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PROGRESSIVE COLLAPSE OF STEEL TRUSS BRIDGES, THE CASE OF I-35W COLLAPSE

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Abstract: Steel deck truss bridges, being determinate systems and not having redundancy, can progressively collapse over the entire span, if a single primary member or gusset plate connection of the main trusses fails. One of the recent tragic examples of such progressive collapse of the entire bridge due to loss of a single gusset plate is the case of I-35W steel deck truss bridge located in the city of Minneapolis in United States which collapsed entirely on August 1, 2007 resulting in deaths of 13 people and injury to more than 100 others. This paper presents a summary of the structure of the bridge, the condition of the bridge prior to collapse, a likely scenario for its progressive collapse and provides lessons learned and design recommendation in the conclusion section. The recommendations can be used in design of new and in the retrofit of existing steel truss bridges to mitigate this serious life safety hazard.

1. INTRODUCTION

On August 1, 2007 at 6:05PM, in a relatively warm evening, the 40 years old I-35W steel deck truss bridge over the Mississippi River in Minneapolis, Fig. 1, suddenly and without almost any noticeable warning collapsed entirely into the river, Fig. 2, causing the deaths of 13 people and injury to more than 100 others who were crossing the bridge in their vehicles at the time of the collapse.

Fig. 1: A vew of the I-35W bridge looking northeast

The bridge had eight lanes of mixed cars and trucks traffic and was on the Interstate highway 35 west thus designated as I-35W. In 1967, when the bridge opened, it had striping that provided for two lanes of traffic in each direction with a third outside lane for acceleration/deceleration. By 1988 the bridge had been re-striped and a third lane of traffic had been added in each direction making the number of lanes equal to four in each direction. The average daily traffic on the bridge was about 140,000 mixed traffic prior to collapse.

At the time of collapse the PSA construction company was working on the deck repairing and replacing the expansion joints on the deck as well as removing parts of the deck and replacing them with new concrete. Before the collapse four of the eight lanes on the bridge were closed to regular traffic and were used for construction work and storage of construction material and equipment.

Photo:National Transportation Safety Board Release

Fig. 2: Views of the collapsed I-35W bridge

2. THE STRUCTURE OF THE I-35W BRIDGE

Fig. 3 shows the structure of the I-35W Bridge [1]. The superstructure of the bridge consisted of two main longitudinal trusses continuous over three spans of 81m, 139m and 81m. The two longitudinal trusses were connected to each other with transverse trusses at each panel point, Fig. 3. The transverse trusses were cantilevered out on both east and west side of the bridge with each cantilever providing one lane of traffic. There were eight lanes of traffic on the bridge with 6 lanes between the main trusses and two lanes, one on each cantilever. The transverse trusses supported floor longitudinal stringers, which in turn were supporting the reinforced concrete deck of the bridge.

The deck initially had a thickness of about 16.5cm, but during the 1977-1998 reconstruction an additional 5 cm wearing surface was added to the roadway making the total thickness of the roadway deck 22cm. The ends of the longitudinal stringers had dense placement of shear studs making the longitudinal stringers somewhat composite with the reinforced concrete deck.

The material of the steel for the main members and gusset plates of main trusses was specified to be equivalent of today's ASTM A242 corrosion resistant steel. The connections in the steel superstructure were shop-riveted, field bolted. The steel members of the truss superstructure were primarily perforated welded steel box sections for heavily loaded members and built-up welded I-shaped sections for the lighter ones. The bridge had two major expansion

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joints at the ends of the main trusses, Fig. 3. It also had deck expansion joints at locations of each truss panel points.

The connections in the main trusses were double gusset plate shop-riveted and field-bolted. Fig. 4 shows a sample of gusset plate details for the bridge. The detail is for the gusset plates U10, which at this time are believed to be the gusset plates that fractured on August 1, 2007 through their net section and initiated the progressive collapse of the entire I-35W bridge.

The bridge had lateral bracing under the deck plane as well as in the plane of the two bottom chords of the main trusses. The specification used in the original design was 1961 and 1962 editions of the Division I Specification published by the American Association of State Highway Officials [2].

