The Infamous Gusset Plates

by

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Introduction

The general public was shocked and saddened by the practically instantaneous collapse of the I-35W bridge and its tragic consequences. In addition to sharing the emotions experienced by the public, structural engineering experts, including the authors of this essay, were perplexed. What could have caused this very common bridge to collapse within a matter of seconds?

The collapse resulted in the media's search for immediate answers to the following two questions; why did the bridge collapse and who is to blame? Speculative answers to the first question were proposed by the "Average Joe" and structural engineering experts alike, and involved the usual suspects; the growth from microscopic to catastrophic lengths of undetected cyclic load-induced fatigue cracks, the reduction in strength of steel components produced by environmentally-assisted corrosion, and settlement of the piers that transfer the weight of the bridge to the ground. The adequacy of the steel truss design, which was used in the longest span of the bridge, was questioned. It is true that steel trusses possess a relatively small level of redundancy. That is, the integrity of a steel truss bridge can be jeopardized if but a few critical members or connections fail. However, the possibility of such catastrophic events is for all intents and purposes eliminated by mandated regularly conducted maintenance, retrofit and inspection procedures. As for blame, fingers were first pointed at the deck repair construction that took place up to the time of the collapse as being the straw that broke the camel's back. This is understandable considering that a few hours before the collapse hundreds of tons of gravel, sand and water trucks used to repair the concrete deck were placed on the main span, while the traffic loading on the bridge was lightened by the construction-accommodating closing of half of the traffic lanes.

The collapse was such an unusual and unexpected event that the authors decided early on that they would not participate in speculation. Instead, they recognized that this atypical catastrophe offered a learning opportunity for undergraduate and graduate

students. A few days after the collapse the authors applied for and obtained financial support from the National Science Foundation (NSF) for an independent academic investigation. Soon after the University of Minnesota's Center for Transportation Studies (CTS) provided supplementary support. The authors assembled an investigative team that included Department of Civil Engineering Professors Ted Galambos and Arturo Schultz, graduate students Minmao Liao and Alicia Forbes, and undergraduate students Tor Oksnevad and Charles DeVore. This essay summarizes the steps involved in this investigation and explains how a few incorrectly designed gusset plates resulted in the collapse of a bridge that served Minneapolis well for forty years. Further details of the investigation are provided in technical publications by the authors (for example, *Analysis of critical gusset plates in the collapsed I-35W Bridge, Structures Congress 09', ASCE, April 30 – May 2, 2009*).

The authors note that the scope of their investigation was not as large as those of the official investigations performed by the National Transportation Safety Board (NTSB), the Federal Highway Administration (FHWA), and the Minnesota Department of Transportation (MnDOT). A reader interested in a more complete investigation is referred to the final report by the NTSB (*Collapse of I-35W Highway Bridge, Highway Accident Report, NTSB/HAR-08/03, November 14, 2008*) and a report prepared by Wiss, Janney, Elstner Associates (WJE), Inc., which were commissioned by MnDOT *(I-35W Bridge Over the Mississippi River: Collapse Investigation, Final Report, November 2008, WJE No. 2007-3702, Wiss, Janney, Elstner Associates, Inc.)*.

The Mechanics of the Bridge


(a)   (b)

Figure 1- (a) Main structural components of the I-35W bridge, photo by John A. Weeks III (http://www.johnweeks.com/twincities/pages/ms16.html); (b) Close-up view of the gusset plates at the U10 node from NTSB (*Photos of I-35W Bridge, http://www.ntsb.gov/dockets/highway/hwy07mh024/387406.pdf*).

The main structural components of the bridge and the location of the U10 node that is the focus of this study are highlighted in Figure 1a. Traffic was supported by a

concrete deck resting on steel beams (referred to as stringers) running along the direction of traffic. The stringers were in turn supported by steel floor trusses, perpendicular to the direction of traffic, and distributed along the length of the bridge. The floor trusses were supported by the main trusses. As shown in the image, a truss is a structural system formed as an assembly of triangular units, where each unit is comprised of three slender members. Figure 1b is an image of a typical node of the main truss, defined as a point where truss members (five in this case) come together. As shown in the image, the truss members in the I-35W Bridge were held together by gusset plates riveted on two sides of the members. Ultimately, the weight of the bridge and the traffic was transferred to the ground through concrete piers.

