NATIONAL TRANSPORTATION SAFETY BOARD
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MATERIALS LABORATORY SEQUENCING STUDY Report No. 08-032

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1.0 BACKGROUND

1.1 Accident

Place : Minneapolis, Minnesota
Date : August 1, 2007
Vehicle : I-35W Highway Bridge
NTSB No. : HWY07MH024
Investigator: Mark Bagnard

1.2 Components Examined

The components examined included all portions of the bridge, including the piers, superstructure, and deck, with primary focus on the truss portion of the bridge.

1.3 Accident Summary

About 6:05 p.m. (CDT), on Wednesday, August 1, 2007, the 35W Interstate Highway (I-35W) Bridge over the Mississippi River, in Minneapolis, Minnesota, experienced a catastrophic failure in the main span of the deck truss portion of the 1,907-foot-long bridge. As a result, approximately 1,000 feet of the deck truss collapsed with about 456 feet of the main span falling into the river. An assessment of the gusset plates within the deck truss revealed that the connections at nodes U10, U10 prime, L11, and L11 prime[1] were under-designed. The bridge comprised eight traffic lanes, with four lanes in each direction. At the time of the collapse, a roadway construction project was underway that resulted in the closure of two northbound and two southbound traffic lanes, causing traffic queues on the bridge. A total of 111 vehicles were documented as being on the portion of the bridge that collapsed. Of these, 17 vehicles were recovered from the water. As a result of the bridge collapse, 13 people died and 145 people were injured.

2.0 SEQUENCE STUDY METHODOLOGY

This study determined the most likely sequence of the collapse of the bridge based on information from multiple sources. The primary source of information was the documentation of fractures, deformations, damage patterns, and recovery positions of the bridge members, as contained in the Structural Investigation Group Chairman Factual Report; this Sequencing Study should therefore be read in conjunction with that report. The Structural Investigation Group Chairman Factual Report was based on the on-scene examinations of the bridge, and it contains a general description of the bridge, the nomenclature for bridge members, and the details of the field examination. Also relevant are NTSB Materials Laboratory Reports No. 07-119 and No. 08-004, which contain information on two specific fracture areas from the truss

[1] From south to north, the nodes of the deck truss portion of the bridge were designated 0 through 14 (midspan) and 13′ through 0′. “U” and “L” distinguish the upper and lower nodes at each of these locations, respectively. For the remainder of this report, the nodes north of node 14 will be cited using the symbol for prime (such as node 13′) instead of spelling out the word “prime.”

portion of the bridge, and Report No. 08-031, which contains additional documentation of nodes L11 East and West. This Sequencing Study also relies heavily on the results of the finite element analysis of the truss portion of the bridge, as contained in reports by the Federal Highway Administration's Turner-Fairbank Highway Research Center and by the NTSB Modeling Group. The results of this Sequencing Study are consistent with the video recording of the collapse as recorded on the security camera at the entrance to the lock on the south[2] side of the river (see Video Study Report for this accident, dated June 3, 2008). However, the video recording shows neither the beginning of the collapse nor nodes U10 East or West, and was used primarily to confirm that the south side of the center portion of the truss displaced downward before the north side and for a few other specific details as noted.

A basic assumption of a structural sequence evaluation is that the initiating event occurs as a result of tension or compression forces acting along a member while the primary structural members of the deck truss structure remain intact and minimally deformed. Thus, initiating failures could include the buckling of a member under compression loads or the fracture of a member in tension with minimal bending deformation associated with the fracture. Another assumption is that deformation directly adjacent to a fracture is produced as a result of loads generated during the fracture process, and not as a result of subsequent collisions or ground impact. Thus, any fracture or deformation that occurs under bending loads, such as a fracture with compression deformation on one side and tension fracture on the opposite side, is secondary damage because such damage requires significant movement of the opposite end of the member, indicating prior separation or deformation of the structure.

