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# **Peer Review of the National Transportation Safety Board Structural Analysis of the I-35W Bridge Collapse**

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## **ABSTRACT**

The Engineering Sciences Center at Sandia National Laboratories provided an independent peer review of the structural analysis supporting the National Transportation Safety Board investigation of the August 1, 2007 collapse of the I-35W Bridge in Minneapolis. The purpose of the review was to provide an impartial critique of the analysis approach, assumptions, solution techniques, and conclusions. Subsequent to reviewing numerous supporting documents, a SNL team of staff and management visited NTSB to participate in analysis briefings, discussions with investigators, and examination of critical elements of the bridge wreckage. This report summarizes the opinion of the review team that the NTSB analysis effort was appropriate and provides compelling supporting evidence for the NTSB probable cause conclusion.

## **ACKNOWLEDGMENTS**

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## NOMENCLATURE

NTSB	National Transportation Safety Board
FHWA	Federal Highway Administration
SNL	Sandia National Laboratories

# 1. INTRODUCTION

On August 1, 2007, the I-35W Bridge across the Mississippi River in Minneapolis, Minnesota collapsed suddenly, resulting in 13 deaths and 145 injuries. As part of an effort to determine probable cause, the National Transportation Safety Board (NTSB) led a thorough on-site investigation. In addition to examining the recovered wreckage, they conducted an extensive review of design files, historic inspection reports, eye witness accounts, and available photographic evidence.

Review of the evidence led to the identification of the likely initiation points for the collapse. Based on this knowledge, NTSB, in conjunction with the Federal Highway Administration (FHWA), commissioned a subsequent analysis effort to examine the stress and deformation of critical structural elements under the reconstructed loading conditions at the time of collapse. The analysis also provided insight into the influence of possible structural abnormalities identified in pre-collapse photographic evidence. A detailed report of the analysis effort is available [Ref. 1].

The NTSB requested Sandia National Laboratories (SNL) to conduct an impartial peer review of the structural analysis. The purpose of the peer review was to provide an independent opinion of the quality and validity of the methods, approach, and conclusions drawn. To fulfill its mission for the National Nuclear Security Administration stockpile stewardship program, SNL maintains a diverse technical workforce including staff skilled in high deformation structural mechanics that are characteristic of accident scenarios. The SNL review team comprised two senior staff members from the Engineering Sciences Center with expertise in the development and application of computational methods for structural collapse and material failure. A SNL line manager responsible for external engagements on structural mechanics also participated.

After initially reviewing numerous records associated with the investigation, the Sandia team visited the NTSB Training Center in Washington, DC on July 23, 2008. The team examined critical elements of the wreckage and was briefed in depth on the analysis approach, results, and conclusions. Follow-up discussions between the investigators and the review team helped to clarify critical aspects of the collapse analysis. As summarized below, it is the opinion of the review team that the NTSB analysis effort was complete, and conclusions concerning the likely cause of collapse are appropriate.

## **2. DEFINITION OF THE ANALYSIS PROBLEM**

Photographs of the bridge wreckage show extensive damage to several sections as a consequence of the progressive collapse [Ref. 2]. The on-site investigation conducted by NTSB helped to focus attention on the center span of the bridge between piers 6 and 7 as the origin of the collapse. Specifically, the evidence summarized briefly below was used to appropriately focus the analysis effort on the connections identified as U10 and L11.

### **2.1 Physical Evidence**

The video taken by the security camera at the lock on the west side of the bridge indicates the failure event initiated to the south of joint U12 [Ref. 3]. Joint L11 West was just visible in the camera's field of view while L11 East was not visible. Neither of the U10 East or West joints was visible in the video of the collapse. Previous field studies captured photographic evidence of severe out-of-plane deformation (bowing) of the U10 gusset plates, and inspection reports documented corrosion in the L11 gusset plates. Forensic evidence (location of the final resting place, final deformed shape, and tearing patterns of the failed truss components) was collected and indicated the U10 joint as the likely failure initiation location.

### **2.2 Review of Original Bridge Design**

The design calculations conducted by FHWA [Ref. 4] showed that the gusset plates at L11 and U10 had inadequate thickness, even by design procedures applicable during the 1960's, at the time the bridge was built. In addition, the free edge length to thickness ratio of the U10 gusset plate was sufficiently large to have required edge stiffening according to code, but no such stiffening existed. Subsequent modification of the bridge, including increasing the deck thickness and addition of median barriers, significantly increased the dead load, further emphasizing the inadequacy of these designs.

### **2.3 Material Inspection**

Tensile and hardness testing [Ref. 1] of samples extracted from the U10 gusset plate and rivets did not indicate any mechanical properties anomalies. The tensile tests of the gusset plate material provided high quality mechanical properties data suitable for non-linear analysis. Corrosion of L11 was noted and used in subsequent analyses

### **2.4 Sequencing Study**

The sequencing report is a compilation of available data into a chronological description of the collapse scenario [Ref. 5]. The review team feels that the focus on the U10/L11 joint locations by the NTSB staff is a logical conclusion of the evidence as supported in the sequencing report. Focusing the subsequent analysis effort on these joints represents prudent engineering judgment.



### **3. STRUCTURAL ANALYSIS**

NTSB commissioned a computational analysis effort to better understand the stress and deformation states of the U10 and L11 joints at the time of the collapse. The effort enabled further examination of the adequacy of the joint designs and the influence of known imperfections such as corrosion and bowing of the gusset plates. Most importantly, it addressed the question of whether the loads known to be present at the time of collapse were, within uncertainty bounds, sufficient to cause geometric instability in these joints, a precursor to collapse of the center span. Photographic evidence indicates that prior to collapse the gusset plate at U10 had out-of-plane deformation on the order of the plate thickness. This is a problematic situation for a gusset plate, as the design methodology only accounts for in-plane behavior. This bowing of the plate edge is important to the determination of the bridge collapse.

