

Failure Analysis of Minneapolis I-35W Bridge Gusset Plates

Acknowledgement

The structural analyses contained in this report were carried out under the direction of the National Transportation Safety Board Modeling Group with the participation of Professor Toshio Nakamura through an external contract with the State University of New York at Stony Brook. Added resources and expertise were acquired through a subcontract with Dassault Systèmes Simulia Corporation for assistance with the Abaqus finite element software used for the structural analyses. Parallel investigations undertaken by the Federal Highway Administration (FHWA) Turner-Fairbank Highway Research Center (TFHRC) in collaboration with this effort are documented in a separate report. The finite element analyses in this report relied on global models of the bridge that were constructed at the FHWA TFHRC and made available to the Modeling Group. The analyses were performed and the results reported with full oversight and approval of the National Transportation Safety Board Modeling Group. The complete and final report on the finite element modeling activity is available at: <http://www.nts.gov/dockets/Highway/HWY07MH024/405446.pdf>

Summary

On August 1, 2007, the I-35W highway bridge over the Mississippi river in Minneapolis, MN collapsed. The subsequent National Transportation Safety Board (NTSB) investigation identified the U10W truss node as a likely initiation site for the failure. (Bridge main truss nodes were numbered from the south starting at 0. U indicates a node along the upper chord, and L indicates a node along the lower chord. E and W indicate a node on the east or west truss) [1, 2, 3].

Finite element analyses were performed to study the states of stress and strain in the gusset plates of the U10W joints, and to investigate potential instability in the bridge structure. A global-local approach was taken, in which a detailed three-dimensional U10W local model was embedded into the global bridge model provided by FHWA [1, 2, 3, 4].

As reported in [2], “the finite element computations indicated the bridge failure was initiated by a local structural instability before any localized material failure occurred. Additionally, the computations indicate that the structural instability that triggered the bridge collapse was a local bending instability in the U10W gusset plates.”

In this Technology Brief, the use of Abaqus in the investigation of the collapse of the I-35W bridge is outlined.



Key Abaqus Features and Benefits

- Riks method for the analysis of unstable, geometrically nonlinear structural collapse
- Ability to include stress-free geometric imperfections in a structure
- Submodeling capability for the study of a local part of a model with a refined mesh based on interpolating the solution from a global model
- Wide variety of kinematic constraints, including:
 - Shell-to-solid coupling
 - Mesh-independent fasteners
 - Kinematic coupling

Background

The I-35W bridge in Minneapolis was 1,907 feet long, with fourteen spans supported on thirteen piers carrying four lanes of traffic in each direction. The central 1,064 foot long deck truss portion of the bridge crossed the Mississippi river, and consisted of two parallel Warren-type trusses with verticals [1]. Each main truss had 56 connection points (nodes), where the vertical, horizontal, and diagonal members were joined with riveted gusset plates.

As part of studies and evaluations of the bridge during its working life, photographs of the east and west U10 nodes were taken in 1999 and 2003. While reviewing these photographs as part of the collapse investigation it was noted by the NTSB that all four gusset plates in the east and west U10 nodes showed visible ‘bowing,’ or out-of-plane displacement. This displacement was on the