As an integral part of the on-scene and subsequent portions of this investigation, the damage patterns in each structural element were evaluated in order to understand how the damage was produced and to differentiate damage that occurred upon ground or river impact from damage that occurred prior to ground impact. In this manner, the localized sequence associated with each primary structural element was integrated into the overall sequence as described in this study. All evidence gathered during the field examinations, the finite element analysis, and the review of the video recording is consistent with the sequence described in this study. Many alternate collapse scenarios were considered, but all were rejected because of significant conflict with factual observations. It should be pointed out that the sequence presented in this study does not necessarily explain in detail how all of the damage was created. For example, vertical member U9/L9E was fractured from both nodes U9 East and L9 East and had a large bend below the attachment location for the lower chord of the floor truss (FT), while vertical member U9/L9W remained attached to its nodes and had only a slight bend below the attachment location for the lower chord of the floor truss. While the reasons for these differences are not fully understood, this damage certainly occurred significantly after the initial failure and is therefore of much less importance. Nevertheless, the damage to these members is not in conflict with the sequence presented in this study, which considers and is consistent with the large majority of the fractures and deformation patterns documented.

[2] The I-35W bridge was primarily oriented in a north-south direction, with the Mississippi River flowing to the east.

The remainder of this report is organized as follows:

- Section 3 contains a summary of the collapse sequence.
- Section 4 contains an overall description of the damage to the bridge. This section also indicates the rationale for focusing heavily on the deck truss portion of the bridge and defines the South Fracture Area and the North Fracture Area of the deck truss portion.
- Section 5 describes the damage patterns in the South Fracture Area.
- Section 6 describes the damage patterns in the remainder of the deck truss portion of the bridge. Each stage of the discussion includes a discussion of the collapse sequence as it relates to that section.
- Section 7 discusses alternate theories of initiating or contributing conditions that were subsequently determined improbable due to significant inconsistencies with the physical evidence and/or their inconsequential effects on the structural integrity of the bridge.

Bridge nomenclature used in this report is intended to be consistent with the nomenclature used in the Structural Investigation Group Chairman Factual Report, which contains definitions of various technical terms at the beginning of Appendix 1.

For ease of reference, the photographs cited in this report are contained in a separate document, “Materials Laboratory Annotated Photographs,” Report No. 08-032A.

3.0 SUMMARY OF THE COLLAPSE SEQUENCE

The physical evidence, analytical methods, and other supporting evidence are all consistent with the collapse initiating with the failure of the gusset plates at nodes U10 East and West. Specifically, the U10 gusset plate deformation and fracture patterns were consistent with in-line compression loads on this diagonal creating compression failure in the portion of the gusset plate between the diagonal and the upper chord and tension fracture in the portion of the gusset plate between the diagonal and the vertical. Physical evidence found on other bridge members was consistent with secondary damage that occurred as the bridge collapsed.

Although the physical evidence was insufficient to establish which of these two nodes failed first, the finite element analysis demonstrated that the gusset plates at node U10 West were more highly loaded because of the placement of the construction material on the bridge. It is likely that the failure proceeded rapidly but incrementally through these two nodes more or less simultaneously. In some areas, the evidence was insufficient to precisely determine the order of events or the cause of specific secondary damage. Nevertheless, the evidence was sufficient to establish the major steps in the general overall sequence as presented here, and all fracture and deformation patterns, modeling results, and other evidence are consistent with the presented sequence.

Overall Sequence of Collapse

1. The gusset plates around the U10 ends of diagonals L9/U10 East and West buckled and fractured, initiating the collapse.