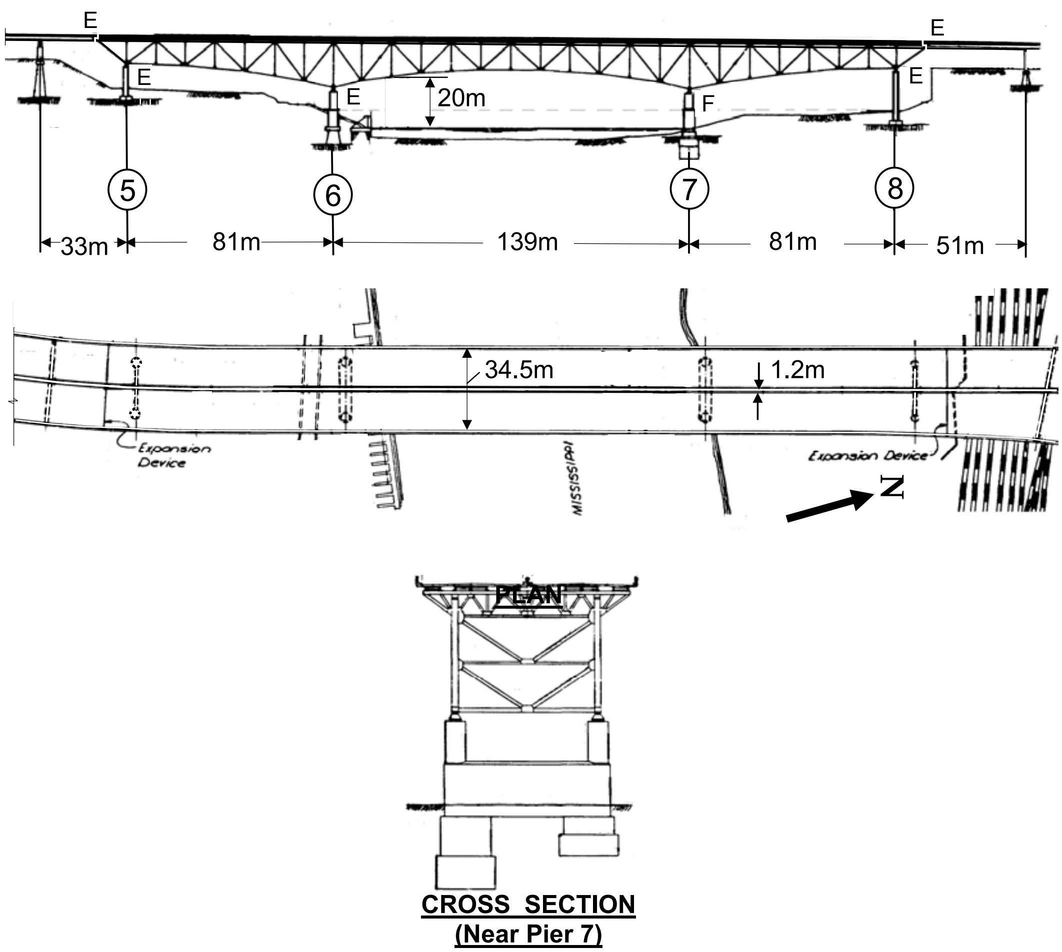

Fig. 3: Structure of the I-35W bridge [1]

The approach structures consisted of reinforced concrete double-column bents supporting a total of 14 longitudinal steel stringers, which in turn were supporting the reinforced concrete deck. The north approach structure had six spans with a length of 9 m to 51 m. The south approach structure consisted of 5 spans, 16 m to 33m in length.

The substructure of the bridge consisted of reinforced concrete round piers supported on the reinforced concrete footings. The footings of the main span and most of the approach spans were supported on the rock. A few foundations of approach spans were supported on 10BP42 steel H piles.