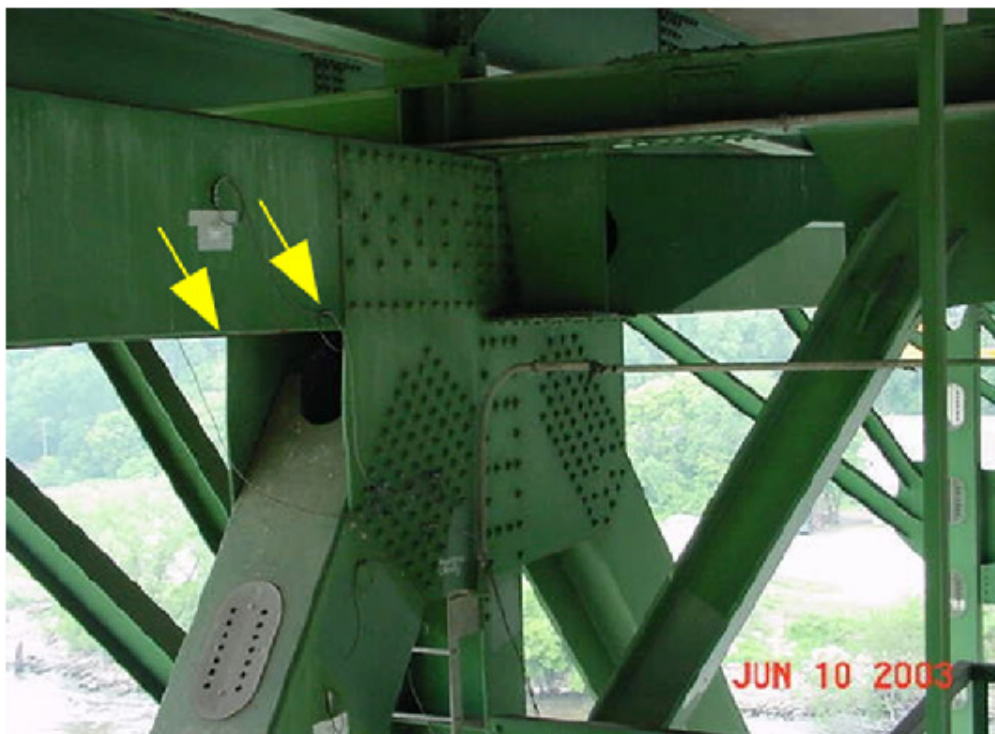


Figure 1: Bowed gusset plates observed at the U10W joint on the actual bridge [2]

order of the gusset plate thickness. The degree of bowing recorded in the U10W node is shown in Figure 1.

After the collapse, the FHWA assessed the adequacy of the gusset plates [6]. Using methodologies consistent with those in use at the time the bridge was designed, it was shown that the gusset plates at the U10 and L11 nodes were only half as thick as necessary to meet their design requirements. The NTSB concluded that the gusset plate inadequacy was the result of an error by the original bridge design firm, which failed to perform all of the calculations necessary to properly design the gusset plates.

Post-collapse 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 nodes as the likely failure initiation location [5]. However, corrosion observed on the L11 gusset plates was an alternative cause of failure that also required investigation.

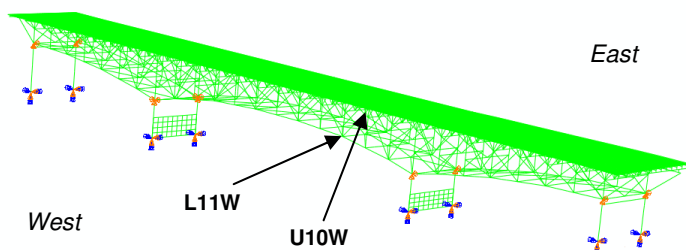


Figure 2: FHWA three-dimensional global model of deck truss portion of I-35W bridge

The subsequent finite element modeling effort thus focused on the detailed analysis of the U10 and L11 nodes.

Finite Element Analysis Approach

Finite element analyses were performed to study the stress and strain in the gusset plates of the U10W and L11W joints and investigate potential instability in the bridge structure. This was achieved by embedding detailed three-dimensional local models of the aforementioned joints into the global structural element bridge model provided by FHWA [1, 2, 3, 4]. Figure 2 displays the global model, while Figure 3 displays the detailed local models embedded in the global model. The local models used solid elements in the area of concern and shell ele-