2. As nodes U10 East and West displaced vertically downward, positive bending loads increased in the portion of the U10 gusset plates that remained across the upper chord members of these nodes, and the plates fractured through the upper chord.
3. FT 10 became temporarily suspended from the deck stringers, and large compression loads developed between the upper ends of verticals U10/L10 East and West and the floor truss lower chord attachment location on these verticals as the northern portion of nodes U10 East and West continued to drop.
4. Tension loads in the lower chords, the lateral bracing, and the deck pulled the south portion of the deck truss northward and off piers 5 and 6, causing most of the bearing rollers at these piers to fall off the north sides of the piers.
5. Lower chord members L9/L10 East and West fractured adjacent to nodes L9 East and West from downward bending.
6. Separation in the South Fracture Area was complete or nearly complete, and the south end of the center portion of the truss continued to drop toward the river.
7. Lower chord member L7/L8 East partially fractured in its center and fractured from the nodes at each end, allowing the portion of the truss from nodes 8 East and West to nodes 4 East and West to topple to the east.
8. In the North Fracture Area, the gusset plates around the U10′ ends of diagonals L9′/U10′ East and West buckled and fractured, allowing the remaining portions of nodes U10′ East and West to displace downward through the diagonals. In addition, the lower chords of the main trusses contained compression buckling between nodes L11′ and L9′.
9. As nodes U10′ East and West displaced downward, positive bending loads increased in the portion of the gusset plates that remained across the upper chord members of these nodes, and the plates fractured through the upper chord.
10. Upper chord members from nodes U8′ to U10′ bent down adjacent to nodes U8′.
11. Lower chord members L9′/L10′ East and West fractured adjacent to nodes L9′ East and West from downward bending.
12. Separation in the North Fracture Area was then complete or nearly complete, and the center portion of the truss dropped into the river, with the south end of the center portion preceding the north end.
13. Secondary fractures and damage occurred in the south and north portions of the deck truss, and these portions also collapsed.
14. Collapse of the deck truss portion of the bridge caused loss of support to the two adjoining approach spans.

4.0 DESCRIPTION OF THE COLLAPSED STRUCTURE

Figure 1 shows an overall view of the center span of the deck truss portion of the bridge before the collapse, and figure 2 shows an overall view of the bridge after the collapse. The

primary damage to the bridge was to the deck truss portion that spanned the Mississippi River. However, the approach spans also sustained damage in areas adjacent to the truss portion. The damage to the approach spans was consistent with loss of support at the ends of the deck truss, with the cantilevered portions of the approach spans dropping after support was lost. Although the approach spans contained previously documented preexisting cracks, there was no evidence that these cracks influenced either the initiation or the sequence of the collapse.

The deck truss spans of the bridge separated into three large sections. Most of the center span between piers 6 and 7 (identified in figure 1) fractured from the remainder of the truss and fell into the river, the section south of pier 6 fell onto land on the south side of the river, and the section north of pier 7 fell onto land on the north side of the river. Fracture areas between the large sections of the truss were located approximately between nodes 8 and 11 (the South Fracture Area) and between nodes 11′ and 8′ (the North Fracture Area). Figure 3 shows an overall view of the collapsed deck truss portion of the bridge, with the South and North Fracture Areas and the south, center, and north portions indicated.

5.0 EARLY FRACTURES AND DAMAGE PATTERNS: DAMAGE IN THE SOUTH FRACTURE AREA OF THE DECK TRUSS

Figure 4 shows an overall view of the postcollapse position of the fractured and damaged main truss members in the South Fracture Area. Based on the following factors, the South Fracture Area was defined as being located south of nodes 11 and north of nodes 8.

- Nodes 11 and adjacent nodes to the north remained largely or entirely intact until they were damaged from impact with the riverbed. The video recording also shows that upper chord member U11/U12W, lower chord member L11/L12W, diagonal L11/U12W, vertical U11/L11W, and additional members to the north were not separated from their nodes as the collapse began.
- Floor truss 8 remained at least partially connected to the main trusses, and the damage to the floor trusses at nodes 8 and adjacent nodes to the south and to the main trusses was consistent with secondary damage created after the south portion of the truss was displaced to the north.

The video recording showed that the fractures in the South Fracture Area preceded damage to other portions of the deck truss, including the North Fracture Area. The finite element modeling also demonstrated that, given the loading conditions at the time of the accident, the most highly loaded deck truss members were also within the South Fracture Area.