It is very important to note that if the bridge had been designed correctly, the gusset plate connections would have been the "strong links" and the truss members the "weak links" in the chain defined by the structure. In other words, failure of the truss members would have preceded failure of the gusset plates in a hypothetical typical collapse.

The bridge underwent a number of repair and modifications during its service life. The reconstructions most significant to the collapse were conducted in 1977 and 1998, and involved increasing the thickness of the concrete deck from 6.5 to 8.5 inches, and the addition of new concrete parapets and guard rails. For those not familiar with the relative weights of the components of a bridge of this type, it is noted here that when the bridge was first opened for traffic, the concrete deck comprised 70% of the total bridge weight (the fact that the weight of the concrete deck is much larger than all of the steel that makes up the bridge is not obvious from the image shown in Figure 1a). Therefore, the concrete added in later years increased the weight of the bridge by more than 20% and thus represented a significant increase in demand on the structural components. In terms of a mental image, the addition of 2.0 inches of concrete to the deck was equivalent to doubling the weight of the steel.
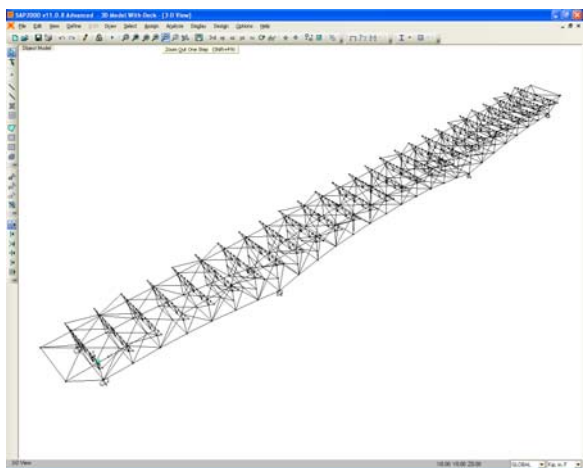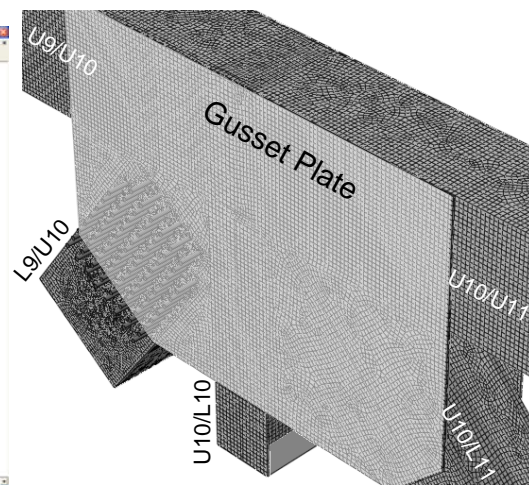
(a)   (b)

Figure 2- (a) Computer structural analysis model of the main span of the bridge; (b) detailed finite element (computer) model of the U10 node.

The first step in the investigation, performed by Tor Oksnevad and Charles DeVore, involved the translation of a large volume of design drawings into the computerized structural analysis model of the bridge shown in Figure 2a. The structural analysis model is referred to as a global model because it includes the main structural components described previously through Figure 1a, but not the finest details of the bridge such as the gusseted connections. At the end of summer 2007, the undergraduate students handed off this mathematical representation of the bridge to Alicia Forbes and Minmao Liao, who used it to calculate the forces produced in all of the main structural components of the bridge in response to different types of loads, including the self-weight of the bridge, the traffic, and the construction material present on the day of the collapse.

The forces calculated using the structural analysis model were applied by Minmao Liao to a refined model (Figure 2b) of the connection referred to on the design drawings as node U10, and also indicated in Figure 1a. This connection involves the infamous gusset plates whose failure we determined to have initiated the bridge collapse. The detailed model is referred to as a finite element model because the connection is represented by a very large but finite number of much smaller volume elements. The mechanical behavior of the connection was determined by solving on the supercomputer housed at the Minnesota Supercomputer Institute a very large system of equations obtained by assembling the equations of each volume element.