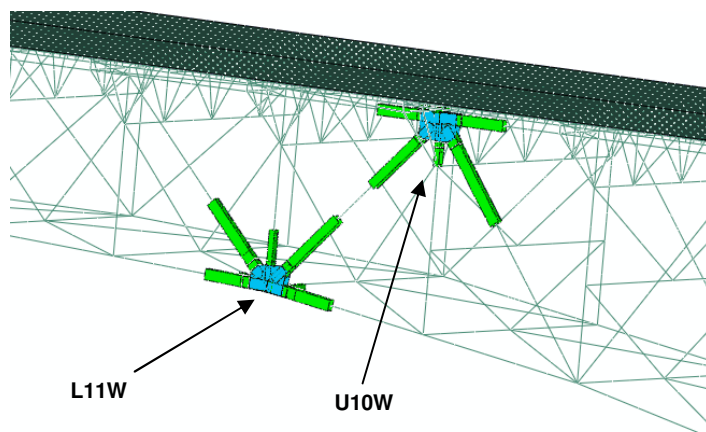


Figure 3: Detailed local models of joints U10W and L11W embedded in the global model

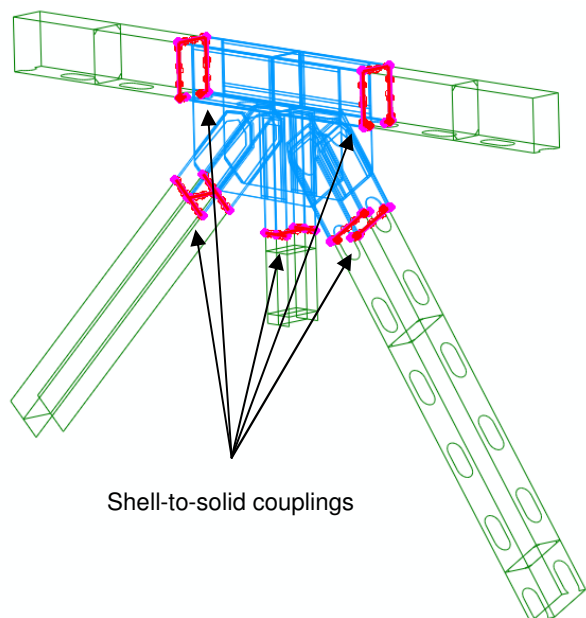


Figure 4: Shell-to-solid couplings used in local three-dimensional model of U10W joint. Shell region is shown in green, solid region is shown in blue.

ments for other components, while the global model consisted of beam, shell, spring, and connector elements.

The models were based on the original bridge design plans and shop drawings; further, the model also reflected the various modifications the bridge had undergone [1]. Material properties were measured from undamaged portions of the gusset plates and truss members recovered from the wreckage.

The loading history was applied in multiple steps to simulate the original bridge design weight, additional concrete weight, traffic loads and construction loads. Concrete was modeled using the “model change” feature. Wet concrete was simulated first by using concentrated loads to represent the weight (without stiffness) prior to curing; the wet concrete load was subsequently replaced with the weight and stiffness of hardened concrete represented by shell elements.

The global and local models were joined using tie constraints and kinematic couplings. Beam element nodes from the global model were tied to reference points of the local model at the transitions. The reference points were then kinematically coupled to appropriate nodes in the detailed local model. The tie capability constrains the slave node to have the same motion as the master node, while the kinematic coupling constrains the motion of a group of nodes to the rigid body motion of a single node.