3. CONDITION OF THE BRIDGE PRIOR TO COLLAPSE

3.1 Design Error in the Original Design

Fig. 4 shows gusset plate U10, which is the gusset plate believed to have fractured first and started progressive collapse of the bridge [astaneh], [NTSB]. The bridge was originally designed by Sverdrup & Parcel in 1965 using AASHO Specification 1961 [2].

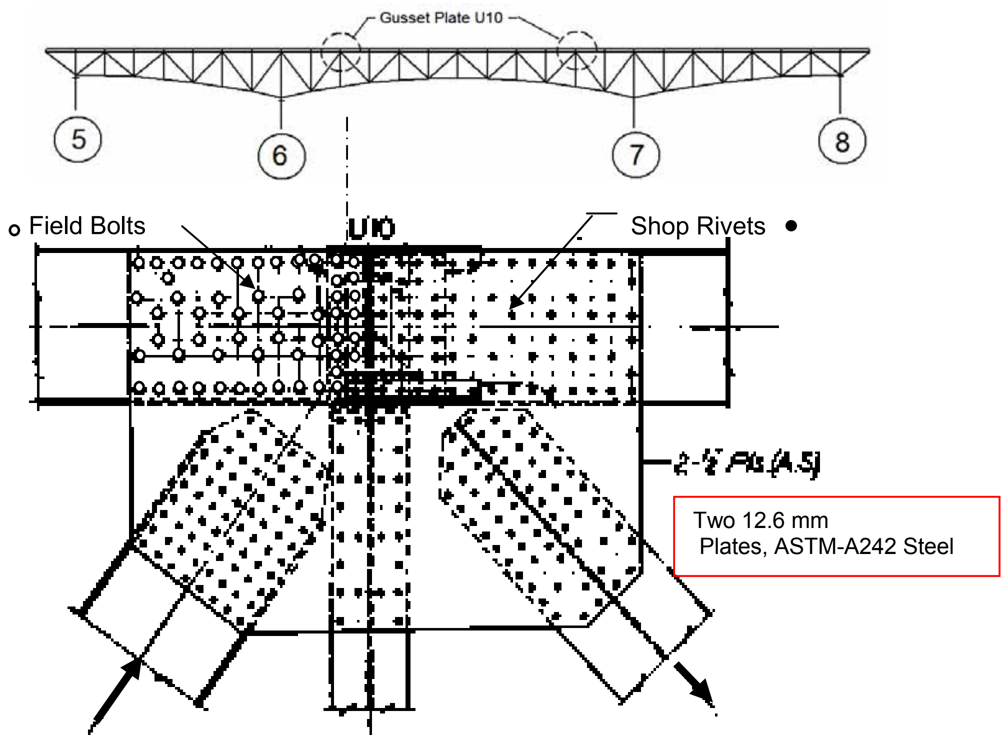

Fig. 4: Details of gusset plate U10 of the I-35W bridge [1]

On August 8, 2007, a week after the collapse the author, while studying the structural drawings of the I-35W bridge posted on the web site of the Minnesota Department of Transportation, [1] discovered that the thickness of gusset plate U10 is only ½ inch (26mm), see Fig.4, much less than what would be needed by design according to the governing specification [2] He was quoted in the press [3] at the time that:

> *Abolhassan Astaneh-Asl, a structural engineer at the University of California-Berkeley who specializes in steel and composite bridges and buildings, said he analyzed blueprints for the bridge and calculated that gussets located just inside the piers at "U10" on the drawings were the weakest points. These gussets, at a half-inch thickness, might have been fine had the bridge been better maintained, said Astaneh-Asl, who has reviewed inspection and consultant reports on the bridge. "You're close to the margin," Astaneh-Asl said. "If you don't inspect your bridge to make sure that your margin is being kept, you might end up with a problem." (Excerpts from the Pioneer Press Newspaper, Minneapolis, August 8, 2007 [3])*

On January 15, 2008, the National Transportation Safety Board (NTSB), which is the federal agency in charge of investigating the I-35W collapse, stated that [4]:

…… the damage patterns and fracture features uncovered in the investigation to date suggest that the collapse of the deck truss portion of the bridge was related to the fractured gusset plates and, in particular, may have originated with the failure of the U10 gusset plates. ." (Excerpts from an NTSB document [4])