Elasticity versus Plasticity

The explanation of why the gusset plate at U10 failed requires an understanding of the concepts of elasticity, plasticity, and the structural design guidelines that were in place when the bridge was built. The simple demonstration involving the bending of a partially uncoiled metallic paper clip, captured in the images shown in Figure 3, illustrates the difference between elastic and plastic behaviors. As the coiled portion of the clip is held tight, pushing the far end of the straight portion produces a deformation that is associated with a rotation about the hinge point labeled *H*. The top three images show that when a relatively small displacement is applied and then removed, the straight portion of the clip springs back to its original position. However if the applied displacement is larger than a critical amount, then the straight portion does not return to its original configuration upon removal of the force. Instead it exhibits a permanent deformation, which is a result of damage of the material in the vicinity of hinge *H*. This damage is referred to as plastic deformation, and it can result in fracture of the paper clip. One way that plastic damage can lead to failure of the paper clip is referred to as plastic collapse, and involves increasing the rotation about the hinge to a point that breaks the paper clip into two pieces. Another way is through so called low cycle fatigue, whereby the clip is subjected to repetitive cycles of counter-clockwise followed by clockwise rotations about the hinge.

When the bridge was built, the design code reflected the philosophy that no component of the bridge should be allowed to experience potentially dangerous plastic deformation. This design paradigm is referred to as allowable stress design, and it demands (and if performed correctly guarantees) that all components will remain elastic under service conditions. The design code also prescribes a safety factor of approximately 2 to each structural component, which means that the gusset plates should be designed to remain elastic even if they are subjected to forces twice those expected.

As explained through the computer analyses described in the next section, for some unknown reason the gusset plates at node U10 were designed incorrectly. In order for them to have remained elastic with an acceptable factor of safety, the design procedures available when the bridge was designed called for the gusset plates at U10 to be 1.0 inch thick. Instead they were ½ inch thick. The results of our analyses showed that the elastic safety factor of the as-constructed gusset plates was approximately equal to 1.0. In other words, addition of forces beyond those in the original design could introduce dangerous plastic deformation into the gusset plates.
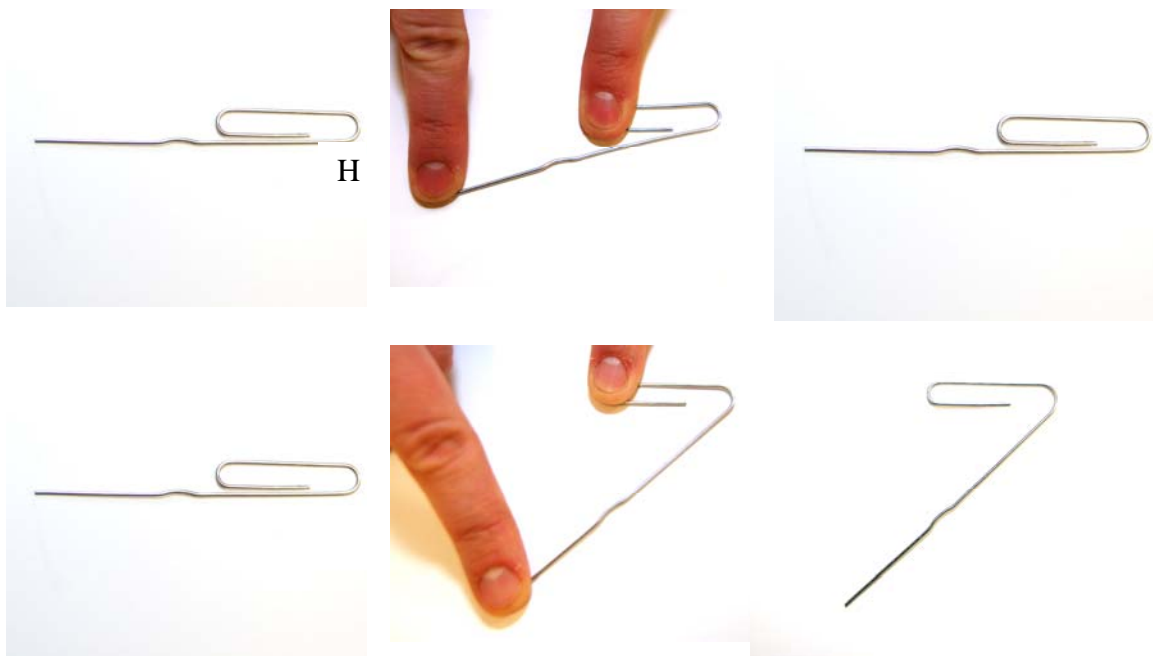
Figure 3- Demonstration of elasticity (top) and plasticity (bottom).