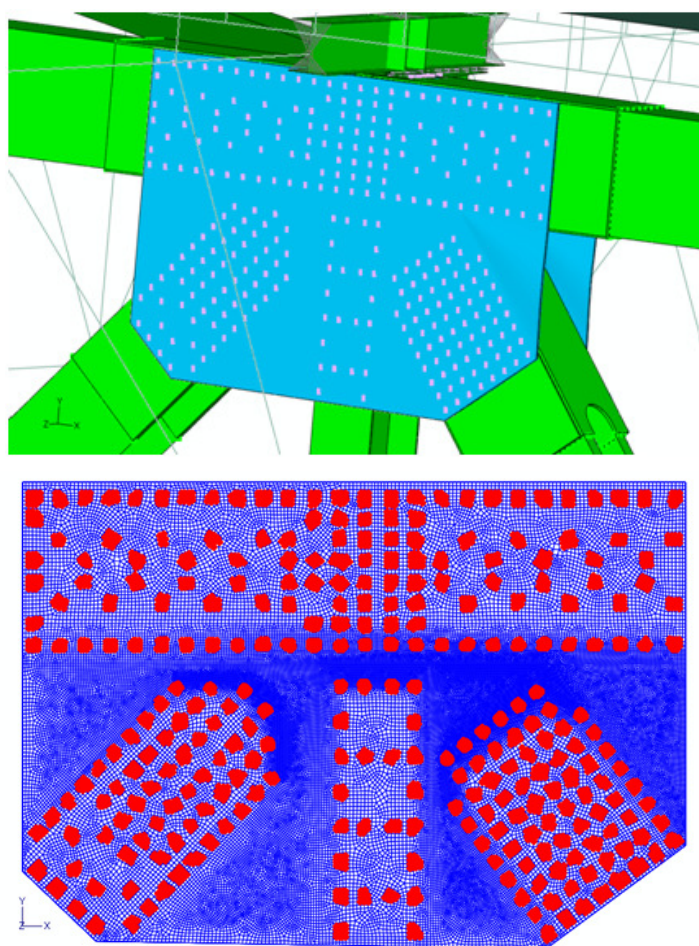
Since the detailed local models used both shell and solid elements, shell-to-solid couplings were used to transition from shell elements to solid elements. Each internal constraint of the shell-to-solid coupling distributes the forces and moments acting at its shell node as forces acting on

the related set of coupling surface nodes on the solid elements. The shell-to-solid coupling locations used in the U10W joint are shown in Figure 4.

Mesh-independent fasteners were used to represent rivets that joined the gusset plates and trusses. Fasteners were located at actual rivet positions, as shown in Figure 5a. The mesh-independent fastener defines a point-to-point connection between two or more surfaces. The attachment to each of the parts is distributed to several nodes on the mating surfaces in the neighborhood of the attachment points. The fastened nodes are highlighted in Figure 5b.

Small-sliding contact pairs were defined between the gusset surfaces and the truss members using surface-to-surface contact discretization.

In the actual bridge, bowed gusset plates were observed by NTSB at the U10W joint as shown in Figure 1. To simulate the deformed gusset plates, an initial imperfection was introduced in the model. The stress-free imperfection was defined by specifying the node number and imperfection values directly.



Figures 5a and 5b: Location of rivet positions (top), and meshed gusset plate with fastened nodes highlighted in red (bottom)

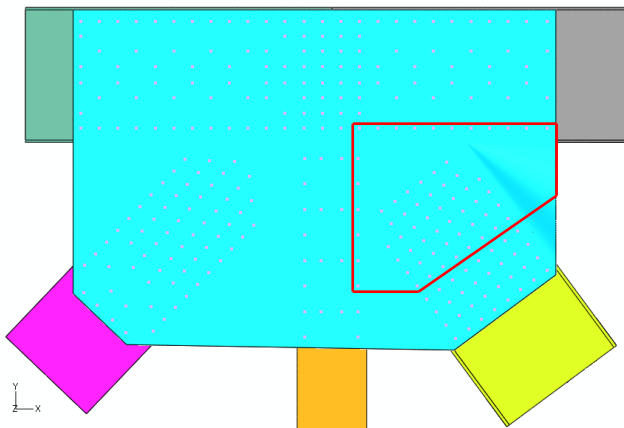


Figure 6: Submodel region of U10W joint, outlined in red

The Riks analysis method was used to investigate the unstable bending behavior of the gusset plates. With this approach, loads and displacements are solved simultaneously using an arc length formulation. This procedure provides solutions even if the response is geometrically unstable, and was necessary in this case to provide insight into the behavior near collapse.