3.2 Edge Buckling of Gusset Plates Prior Years before the Collapse

Photographs taken in 2003 of the bridge, Fig. 5, show that gusset plate U10 had already developed edge buckling failure mode during or prior to 2003, four years before the bridge collapsed in 2007. The edge buckling of gusset plate U10, shown in Fig. 5, is on the compression side of the gusset plate.

a) Node U10 on west truss, viewed looking northwest from inside the structure

b) Node U10 on east truss, viewed looking northeast from inside the structure

Fig. 5: Edge buckling of gusset plate U10 of the I-35W bridge photographed in 2003 [4]

Edge buckling is one of the major failure modes of gusset plate connections in braced frames as well as in trusses [5]. This failure mode were known from the early days of bridge building using steel riveted trusses, and edge stiffeners often are found in old bridges that are added to the edge of gusset plates to prevent the edge buckling.

Although edge buckling of gusset plate itself is not expected to result in progressive collapse of entire span, when it occurs in a gusset plate, it is a definite sign of over-stressing of the gusset plate. In addition, when the edges of compression side of gusset plate buckle, the buckled areas can no longer support additional load. Also, since the edge buckling is usually elastic buckling, the buckled area cannot maintain the buckling capacity. As a result, the stresses that were carried by the compression zone of gusset plate prior to buckling, will be redistributed to other areas of the gusset plate such as the tension areas. The additional load applied to the gusset also is carried by the tension zones and areas that have not buckled, further increasing tensile stresses in the gusset plate. When these increased stresses reach the capacity of net section of the gusset, which in these gusset plates with large number of rivet holes is the governing failure cross section, the net section fractures and the progressive collapse of the determinate truss starts.

In design of new gusset plates and evaluation of condition of existing gusset plates, it is necessary that this failure mode is investigated and if it was governing, stiffeners in the form of angles (usually) or plates be added to the edge of gusset plates to prevent the edge buckling such as shown in Fig. 5. The AASHO Specification-1961 [2] , which was the design code for this bridge, has a provision stating that the ratio of free length of the gusset plate edge divided by the thickness should not exceed 48 for the type of steel used in gusset plates of this bridge. In gusset plates U10 of the I-35W Bridge the ratio of free length of gusset plate exceeded 60, far more than 48 allowed.

During the period of 2003-2007, the URS Corporation was commissioned by the Minnesota Department of Transportation (MN-DOT) to conduct a fatigue evaluation and redundancy analysis of the I-35W Bridge and to make recommendations to MN-DOT on necessary retrofit and strengthening. Both the final URS report issued in 2006 and its amendment issued in 2007 a few months prior to the collapse, have focused on studying only the truss members with gusset plates not studied at all. Not including the gusset plates in the study, in the opinion of the author, is in violation of the requirements of the Federal Highway Administration's AASHTO Standards for evaluation of bridges [6] which emphasize inspection and evaluation of conditions of not only the members but also the connections in bridges. In particular the Standard [6] in the section on Steel Structures states that:

> "*External connections of non redundant members shall be evaluated during a load rating analysis in situations where the evaluator has reason to believe that their capacity may govern the load rating of the entire bridge*" requires that: when evaluating steel bridge structures both *members and connections* need to be inspected and their existing conditions evaluated." (Excerpts from the national U.S. Standard for evaluation of bridges [6].

It appears that, since gusset plates U-10 had already buckled at the time of the URS study [7], and the fact that gusset plate U-10 is located right at the top of permanent ladder shaft of the bridge, a cursory inspection of the gusset plate U-10 would have revealed that the gusset plate had failed and buckled, Fig. 5. Such failure would have been reported to the MN-DOT, the bridge owner, with recommendations for mitigating the danger of collapse, and the catastrophe would have been avoided.