The Sandia review of the NTSB analysis effort focused on the approach and methodology of the bridge collapse determination. This review assessed the appropriateness of the work completed by the NTSB staff and whether the engineering approach is prudent to support the conclusions. Summary comments concerning the analysis approach, inputs, and results interpretation are provided below.

#### **3.1 Modeling Approach**

The finite element analyses of the truss section of the bridge comprised two types: a beam model, and secondly this beam model enhanced with localized, embedded detail models of the U10 and L11 joints employing shell/continuum elements. A nonlinear analysis using the Riks algorithm was used to identify stable configurations in response to the applied loads. Failure to converge to a solution using this approach is indicative of a geometric instability of the joint, a precursor to likely structural failure. The instability or capacity determination showed no significant sensitivity to analysis options, including element type, hourglass mode control, and mesh refinement, providing confidence that there were no unidentified numerical issues [Ref. 6].

The photographs of the U10 gusset plate bowing were very beneficial to the analysis effort [Ref. 7]. Purely geometric representations (zero initial stress) were incorporated into the model to assess the potential for weakening of the joint. It should be noted that there is no photographic evidence of the L11 gusset to suggest the presence of bowing, so none was included in the model. L11 did show evidence of corrosion as reported in prior inspection reports. The presence of corrosion in the L11 gusset plate was addressed in the modeling through thinning of the plate definition [Ref. 8]. The distributed thickness was based on measurements of the deformed plate recovered from the wreckage.

#### **3.2 Loads and Boundary Conditions**

Both models used very detailed and thoroughly researched load definitions [Ref. 9]. The level of uncertainty in the loading definitions was reduced to a very acceptable engineering level. Cores were taken and tested to define the thickness and density of the bridge deck. Recovered vehicles were weighed and their likely locations were determined from their final resting place and eyewitness accounts. The weights of the concrete barriers for the center median were calculated based on known volume and density. Aerial photographs taken prior to the collapse combined with delivery information provided the weight and location of the construction materials. These

construction materials represent the largest source of variability in loading, and NTSB staff have adequately researched and identified these loads and their variability. All loads were appropriately placed on the bridge model regarding both magnitude and location. Boundary conditions used for both model types are appropriate for the representation of the bridge and were verified by early dynamic testing conducted by the University of Minnesota [Ref. 10].

### **3.3 Material Properties**

Material properties definitions used in both models were based on physical cores and material testing of the components, providing an accurate material behavior definition for the analyses. The translation of the mechanical properties of the gusset plate steel from engineering-stress, engineering-strain (typical result from tensile testing) to Cauchy-stress, logarithmic-strain (suitable for input to a large deformation finite element analysis) was appropriately performed [Ref. 11].

## 4. ANALYSIS RESULTS

The analysis review team agrees with the finding by the NTSB investigators that the initiation of the bridge collapse likely occurred at the U10 gusset plate. The geometric bowing of the gusset plate reduced the capacity compared to the undeformed joint, bringing it to within a reasonable estimate of the load at the time of collapse. The analyses also showed that without the initial bowing of the 0.5 inch gusset plate, the capacity of the bridge was greater than the loads present at the time of the collapse, illustrating the importance of this initial imperfection. Support of the free-edge as defined by code would have been beneficial to the stability of this under-designed joint. When analyzed using 1 inch thick gusset plates without stiffening (code allowable design) the capacity of this joint far exceeded the load present on the bridge.

It is fundamental to note that this collapse is a geometrically induced failure, not a tensile material failure. This is why the state of strain in the gusset plate was below the failure strain in all of the analyses presented by the NTSB (4% plastic strain vs. >20% failure strain). The sensitivity of the bridge capacity to out-of-plane gusset bowing is direct – as the bowing approaches the plate thickness the capacity drops. The failure scenario is initiated by out-of-plane or lateral displacement of the gusset – this lateral displacement requires a moment in the gusset plate to maintain the joint stability. When the moment capacity of the plate is exceeded the joint becomes unstable, forming a plastic hinge in the gusset plate, subsequently tearing from the rivet line as the plastic hinge progresses down the length of the plate. At the point of instability, the analysis code could no longer find an equilibrium state for the structure. The analysis of the post-instability failure sequence is very difficult, and unnecessary to the conclusions of this investigation, as the plastic hinge capacity is greatly exceeded by the load requirement.

The effect of the corrosion in the L11 gusset plate was included in several analyses. Analyses that included the corroded L11 gusset plate without the bowing in the U10 plate showed greater load capacity than that of the bowed U10 gusset plate alone [Ref. 10]. In all cases addressed, the deformations in the L11 joint were lower than those recorded by U10. Combined with the video evidence that shows that L11W maintained its integrity as the center span approached the water, the analysis supports the bowed U10 joint as the weakest link.

## **5. CONCLUSION**

At the request of the NTSB, a team of structural mechanics engineers from Sandia National Laboratories reviewed the analysis supporting the investigation of the collapse of the I-35W Bridge in Minneapolis, Minnesota. Based on extensive review of the analysis effort including background investigative details and supporting documentation, it is the opinion of the review team that the NTSB analysis was conducted thoroughly and that the conclusions drawn supporting the probable cause of collapse are appropriate. Analysis results support the conclusion that the capacity of the under-designed U10 joint was reduced by the presence of bowing in the gusset plates, making it the likely point of collapse initiation.

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