased the bridge's weight bearing capacity. The weak gusset plates fractured under the concentrated weight of the construction materials, the burden of rush hour traffic and the increased load from previous bridge modifications. The diagonal steel beams within the failed nodes shifted to the west and fractured the gusset plates around the ends of the diagonals (Figure 3). Once the diagonal beams separated, the rest of the truss fell.

Underlying Issues

No single element caused the I-35W bridge collapse. Rather, several issues led to the failure of the weak gusset plates. The original gusset plate design was incorrect. When correctly designed, the plates are stronger than the steel beams they connect. Inspectors, unaware of the design error, assumed the gusset plates were unlikely to fail and paid little attention to them during inspections. On the day of the collapse, the heavy renovations, concentrated placement of construction materials, and rush hour traffic finally stressed the bridge enough to reveal its weaknesses.

Faulty Design

The Safety Board traces the cause of the collapse to the original bridge design. Several of the gusset plates, including the gusset plates that fractured, were only half an inch thick when they should have been a full inch thick. The plates were not designed to support the bridge's original weight, let alone the additional weight of the 1977 and 1998 renovations. The Board believes that the original designers probably did not exercise quality control to ensure the calculations were correct for these gusset plates. Although the State reviewed the designer's original calculations before the bridge was built, it probably did not have the resources to fully verify the consultant's work. This was not an unusual

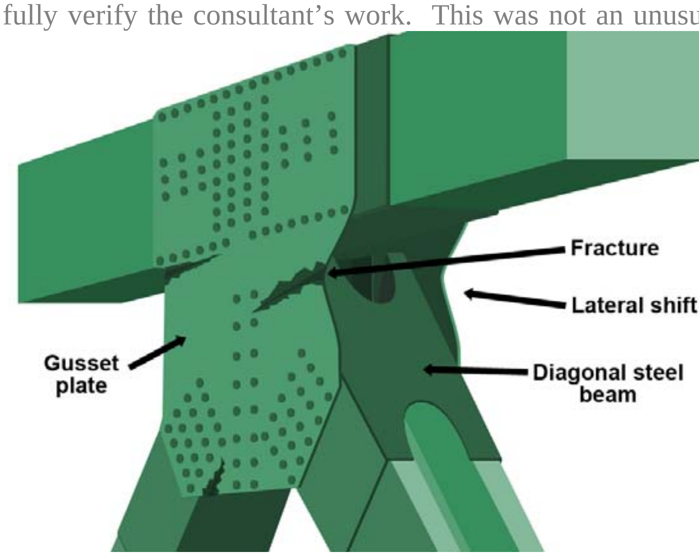

Figure 3: Artist's Rendering of a Fracturing Gusset Plate

situation; states commonly lacked sufficient resources for a thorough design review.

Gusset Plate Bowing and Inspections

The Safety Board could not determine when the gusset plates bowed. Photographs taken in 1999 show that they were bowed at least eight years prior to the collapse. One safety inspection engineer remembered noticing the bowed gusset plates during his inspection in the late 1990s, but thought the bowing occurred during the original construction of the bridge. He did not report his observations of the gusset plates because "our inspections are to find deterioration or findings of deterioration on maintenance. We do not note or describe construction or design problems." Additionally, he did not think gusset plates were critical to bridge safety because he had learned in college that gusset plates are designed to support 2 to 3 times the expected bridge loads.

The gusset plates did not worry other bridge inspectors either. Inspectors' reports since 1994 noted rust, corrosion, and section loss in the gusset plates, but did not measure changes over time. Often, inspectors simply copied the gusset plate description from a previous report. Inspector training materials, such as the FHWA's Bridge Inspector Reference Manual, did not address gusset plates in steel truss bridges. No training materials emphasized the importance of gusset plates, or identified distortion as a serious hazard. The cumulative effect of these oversights was that, despite the bridge's structurally deficient rating, gusset plates were not one of the elements that worried inspectors.

Communication and Load Ratings

The state provided contractors with little guidance on construction material placement. The foreman asked the construction inspector for permission to place materials on the bridge deck, unaware that the project engineer should have been asked instead. For day-to-day concerns, the project engineer relied heavily on the project construction supervisor to inform him of any problems, but the project construction supervisor was not onsite on August 1. Afterwards, he said he was not sure if he would have voiced concern about putting heavy materials on the bridge. "My best guess is it would have been a 50-50 chance that I might have done something," he said.