3.3 Construction Activities and Loads on the I-35W Prior to the Collapse

For several months prior to the collapse, the I-35W bridge was undergoing repair and replacement construction activities on its deck. According to construction contract documents [1], the construction activity on the bridge in the months leading to the collapse consisted of removing the top 5 cm wearing surface concrete as well as cutting about 100cm of the entire deck slab at location of the expansion joints and replacing the expansion joints as well as the removed part of the deck. Fig. 6 shows the traffic and construction equipment on the bridge on the day of the collapse. The drawings are from NTSB publication [4] and were prepared using aerial photographs taken by a passenger in a plane flying over the bridge a few hours before the bridge collapsed. The construction load on the bridge was extra-ordinarily heavy. According to the NTSB report [4], as indicated in Fig. 6, the total weight of construction material and equipment on the deck just above the gusset plates U10 or near them was about 2600 kN. Apparently in order to do the deck and expansion joint repairs, the staging area for construction was selected to be on the bridge itself.

3.4 Corrosion of Steel in the I-35W Bridge

A study of the inspection reports prepared by the Minnesota Department of Transportation, the owner and maintainer of the bridge, as well as photographs taken in the past, indicated that the I-35W Bridge had previous corrosion problems in the main river crossing, see Fig.

7(a). Inspection reports issued by the Minnesota Department of Transportation show the presence of corrosion on some gusset plates and adjacent areas, Fig. 7(b), indicating that due to corrosion, some gusset plates and even some members may have thinned over the years and did not have the originally designed thicknesses at the time of collapse.