This section of the report contains a detailed discussion of each fractured or damaged element within the South Fracture Area and establishes that the collapse began with the failure of the gusset plates at nodes U10. This section initially describes the damage to the main truss structural members in the South Fracture Area, then describes the damage to the deck and stringers above the South Fracture Area, and finally describes the damage to the floor trusses and bracing. For those elements that interacted significantly during the collapse, this

organization is not strictly followed. A summary of the collapse sequence in the South Fracture Area is included at the end of the section.

5.1 South Fracture Area - Main Trusses

In the South Fracture Area, the main truss elements that were found to be separated from their node, fractured, or deformed included the following members:

Table 1: South Fracture Area Damage Summary

Member	Description
Diagonals L9/U10 East and West	Separated from nodes U10 East and West through the gusset plates, bent close to nodes L9 East and West
Upper Chord Members U9/U10 East and West	Separated from nodes U10 East and West through the gusset plates, bent adjacent to nodes U9 West and U8 East
Lower Chord Members L9/L10 East and West	Fractured in bending adjacent to nodes L9 East and West, bent close to nodes L10 East and West
Vertical Members U10/L10 East and West	Compression deformation and fractures in the upper portion of the members above the attachment location for the lower chord of FT 10 and bending deformation in the lower portions of the members
Vertical Member U9/L9 East	Fractured at lower end, separated from node U9 East through the gusset plates, bent below the floor truss
Vertical Member U9/L9 West	Slight bending deformation below the floor truss

Most of the damaged members listed above are visible in figures 5, 6, and 7, which show overall, postcollapse views. Figure 5 shows an overall view of the pieces remaining on the south bank in the South Fracture Area and the adjacent pieces in the water. On both the east and west main trusses, the U9/U10 upper chord member was attached to the south portion of the truss at the U9 end, but was fractured from node U10 through the U10 gusset plates around this member. The diagonal members L9/U10 from both main trusses were attached to node L9, and the U10 end was in the water (West member) or pointing down toward the water (East member). The diagonal L9/U10 East did not contain bending deformation directly adjacent to the node on either end, but was severely bent starting about 9 feet from the L9 end gusset plate. The diagonal L9/U10 West was severely bent adjacent to node L9. These members are labeled in figure 5.

Figure 6 shows a closer view of a portion of figure 5. In this figure, the upper and lower ends of vertical U9/L9E and the upper and lower chords of FT 9 are indicated. The lower chord of FT 9 remained attached to vertical U9/L9E, and this vertical member had a severe bend at a location slightly below the lower chord of the floor truss.

Figure 7 also shows a closer view of a portion of figure 5. In this figure the visible portions of FT 10 and verticals U10/L10 East and West are indicated. The upper chord of FT 10 is also indicated in figure 6.

As discussed in the remainder of this section, deformation patterns and fracture features along both main trusses in the South Fracture Area were typical of secondary damage, with the exception of the damage and fractures associated with nodes U10 East and West. Therefore, the discussion in the remainder of this section starts with these nodes, followed by a discussion of other damaged or fractured main truss members in the South Fracture Area.

Nodes U10 East and West

Figures 8A and 8B show CAD drawings of the fracture locations in the gusset plates at nodes U10 East and West. Because the fracture locations in the west gusset plates of the nodes were so similar to each other, they are shown in figure 8A. The fracture locations in the east gusset plates were also similar to each other, and they are shown in figure 8B. The gusset plate fractures in these nodes separated diagonals L9/U10 East and West and the upper chords U9/U10 East and West from the nodes. The remaining portion of the gusset plates did not totally fracture, and the upper end of vertical U10/L10, the U10 ends of diagonal U10/L11, and upper chords U10/U11 remained connected to each other through at least one of the gusset plates on both the east and west main trusses.