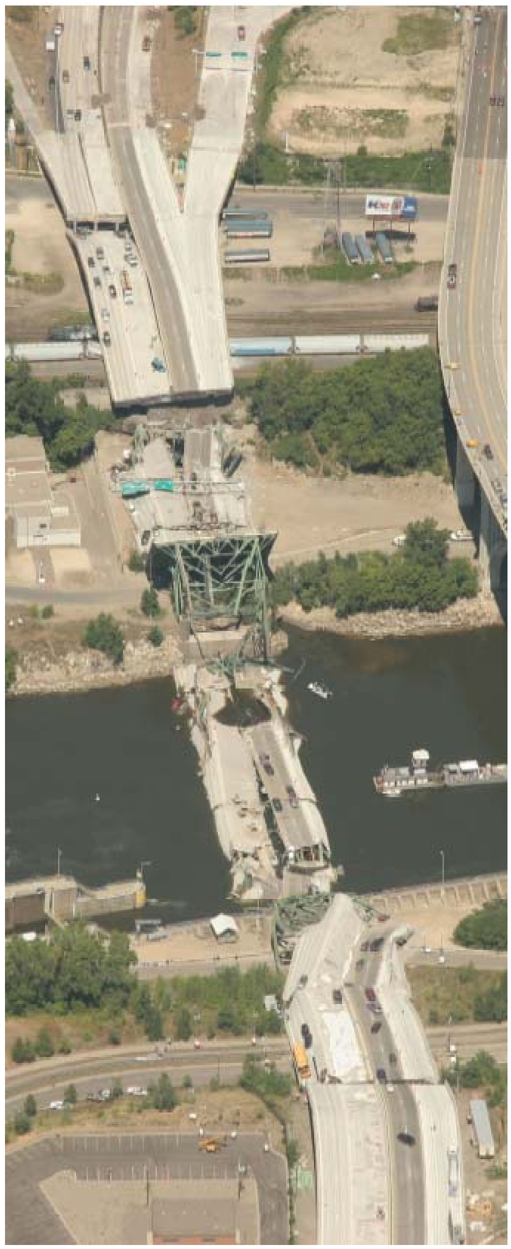

Figure 4: I-35W Bridge on August 2, 2007, the day after the collapse

If the construction contractor had formally requested permission to place materials on the bridge deck, the state might have referred to a technical model used to determine bridge load ratings. Model calculations, however, did not include gusset plates because engineers expected beams to fail prior to gusset plates. According to the state's model, the bridge was capable of bearing the August 1 loads. The model would not have predicted the collapse.

Aftermath

As a result of the National Transportation Safety Board's findings, the FHWA now recommends that bridge owners inspect gusset plates "whenever planned modifications may significantly increase stresses."

MnDOT also increased design review requirements for new bridge construction and existing bridge inspections. Minnesota now requires that all bridges designed by consultants undergo an independent design review.

Bridge inspections in Minnesota were revamped. The State examined all 25 steel truss bridges in the state and found gusset plate problems in four bridges. The State repaired the gusset plates on three of the bridges, closed the fourth bridge and accelerated its replacement schedule. Other states also re-inspected their steel truss bridges, paying special attention to gusset plates.

Applicability to NASA

There are a number of parallels between I-35 and NASA facilities. The I-35W bridge endured forty years of use and three major modifications. Many NASA facilities are several decades old and have been modified to house different projects.

I-35's lurking design error of thin gusset plates escaped notice during its design review. The consequences of a design error must be considered when allocating resources and time to expert internal and independent design reviewers. If Minnesota had conducted a more thorough review of the I-35W designs in the 1960s, they might have caught the gusset plate design flaw and prevented the 2007 tragedy. The design process at NASA is subject to oversights in the review process as well. Like state departments of transportation, NASA often hires design consultants and verifies their work internally or through third party review.

Questions for Discussion

- How do you ensure design reviewers have adequate resources (funding, expertise, experience) to be thorough?
- Can you think of other examples of when something was incorrectly assumed to be safe?
- How do you change inspections as infrastructure ages? Do your inspections rely too much on checklists?
- What change management practices do you employ when modifying a facility?
- How do personnel and contractors know the correct authority to go to if they have a question?

NASA project managers must ensure that reviewers have the knowledge, experience, time and access they need to conduct a thorough review.

When a structure is already in place, it is not always feasible to conduct a complete review of the original design. There are other ways, however, that the I-35 tragedy could have been prevented. Inspectors did not recognize bowed gusset plates as a serious safety concern. Hindsight exposes the false assumption that these gusset plates were sound, but prior to the collapse, inspectors were probably unaware of any such failure mode. Previous successes and failures biased inspections and undermined hazard identification skills. The model used to determine bridge load ratings was also biased by the assumption that gusset plates were stronger than beams; it did not include gusset plates in its calculations. At NASA, we must recognize changes to any baseline configuration and question assumptions about aging systems.

An object lesson is the bridge inspectors' cursory observation of the gusset plates. Inspectors did not quantify gusset plate changes from year-to-year, and they often merely recycled the previous year's description, providing an outdated and incomplete review. "You get what you inspect" and a repetitive, narrow checklist limits potential hazard discoveries. At NASA, we need to train and encourage system and process knowledge in our inspectors, and reward active hazard identification beyond the checklist.

Each I-35 bridge renovation presented an excellent opportunity to assess the current state of the whole structure. Safety inspectors should have been expected to measure new (and explain old) changes caused by the weighty renovations. At NASA, where facilities are modified to accommodate new projects, we must check for hazardous effects a change might have on an aging facility. Conduct an impact analysis and follow change management best practices to mitigate unexpected problems from modified infrastructure.

A final lesson from the bridge collapse comes from the communication issues between the State and the construction contractor. The State did not clearly communicate who could authorize the placement of equipment and materials on the bridge. While it is not clear whether the authorities would have refused the contractor's request to place heavy equipment on the bridge, the confusion contributed to the contractor's belief that they had the state's permission when, in fact, they did not. We should use clear lines of authority to communicate safety-critical information both internally and externally. Verify who is empowered to accept a risk before a time-critical decision is needed.

References

Matsuo Bridge Co., Ltd. (n.d). Bridge Types - Truss. In *The Basic Bridge Types*. Accessed 27 May 2009 from http://www.matsuo-bridge.co.jp/english/bridges/basics/truss.shtm.

Minnesota Department of Transportation. (2007). *Aerial Photos of I-35W Bridge Collapse*. Online Image. 2 Aug. 2007. Accessed 27 May 2009 from http://www.dot.state.mn.us/i35wbridge/photos/aerial/aug-2/index.htm

National Transportation Safety Board. (2008, November). *Highway Accident Report: Collapse of I-35W Highway Bridge, Minneapolis, Minnesota, August 1, 2007* (NTSB/HAR-08/03). Washington, D.C. Accessed 27 May 2009 from http://www.ntsb.gov/publictn/2008/HAR0803.pdf

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