Computer Simulation of Plastic Deformation in Gusset Plates at U10

In this section we demonstrate through computer simulations that just prior to the collapse the demand on the gusset plates at node U10 was essentially equal to their capacity.
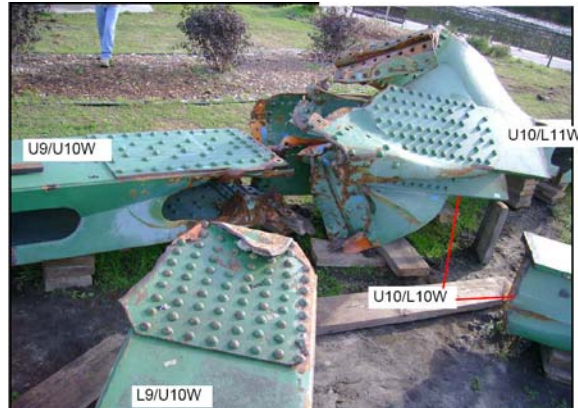
Figure 4- U10 node after bridge collapse from NTSB (*Photos of I-35W Bridge*)

A few days after the collapse the NTSB and MnDOT allowed the authors to visit the site of the bridge collapse. What immediately appeared strange was the fact that some of the connections failed, even though (as mentioned previously) they are supposed to be the strong links in the chain defined by the bridge. The post-collapse image shown in Figure 4 suggests that failure of the connection at node U10 was associated with separation between the chord truss member U9/U10W and the diagonal truss member L9/U10W.

A finite element model of the U10 connection that includes the detailed geometry of the truss members, the gusset plates, and the rivet holes is shown in Figure 2b. Figure 5 presents simplified schematics of the detailed model of the U10 node that show the extent of plastic deformation experienced by the gusset plates as a result of the forces produced by various loadings as calculated by the global structural analysis model. In these drawings the plastic deformation within the gusset plates is shown in black. One should remember that if the gusset plates had been designed correctly, the occurrence of plastic deformation inside the plate would be limited to extremely small regions in the vicinity of sharp geometric discontinuities.

Figure 5a shows that the original weight of the bridge produced forces in the members framing into node U10 in the range of 1,586 kips tension to 1,713 kips compression (1 kip equals 1000 pounds), and that these forces introduced plastic deformation within a small volume within the gusset plate. The condition of the gusset plate is not particularly discernable at this stage.

The addition of 2.0 inches of concrete deck increased the forces in the members by almost 30%, and as shown in Figure 5b this increase extended the plastic deformation across the gusset plate along the top chord. The extent of plastic deformation is beyond what is permitted in allowable stress design. More precisely, these results imply that the

elastic safety factor of the gusset plates at U10 was barely 1.0, while the allowable stress design requires a safety factor of 2.0.

Figure 5c shows the condition produced by adding traffic weight on the day of the bridge collapse. Due to traffic lane closures, the traffic weight was rather light. However, because the gusset plates were substantially yielded under the self-weight of the bridge and the additional concrete, as seen in Figure 5b, even the small load addition produced noticeable extension of plastic deformation. The reason why the extent of plastic deformation increases disproportionately with respect to increased force is because the stiffness of a plasticized steel component is greatly reduced as compared to its elastic stiffness.