Deformation patterns on the gusset plates around the U10 ends of diagonals L9/U10 East and West indicated that (1) the gusset plates buckled and bent in the portion of the plate between the diagonal and the upper chord and fractured mostly under tension loading[3] in the portion of the plate between the diagonal and the U10/L10 vertical, (2) the diagonals moved to the west relative to the remainder of the U10 nodes, and (3) the remainder of the nodes then displaced downward into the diagonal.

Figures 9, 10, 11, and 12 show views of the U10 ends of diagonals L9/U10 East and West. As these photographs show (and in comparison with the drawings in figures 8A and 8B), the fracture locations on all four gusset plates from nodes U10 East and West left a V-shaped piece of the gusset plates above the upper end of the diagonal. For the west gusset plates (figures 9 and 10), these V-shaped pieces were folded over the end of the diagonal, indicating that the west side plates of the diagonals translated west relative to the remainder of nodes U10. For the east gusset plates (figures 11 and 12), these V-shaped pieces of the gusset plates were folded back over the east side plate, indicating that the east side plates of the diagonals also translated west relative to the remainder of nodes U10. Figure 13 shows an oblique view of the U10 West end of diagonal L9/U10W, with the folded V-shaped pieces of the gusset plates visible on both side plates of the diagonal.

The deformation and fracture patterns in the node U10 gusset plates associated with the upper ends of the L9/U10 diagonals indicate that both diagonals translated west as the remainder of the node displaced downward into the diagonals, meaning that both east side plates of these diagonals penetrated through the interior of the nodes and that the west side plates transitioned west (outside) of the nodes. Pieces associated with the remainder of the

[3] See Materials Laboratory Report No. 07-119 for a more detailed description of a portion of the fractured area on the east gusset plate from node U10 West.

nodes and FT 10 contained multiple impact marks from being struck by the upper ends of the diagonals. The following table lists some of these impact marks. Deformation patterns associated with a fracture in the upper chord of FT 10 east of node U10 East were consistent with creation of this fracture as a result of impact of the west side plate of diagonal L9/U10E with the lower side of the upper chord of the floor truss. See section 7.1 for a more detailed description of this fracture in FT 10.

Table 2: Impact Damage, Nodes U10 East and West

Node U10 West		Node U10 East	
Location Impacted by L9/U10W	Impacted by	Location Impacted by L9/U10E	Impacted by
Lower cover plate, upper chord U9/U10W	East side plate	Lower cover plate, upper chord U9/U10E	East side plate
Lower cover plate, upper chord U10/U11W	East side plate	Lower cover plate, upper chord U10/U11E	East side plate
Bottom corner, west side plate, upper chord U10/U11W adjacent to the node centerline	East side plate	Bottom corner, west side plate upper chord U10/U11E adjacent to the node centerline	East side plate
North face of the west gusset plate fracture through the upper chord	Upper cover plate	North face of the west gusset plate fracture through the upper chord	Upper cover plate
Upper end of the web of vertical U10/L10W	East side plate	Upper end of the web of vertical U10/L10E	East side plate
South side of the web of the node's upper chord internal vertical stiffener	East side plate	South side of the web of the node's upper chord internal vertical stiffener	East side plate
Lower surface of the upper cover plates of upper chord U9/U10W and U10/U11W	East side plate	Lower surface of the upper cover plate of upper chord U9/U10E	East side plate
Lower surface of the top splice plate of the upper chord	East side plate	South side of the upper lateral brace vertical stiffener	West side plate
Doubler plate and bottom flange of FT 10 upper chord, above node U10 West	East side pate		
Bottom surface of the upper chord of FT 10 west of node U10 West	West side plate		

Figure 14 shows an overall and closer view of the impact mark on the lower surface of the upper cover plate of upper chord U10/U11W. Also visible in this figure are the flanges of vertical U10/L10 West. The web of this member had been impacted by the east side plate of diagonal L9/U10 West and was fractured from its flange plates. Figure 17 shows a view of this impact mark, and figure 18 shows a view of the similar mark on the upper end of the web of vertical U10/L10 East.

