The I-35W Highway Bridge collapse: les

From its initial design to the stockpiling of materials during subsequent renovation, Sean Brady details a succession of failures and missed opportunities that resulted in the catastrophic collapse of a highway bridge in Minnesota.

In the early afternoon of 1 August 2007, Progressive Contractors Inc. (PCI) were preparing for a 160m long concrete pavement pour on the southbound lanes of the I-35W Highway Bridge in Minneapolis, Minnesota. Seven previous pours had been completed since the project's commencement in June, and for this, the eighth, 50mm of existing concrete wearing course had been removed in preparation for the pour planned for 7pm that evening.

PCI's preparations included stockpiling gravel and sand on two of the bridge's southbound lanes, which was not an unusual procedure, as the Minneapolis Department of Transport's (Mn/DOT) specification provided only a one hour window between initial concrete mixing and final screeding – thus necessitating that concrete be mixed as close to the placement site as possible. By 2:30pm that afternoon, 84t of gravel, 90t of sand, and 90t of construction vehicles, equipment and personnel - totalling 264t spread over an area of approx. $300m^2$ - was in place for the pour.

As we now know, this pour never took place. At 6:05pm a 300m section of the main truss span collapsed, with a 140m section falling 33m into the river below (Figure 1). A total of 111 vehicles were on the collapsed section, and only 17 were recovered. Tragically, 13 people lost their lives and 145 were injured.

The subsequent National Transportation Safety Board's (NTSB) investigation would identify undersized gusset plates, due to a design error, in combination with recent increases in dead load and live load as the cause of the failure[1]. This article explores how the load increases occurred and the role they played in the collapse, as well as exploring the design error and, just as importantly, how it went unnoticed throughout the bridge's 40 year service life.

The Bridge

The I-35W bridge was designed by engineering consulting firm Sverdrup & Parcel and Associates, and was opened to traffic in 1967. It was 580m long, carried eight lanes of traffic (four northbound and four southbound), and comprised 11 approach spans and three truss spans. By 2004 it carried an average of 141,000 vehicles daily.

Three major renovation/modification projects were undertaken on the structure during its lifetime, two of which increased its dead load. In 1977 a wearing course was applied to the bridge by milling 6mm of concrete from the deck and replacing it with 50mm of low slump concrete. In 1998, renovations/modifications continued, primarily with the replacement of the medium barrier, an upgrade of the outside concrete traffic railings, and the installation of an anti-icing system. At the time of the collapse, the third set of works was underway, which consisted of the replacement of the concrete wearing course, and the stockpiling of materials occurred during these works.

Stockpiling

This was not the first time such stockpiling took place. Of the seven overlays completed, stockpiling occurred on five of them, with the first occasion being on an approach span on the night of 6 July 2007. The first staging on the main truss span occurred on the night of 23 July 2007. On the afternoon of 1 August, the staging for the eighth pour was complete, with the NTSB estimating that the loading, from the stockpiled materials alone, was equivalent to four times the design live load of the bridge. (The NTSB's estimate was based on eyewitness accounts, post-incident vehicle positions and, interestingly, from a photograph taken by a passenger travelling on a commercial airliner as it flew over the bridge approximately 2 hours and 15 minutes before the collapse). How were PCI permitted to stockpile such a significant load of sand and gravel on the structure?

On site, the Mn/DOT provides construction inspectors. These inspectors were not trained engineers and, as a result, the Mn/DOT informed the NTSB that questions regarding stockpiling should have been directed, in writing, to the bridge's project engineer. However, the Mn/DOT had no policy that specifically required contractors to obtain such permission. Thus, when preparing for the pour on 23 July, the PCI foreman asked the Mn/DOT inspector if material could be staged on the span, and when "the inspector evidenced no concern about the staging" the PCI job foreman interpreted this as permission[1]. So during the preparations on 1 August, PCI again commenced stockpiling and permission was not obtained from an Mn/DOT engineer.

Subsequent to the failure, the NTSB investigated if Mn/DOT would have granted approval for the stockpiling, if such a request had been received. The Mn/DOT stated that, due to the loading being four times higher than the design live load, they would likely not have granted approval without first undertaking analysis. The NTSB requested that the Mn/DOT undertake such analysis, and this load rating indicated that the stockpiling was satisfactory. The NTSB therefore, concluded that "had Mn/DOT made a decision based solely on such an analysis, it likely would have approved the stockpiling"[1].