The computationally predicted condition of the connection at the instant of bridge collapse is shown in Figure 5d. All load effects, including the self-weight of the bridge, traffic weight, and construction material and equipment placed on the day of bridge collapse, are accounted for. The figure implies that a very substantial portion of the gusset plate was yielded. It is also noted that the pattern of plastic deformation suggests that the gusset plate is approaching a failure corresponding to separations between the horizontal U9/U10W chord and the L9/U10W diagonal, and across the rivet holes on the L9/U10W diagonal. The predicted failure scenario is consistent with the observed failure shown in Figure 4.
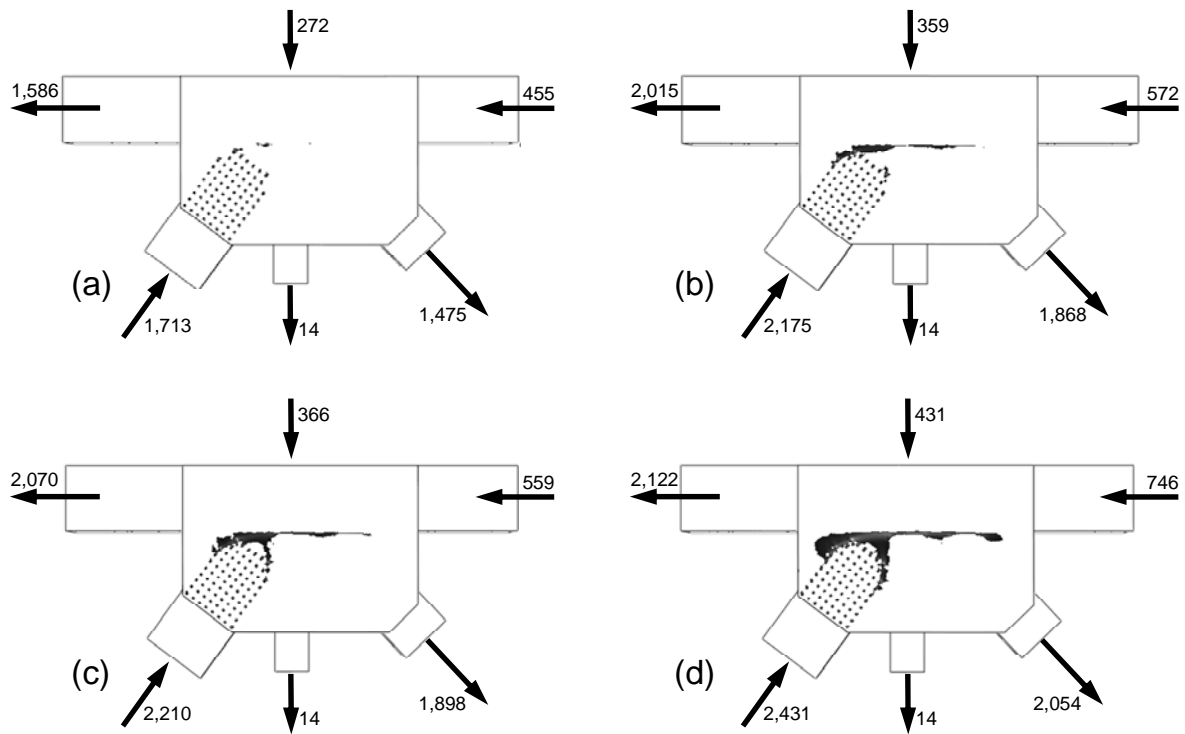
Figure 5- Plastic deformation in gusset plates at U10 resulting from (a) the weight of the bridge at the time of original construction, including all steel and concrete; (b) the addition of 2" of concrete deck in 1977 and 1998; (c) the weight of traffic added; (d) the weight of construction material and equipment added. All forces have units of kips (1000 pounds).