Submodeling was used to study a portion of the local model in even more detail. The region of interest is shown in Figure 6. The global model solution was used to drive the submodel at the submodel cut planes. Two rivets in the high stress location were modeled in detail with solid

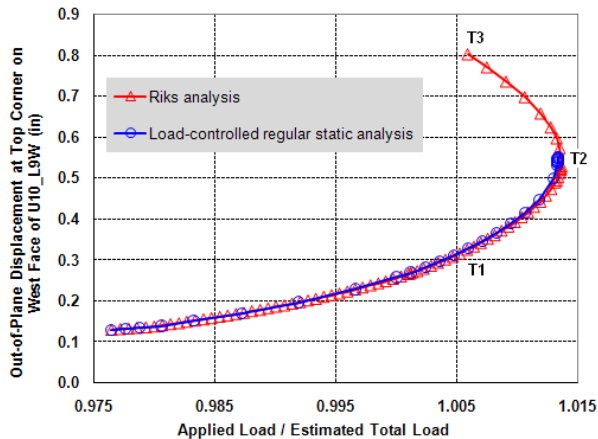


Figure 8: Bridge load-displacement behavior at instability

elements and contact pairs while the rest of the rivets were included as mesh-independent fasteners.

Results

We present a representative sample of the large body of results typical of an investigation of this nature. Mises stress in the U10W joint is shown in Figure 7, where it is clear that the highest value occurs in the gusset plate.

The utility of the Riks method is highlighted in Figure 8, which displays the total load being carried when the bridge finite element model reaches the point of unstable bending in the gusset plates (point T2). The results of a