The loss of structural integrity associated with nodes U10 displacing downward over diagonals L9/U10 East and West caused structural deformations to begin in the deck truss south of these nodes. This deformation would have added positive bending to the horizontal tension load already present in the remaining portions of the node U10 gusset plates across the upper chord. The gusset plates across the upper chord were fractured, largely vertically through the first row of rivets south of the node centerline. Examination of these fracture areas showed that between each rivet hole, the gusset plate was elongated in a direction slightly offset from horizontal, with the angle gradually increasing from nearly horizontal at the lowest hole to more skewed (down and to the north) at the upper hole. This change in the angle of elongation and the deformation adjacent to the upper edge of the gusset plate were consistent with fracture under primarily horizontal tension in the lower portion of the fracture and more shear in the upper portion of the fracture, with the direction of shear indicating that the structure on the north side of the fracture was moving down relative to the structure on the south side of the fracture. Figure 15 shows the gusset plate fracture area on the gusset plate pieces that remained attached to upper chord members U9/U10 East and West. The fractures in the portions of the U10 gusset plates on the upper chord were consistent with the expected forces in this region after nodes U10 began to displace downward over diagonals L9/U10 East and West.

Vertical Members U10/L10 East and West

Vertical members U10/L10 East and West exhibited significant deformation and fractures in the area above the location where the lower chord of FT 10 attached to the vertical members. Figure 16 shows the western and central portion of FT 10 as it was being removed from the river. As this figure shows, the floor truss remained remarkably intact,[4] including the entire region around node U10 West. Severe compression deformation was noted in vertical U10/L10 West at the location indicated by arrow “CD” in figure 16. Figure 17 shows a closer view of this compression damage. Similar compression damage was noted in the upper portion of vertical U10/L10 East, as shown in Figure 18. In both figures 17 and 18, impact marks where the webs of the vertical members were contacted by the east side plate of diagonals L9/U10 are visible and indicated.

Fractures through the node U10 gusset plates in the area of the upper chords would have completely separated the main trusses at nodes U10, and the lower chords of the main trusses would have provided minimal resistance to continued downward displacement of the center span north of nodes U10. However, the deck and stringers would still have been largely intact across nodes U10, and as FT 10 and the truss north of nodes U10 dropped, the deck and stringers, which were connected to F10, would have provided some resistance to continued downward displacement.

The downward load on FT 10 was largely applied to the floor truss at the location where the lower chord of the floor truss was connected to verticals U10/L10. These verticals remained attached to the tension diagonals (U10/L11) and the upper chords (U10/U11) through the remainder of nodes U10. Thus, once the deck stringers began to support FT 10,

[4] Member ends that were sheared during the removal process are indicated in figure 16.

the upper portions of verticals U10/L10 (the portions between the lower chord of FT 10 and nodes U10) were loaded in compression, consistent with the severe compression damage found in the upper portions of verticals U10/L10 East and West. The video recording shows that the west main truss separated from the deck in the area above and to the north of node 11, with increasing separation to the south, consistent with the deck stringers supporting FT10 and the generation of compression loading in the upper portion of verticals U10/L10.

Lower Chord Members L9/L10

Lower chord members L9/L10 East and West were both fractured through the northernmost vertical row of rivets at nodes L9 East and West after significant negative bending deformation. Examination of these fractures showed clear evidence of fracture under tension at the top of the members and compression at the bottom of the members consistent with downward movement of the node L10 end of these members. Figure 19 shows views of the fracture in lower chord L9/L10 West. These fractures completed the separation of the main trusses in the South Fracture Area. The excessive bending associated with the fractures in these members is a clear indication that these fractures were secondary events, consistent with downward movement of nodes L10 after separation at nodes U10.