However, there was an issue with the analysis. It only rated the bridge's main members and did not consider the performance of gusset plates. The NTSB investigation would identify a number of gusset plates as being the weak link, due to a design error in the structure. Once their actual capacity was determined, the increases to the bridge's dead load, as a result of the renovation works, in combination with the stockpiled materials on the 1 August, were sufficient to overstress the structure. Conversely, the investigation also concluded that if the gusset plates been designed correctly, the loading would not have been sufficient to cause the collapse. Indeed, it is a testament to the conservatism that is built into designs, that the bridge survived for forty years despite the presence of the design error – the loading on 1 August was simply the enabling conditions necessary for the latent error to culminate in catastrophic failure.

So how did this design error occur and how did it go unnoticed for forty years despite the design being subject to:

sons learned

- An internal design review
- Design reviews by both the Mn/DOT and the Federal Highway Administration (FHWA)

And despite:

- The bridge being subjected to two load ratings, and
- the bridge being inspected more regularly than required by best practice?

The investigation would uncover a systematic breakdown in the very layers of protection the engineering profession erects to prevent such failures occurring.

Design

The NTSB was unable to track down the original design calculations for the critical gusset plates. However, documents from the preliminary design stage were uncovered, which provided some insight into the gusset plate design. These (unchecked) calculation sheets indicated that gusset plate thickness was determined based only on the forces that were expected to pass across the splices between chord members. Considering these forces alone, the gusset plates were sized appropriately. However, their correct design also required the consideration of shearing forces introduced into the gusset plates by the trusses' diagonal and vertical members – which would have resulted in thicker plates. The NTSB found that while other gusset plates were thickened between the preliminary and final design stages, the final design thickness for the critical gusset plates were not increased, remaining the same as that shown in the preliminary calculations. The NTSB would conclude that "even though the bridge design firm knew how to correctly calculate the effects of stress in gusset plates," as evidenced by its correct design of other gusset plates in this, and other, structures, "it failed to perform all necessary calculations for the main truss gusset plates of the I-35W bridge, resulting in some of the gusset plates having inadequate capacity"[1].

Review

Moving to the review phase, the NTSB began by examining the designer's review procedures, and identified that these procedures, provided for an appropriate level of review, including for the review of gusset plate calculations. However, the review did not have an explicit procedure for ensuring all such calculations were actually performed. Ultimately, the NTSB would conclude that such a review process was inadequate.

A failure to check that gusset calculations were actually undertaken was also evident in the Mn/DOT and FHWA reviews. While the NTSB found that these authorities had provision for checking calculations, these provisions did not extend to checking gusset plate calculations. Not only did the authorities fail to identify the design error, but their review processes were not equipped to do so.

Load ratings

The same trend continued with the load ratings undertaken in 1979 and 1998, neither of which considered the gusset plates. The NTSB concluded that had AASHTO guidance "included gusset plates in load ratings, there would have been multiple opportunities to detect the inadequate capacity of the U10 gusset plates of the I-35W bridge deck truss"[1]. Interestingly, the NTSB found that the reason for this neglect was the apparent belief among bridge owners that gusset plates were more conservatively designed than the members they connected. In other words, once the capacity of the members was deemed to be sufficient, it appears to have been assumed that the gusset plates also had sufficient capacity.

Inspections

Finally, opportunities to detect the error through inspections were also missed. The NTSB concluded that the bridge was inspected in accordance with the National Bridge Inspection Standards. Indeed, it was inspected more frequently than these standards required. However, the inspections would not have been expected to detect design errors because they focused on quantifying condition. Nevertheless, there was visual evidence in seven of the eight critical gusset plates that the NTSB described as symptomatic of the inadequate capacity: photographs taken by URS and the University of Minnesota in 1999 and 2003, both of whom were engaged to undertake strain gauging on the bridge, clearly show bowing in some of the critical gusset plates. Based on these photographs, the NTSB estimated this bowing to have been in the order of 11mm to 25mm. Indeed, one Mn/DOT Metro District bridge safety inspection engineer was aware of the bowing, but informed the NTSB investigators that he believed it to have occurred during construction of the bridge. Consequently, the bowing was not noted in any inspection report, and the NTSB found no evidence of any analysis to determine why the distortion had occurred or to what extent it had affected the load-carrying capacity of the gusset plates[1].

The I-35W bridge is a reminder of the role that human factors play in catastrophic failures. From a technical perspective alone, the failure could have been avoided. The design of gusset plates was well understood, but was not implemented correctly, while the risks involved in stockpiling, obvious in hindsight, went unexamined.

As with most failures, there were numerous occasions when the potential for failure could have been identified, but such opportunities were missed or the warning signs were misinterpreted.

GETTY

Figure 1 **Collapsed section of I-35W Highway Bridge**

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1) National Transport Safety Board (2008) *Highway Accident Report, Collapse of I-35W Highway Bridge, Minneapolis, Minnesota,* August 1, 2007 [Online] Available at: www.dot.state.mn.us/i35wbridge/ntsb/finalreport.pdf (Accessed: October 2012)