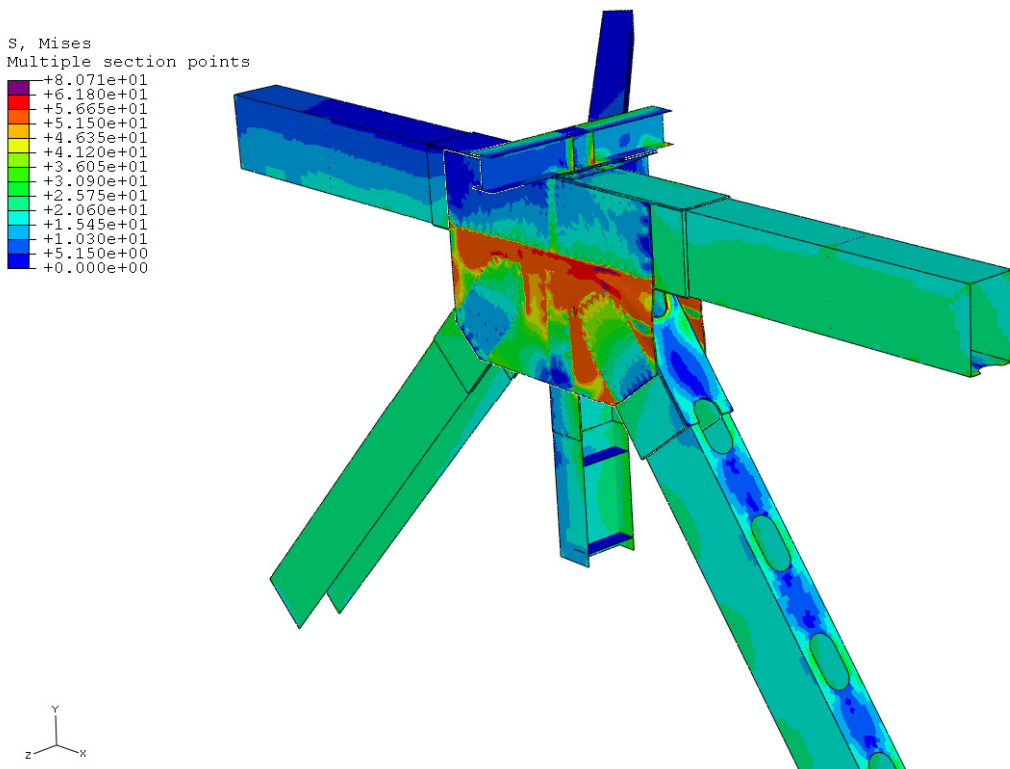


Figure 7: Mises stress in the U10W joint

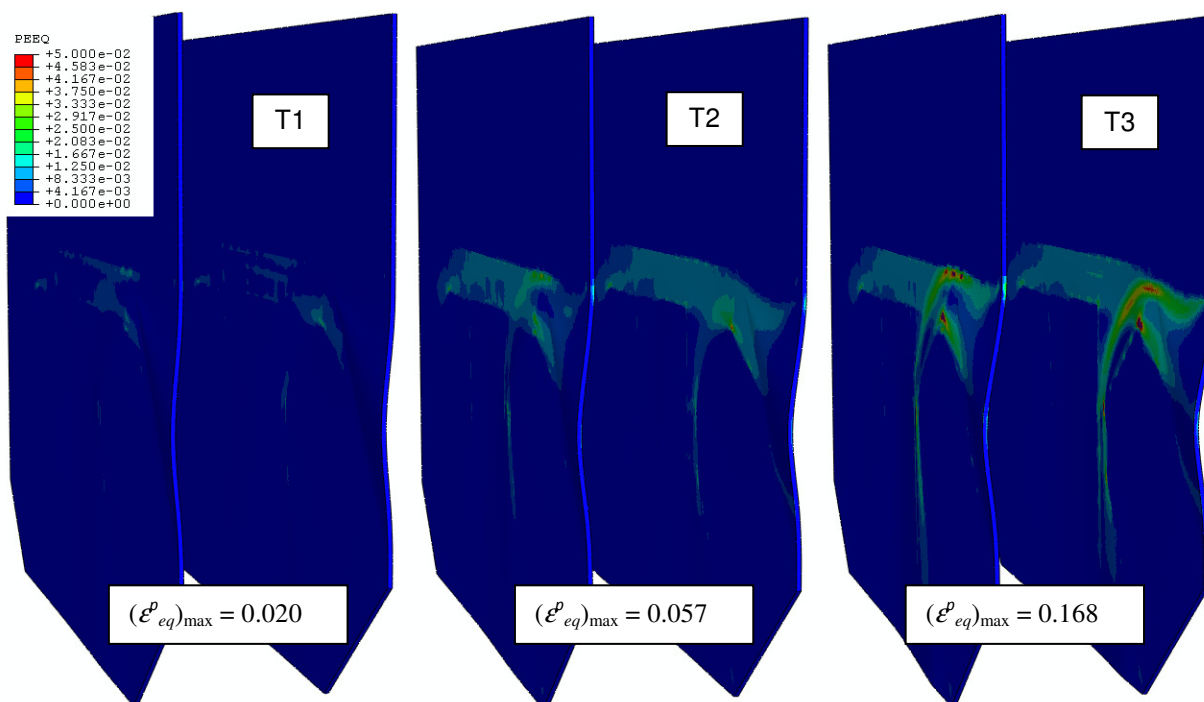


Figure 9: Equivalent plastic strain in the U10W gusset plates through the load history of Figure 8

regular load control analysis are also included. Beyond T2, the Riks method predicts that the load must decrease to maintain equilibrium; the load control analysis cannot proceed further because the structure is softening. Figure 9 shows the equivalent plastic strain in the U10W gusset plates at points T1, T2, and T3 of Figure 8, and shows that the strain continues to increase while the load decreases.

Figure 10 displays the Mises stress in the submodel rivets. Gusset plate equivalent plastic strain results from the submodel are shown in Figure 11. The maximum Mises stress and equivalent plastic strain occurred on the edge of the rivet hole at the top corner.