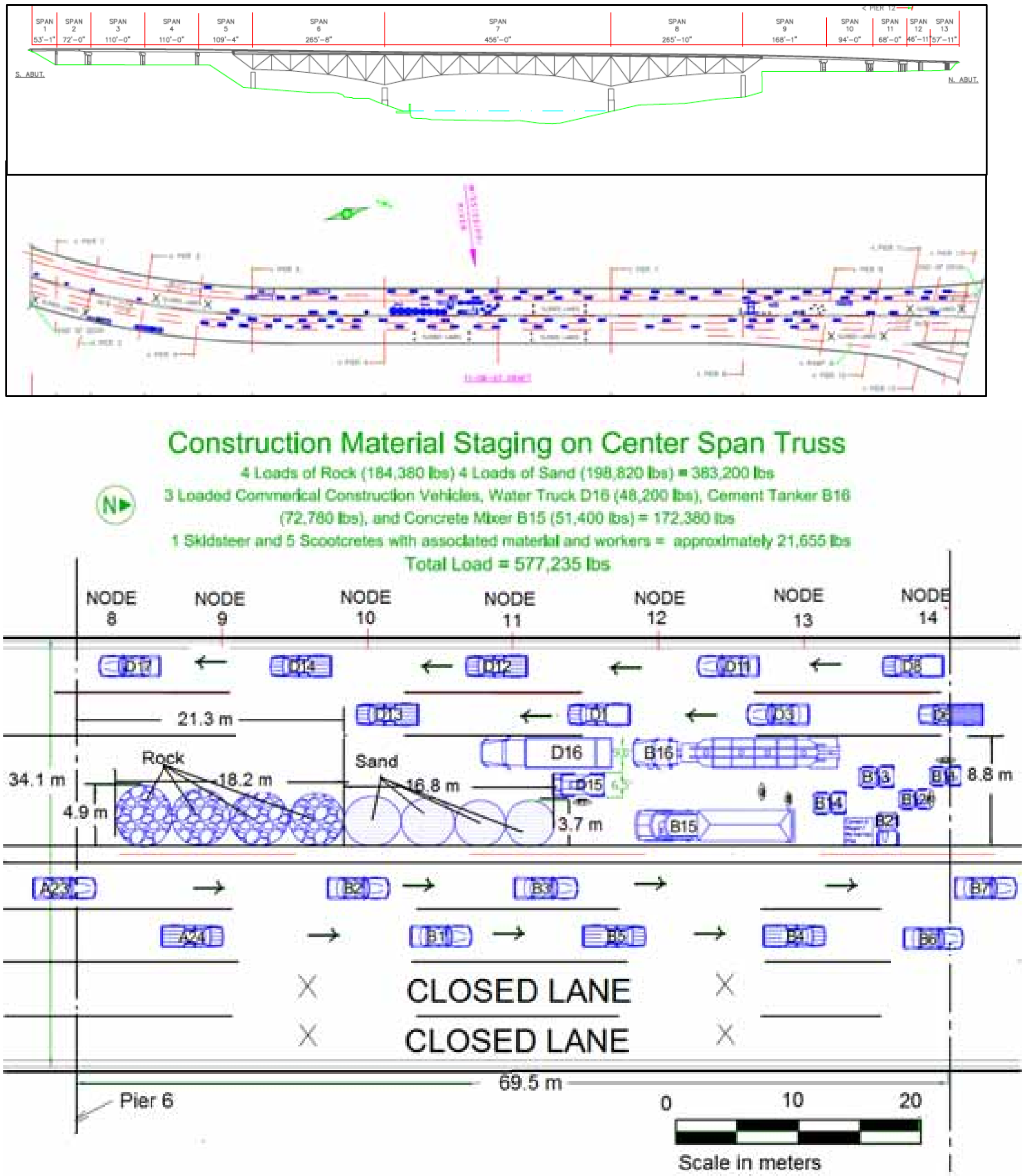

Fig. 6: Construction loads on the brideg according to a NTSB report [4]

3.5 Fatigue Cracks and Fatigue Prone Welded Details in the I-35W Bridge

According to a 1998 inspection report [1] numerous fatigue cracks were found in the approach spans. The cracks were located in negative moment regions where the diaphragm web stiffener was not welded to the top flange. The I-35W bridge was designed and constructed prior to 1970's when there was very limited understanding of the fatigue behavior of welded members and connections of steel bridges. As a result, in the I-35W Bridge, the fatigue-prone details could develop fatigue cracks; such cracks can propagate and result in fracture of a primary member or a connection of main truss causing the progressive collapse of the entire span, due to lack of redundancy and a secondary load path.

a) corrosion of roller bearing b) orrosion in the gusset plate areas

Fig. 7: Corrosion in the roller support at Pier 6 and gusset plate area, I-35W bridge (dates and photographers unknown)

At the time of this writing, it is not clear whether there was an undetected fatigue crack in gusset plate U10 or any other member or gusset plate that has initiated the fracture of a fracture critical member or connection leading to progressive collapse of the entire span. Such scenario can only be confirmed if a detailed examination and testing of the fractured gusset plate U10 is conducted. At this time, all material of the bridge including gusset plates U10 are in the possession of NTSB and no information are released on this issue.

There were also fatigue cracks found in the plate girders of the approach spans and in its gusset plates and members.

4. ANALYSIS OF PROGRESSIVE COLLAPSE OF I-35W

4.1 Objectives of the Analysis

The main objectives of the analysis are (a) to establish the initiating cause of this progressive collapse and; (b) to establish the progression of failure after the first critical element fractured and started the progressive collapse.

4.2 Analytical Model

Three analytical models are planned for this case; 3D elastic model using SAP2000 software and 3D inelastic model using Perform software.

4.3 Interim Results of Analysis

Fig. 8 shows the 3D elastic model of the bridge which predicts the initiation of progressive collapse after fracture of gusset plate U10. At this time, we are in the process of building Perform and Nastran models.