The plot in Figure 6 shows the computed relationship between the compression in the diagonal truss member L9/U10W and contraction of the selected gauge *L*. Two curves are shown, one for the actual U10 gusset plate, and another for a hypothetical gusset plate that is identical to the U10 gusset plate but is 1 inch thick. The four dotted horizontal lines indicate the force levels corresponding to the four stages shown in Figure 5. As the compression was increased from 1,713 kips to 2,431 kips, the response of the ½ inch gusset plate softened. The softening is due to the extension of plastic deformation shown in Figure 5. The curve indicates that the ½ inch thick gusset plate was approaching its capacity limit where the compression in member L9/U10W cannot be increased any further. The capacity limit indicates failure of the gusset plate. Meanwhile, the 1 inch thick gusset plate remains elastic under the forces experienced the day of the collapse; it does not exhibit similar softening behavior. Therefore, Figure 6 indicates that had U10 gusset plates been 1 inch thick instead of ½ inch thick, the tragic bridge collapse would not have happened. We note that the results of this investigation are consistent with those obtained using similar computer modeling by NTSB and WJE. As shown in Figure 6, WJE's prediction of the capacity of the ½ inch gusset plate is practically the same as the capacity predicted by the authors. This figure also shows that WJE predicted that a 7/8 inch thick gusset plate would have had sufficient capacity to resist the forces that existed prior to the collapse.
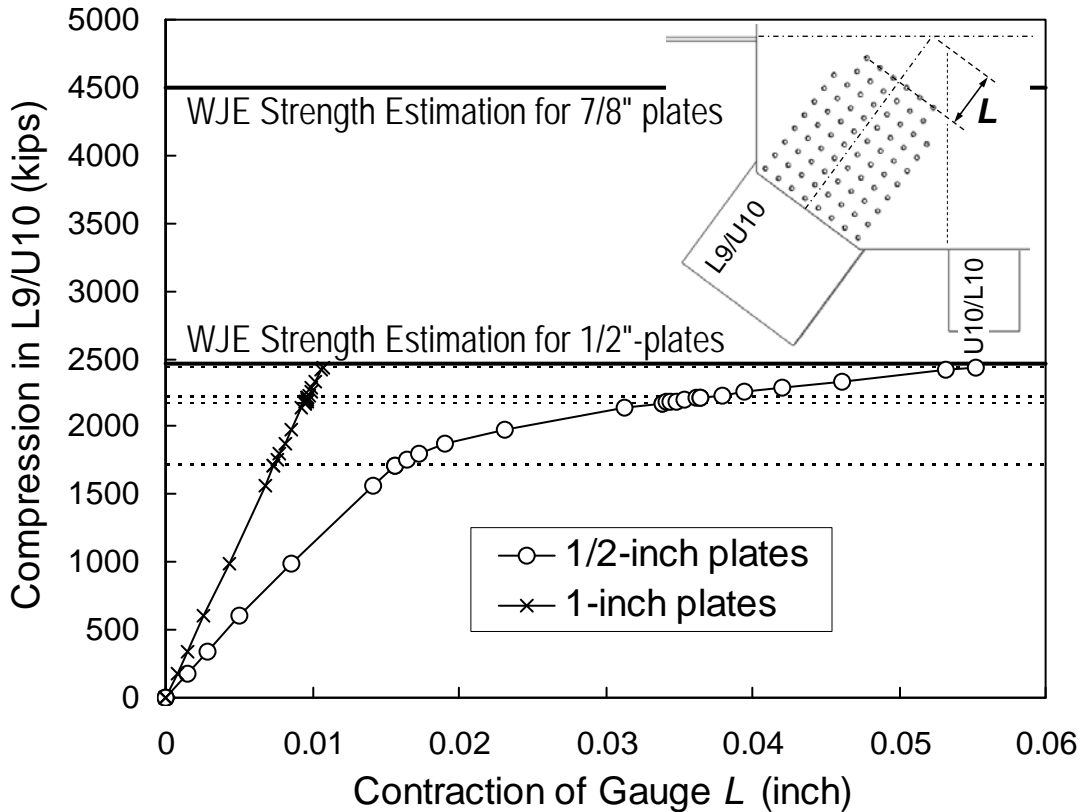
Figure 6- Plot of force in the L9/U10W diagonal versus the compression of a selected gauge length at the U10 node, as predicted by the finite element model for the ½ inch gusset plate and for a 1 inch thick gusset plate. Also shown on the figure are the capacity of the gusset plates at U10 predicted by the finite element model of WJE and the capacity that would have been achieved by a 7/8 inch thick gusset plate.

Conclusions

The results of our academic investigation can be summarized as follows:

1. It was determined using a computerized structural analysis of the I-35W bridge that the members of the main truss had acceptable safety factors when they were designed. The capacity of the truss members was larger than the demands placed on them throughout the life of the bridge, including those on the day of the collapse. While many truss members fractured when they fell to the ground, we are not aware of any evidence that indicates failure of a truss member initiated the collapse.

2. With respect to the design service loads, the elastic safety factor of the gusset plates at nodes U10 was approximately equal to 1.0, instead of the approximate 2.0 required by the design code in 1967. For some unknown reason, these gusset plates were ½ inch instead of 1 inch thick.

3. The bridge collapsed as a result of the failure of the gusset plate(s) at a U10 node, in the vicinity of the L9/U10 compression diagonal. These plates experienced extensive plastic deformation. The calculated capacity of the gusset plates that failed was very close to the demands that were placed on it at the time of the collapse. Had the plates been 1 inch thick, their capacity would have exceeded the demand placed on them, and they would not have experienced any plastic deformation.

4. Temperature cycles could have significantly influenced the forces in the truss members framing into the U10 nodes, and in the stresses experienced by the gusset plates, as could have a number of heavy vehicles passing over the bridge near the time of collapse.

5. The "final straw" was most likely the weight of the construction material placed on the bridge hours before the collapse. The calculations show that the addition of this weight produced a very large region of plastic deformation in the gusset

plates, and rendered a demand on the gusset plates that for all intents and purposes was equal to their capacity.

One of the authors (RB) was recently asked what could be learned from the collapse of the I-35W bridge. The only answer he could think of was "the Devil is in the details."