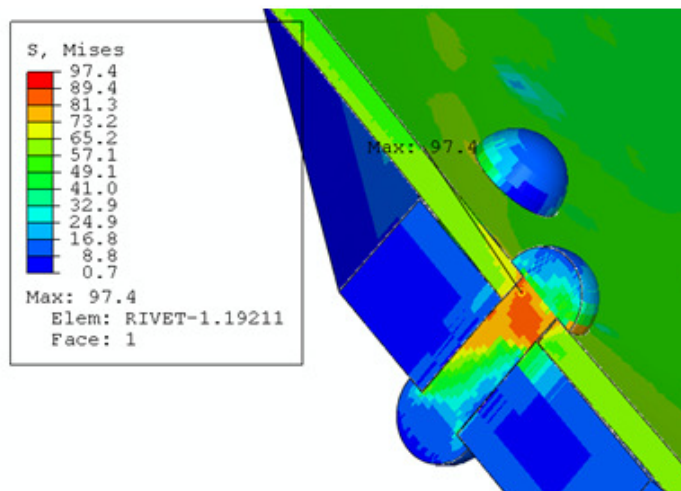


Figure 10: Mises stress results in the submodel rivets

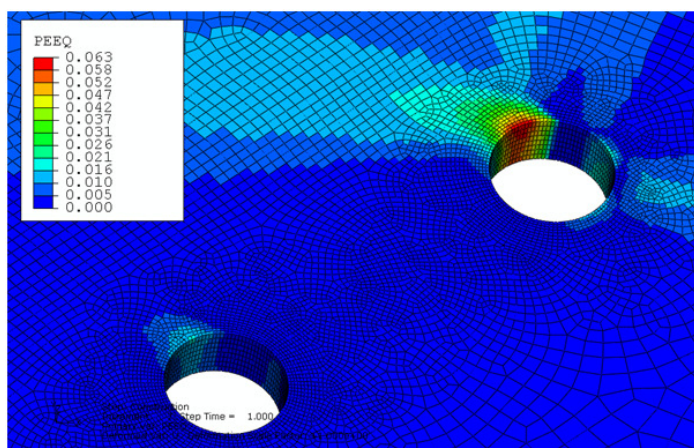


Figure 11: Gusset plate submodel equivalent plastic strain results

Conclusion

As part of an extensive post failure study, Abaqus/Standard was used to investigate the potentially unstable behavior of the I-35W highway bridge in Minneapolis, MN. Using many of the nonlinear modeling capabilities, the analyses predicted that the collapse of the bridge was initiated by a bending instability in the U10W gusset plates.

The ability to efficiently model the bridge span in its entirety while obtaining detailed results in critical areas, to simulate the entire loading history leading to failure, and to capture the highly nonlinear behavior of the unstable bending event provided investigators with a powerful tool to understand the factors that contributed to the collapse.

References

1. "Collapse of I-35W Highway Bridge, Minneapolis, Minnesota August 1, 2007," Highway Accident Report NTSB/HAR-08/03 PB2008-916203, National Transportation Safety Board, Washington, D.C., November 14, 2008.
2. "Structural and Local Failure Study of Gusset Plate in Minneapolis Bridge Collapse," Modeling Group Contractor Final Report, National Transportation Safety Board, Washington, D.C., November 12, 2008.
3. "Structural and Local Failure Study of Gusset Plate in Minneapolis Bridge Collapse," Modeling Group Contractor Interim Report, National Transportation Safety Board, Washington, D.C., February 14, 2008.
4. Ocel, J.M., and Wright, W.J., "Finite element Modeling of I-35W Bridge Collapse Final Report," Federal Highway Administration Turner-Fairbank Highway Research Center Report, October 2008.
5. Gwinn, K.W., Wellman, G.W, and Redmond, J.M., "Peer Review of the National Transportation Safety Board Structural Analysis of the I-35W Bridge Collapse," Sandia National Laboratories Report, October 2008.
6. Holt, R. and Hartmann, J., "Adequacy of the U10 Gusset Plate Design for the Minnesota Bridge No. 9340 (I-35W over the Mississippi River), Final Report," Federal Highway Administration Turner-Fairbank Highway Research Center Report, October 2008.

All of the reports regarding the accident, including those cited in this document, can be found on the NTSB website at www.nts.gov/dockets/Highway/HWY07MH024

Abaqus References

For additional information on the Abaqus capabilities referred to in this brief, please see the following Abaqus Version 6.13 documentation references:

- Analysis User's Guide
 - 'Unstable collapse and postbuckling analysis,' Section 6.2.4
 - 'Element and contact pair removal/reactivation,' Section 11.2.1
 - 'Introducing a geometric imperfection into a model,' Section 11.3.1
 - 'Connector elements,' Section 31.1.2
 - 'Coupling constraints,' Section 35.3.2
 - 'Shell-to-solid coupling,' Section 35.3.3
 - 'Mesh-independent fasteners,' Section 35.3.4
 - 'Defining contact pairs in Abaqus/Standard,' Section 36.3.1

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