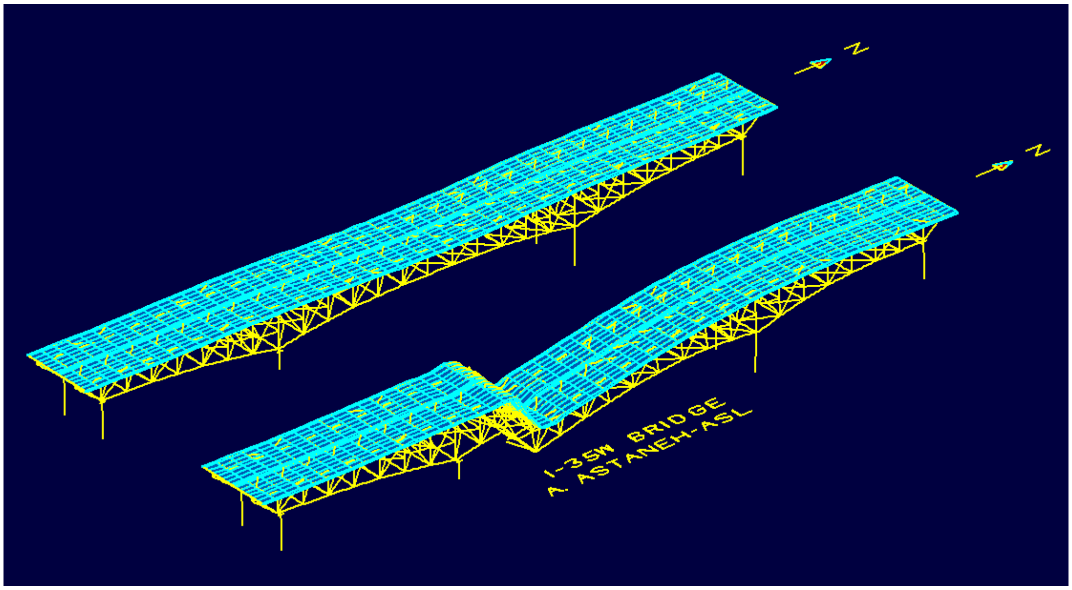

Fig. 8: The I-35W bridge collapse initiation predicted by SAP2000 [ ]

5. A PLAUSIBLE SCENARIO FOR COLLAPSE OF THE I-35W BRIDGE

Based on our studies of the available data on I-35W and its collapse, including original drawings, inspection and other investigative reports as well as photographs of the bridge, the author has been able to establish a "plausible' scenario for this tragic progressive collapse. The scenario will remain "plausible" until the fractured gusset plates are made available to research community to examine them. Currently, the National Transportation Safety Board has possession of all the material of the collapsed bridge and has not made the material available to others for visual inspection or non-destructive testing.

5.1 A Plausible Scenario of the Collapse

In the opinion of the author, and based on the results of the analysis discussed in the above section briefly, the stresses created in the bridge, due to addition of very heavy weight of construction equipment and material placed on the bridge itself combined with the already high stresses due to under-designed thicknesses of the gusset plates U10 and addition of 5 cm of wearing surface concrete, resulted in tragic and brittle progressive collapse of I-35W.

6. CONCLUSIONS

The main interim conclusions of this ongoing research are:

1. In the collapsed I-35W deck truss bridge, gusset plates U10 at four locations on the main trusses were under-designed originally and had already developed edge buckling during or prior to 2003 due to addition of dead load of 5 cm wearing surface and curbs.
2. The addition of considerably heavy load due to construction material and equipment , in the opinion of the author, have caused the already over-stressed gusset plates U10 reach the limit of their net section capacity and fracture through the net section
3. After fracture of the net section of gusset plate U10, the progressive collapse of main trusses occurred quite rapidly and in a brittle manner due to lack of redundancy in the

trusses and presence of net sections in the perforated members and riveted/bolted gusset plates.

4. If the inspections and evaluations that were done during 2003-2007 by the URS corporation had not excluded the gusset plates, the under-designed gusset plates U10 would have been detected by observing their edge buckling and/or by analysis of their strength, and the remedies would have been provided to mitigate the brittle failure of the gusset plate
5. If the construction company had studied the effects of adding heavy load of construction equipment and material on the bridge and increasing the stresses in the bridge, very likely it would have realized that the bridge, given its already stressed and fatigued state of stress as well as its non-redundant character, cannot support such loads and would place the "staging area" of the construction not on the bridge but outside and on the solid ground.

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Since March 21, 2008, the author is retained as Expert Consultant by the Law Office of Schwebel, Goetz & Sieben, and P.A. in Minneapolis, Minnesota, USA.

The opinions expressed in this paper are solely those of the author and do not necessarily represent the views of the University of California, Berkeley, where the author is a professor, the SGS, the SSEC and others whose name appear in this report.

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