Vertical Member U9/L9 East

Vertical member U9/L9 East was separated from the main truss through fractures of the gusset plates at node U9 East and through fractures of the side plates of the member in node L9 East. The member was also severely bent to the south at a location just below the lower chord of the floor truss. In the postcollapse position, the member was found translated to the west and still attached to the lower chord of FT 9, as shown in figure 6. The damage patterns associated with the fractures at the upper and lower ends of the member indicated that the center portion of the member moved to the south relative to the upper and lower ends, consistent with the southward bend of the vertical member slightly below FT 9. The lower chord of FT 9 in the segment adjacent to main truss vertical member U9/L9 East was twisted in a direction that would impart bending into the vertical member, also consistent with the southward direction of the bend below the floor truss. Figure 20 shows the southward bending deformation in vertical member U9/L9 East below the lower chord of the floor truss.

Overall, the fractures and deformations in vertical U9/L9 East were consistent with the member initially bending to the south at the location below the floor truss, followed by fractures at the upper and lower ends of the member as the buckling deformation increased.

The finite element analysis showed that, at the time of the collapse, vertical members U9/L9 East and West were loaded in compression, but that the loads were significantly below the loads necessary to cause elastic buckling.

Vertical Member U9/L9 West

Vertical member U9/L9 West remained attached to the west main truss at both its upper and lower ends, as shown in figure 5. This member was bent slightly to the south just below

the lower chord of FT 9 (the same location as the severe bend in vertical member U9/L9 East). The location of this bend is indicated in figure 6. The lower chord of FT 9 in the segment adjacent to main truss vertical member U9/L9 West was twisted in a direction that would impart bending into the vertical member, also consistent with the southward direction of the bend below the floor truss. The amount of twisting in this segment of the floor truss lower chord was less than the amount of twisting in the corresponding segment of the lower chord adjacent to U9/L9 East.

South Ends of Upper Chord Members U9/U10 West and U8/U10 East

With the ongoing collapse of the center portion of the deck truss, the upper chords south of nodes U10 were bent down under their own weight and by the deck above dropping, with eventual negative bending deformation in the upper chord members adjacent to node U8 East (for upper chord member U8/U10 East) or node U9 West (for upper chord member U9/U10 West), as figure 5 shows. The lack of significant bending deformation in the upper chord adjacent to node U9 East indicates that vertical U9/L9 East was separated from the east truss or bent before the upper chord member from U8 to U10 began to move downward.

South Ends of Diagonals L9/U10 East and West

With continued dropping of the center portion of the deck truss, diagonals L9/U10 East and West, which were fractured from nodes U10 but still connected at nodes L9, were bent down, with severe bending deformation in these members adjacent to or near nodes L9, as figure 5 shows.

5.2 South Fracture Area – Deck and Stringers

Examination of the postcollapse position of the bridge structure showed that the expansion joint in the deck at FT 14 did not appreciably open. At FT 12, the deck stringers were bent down, and the deck was fractured at what appeared to be a construction joint. The deck south of this construction joint had displaced to the south relative to the underlying stringers. FT 11 and the stringers and deck above this floor truss were under water. Three layers of deck and stringers, from node 11 to node 10, from node 10 to node 9, and from node 9 to the expansion joint at node 8 were stacked in a Z-fold pattern in the area originally between nodes 10 and 11. The folded layers in the southbound deck slab were skewed longitudinally more than the layers in the northbound slab. Figure 21 shows an overall view of the postcollapse position of the deck and stringers above the South Fracture Area. Based on the visible portion of the deck, the deck and stringers had a positive bend approximately above FT 10 and a negative bend above FT 9. The deck had an expansion joint at node 8, and the deck and stringers above the South Fracture Area were constructed with the stringers only bearing on FT 8 without any mechanical fasteners.

The location of the positive bend in the deck above FT 10 is consistent with the direction of loading placed on the stringers when the deck and stringers resisted the downward movement of FT 10 following separation of the L9/U10 diagonals from nodes U10. Simultaneously, as the deck and stringers at FT 10 were pulled down, the deck and stringers

above FT 9 were loaded in negative bending. The postcollapse location of the deck and stringers above the South Fracture Area indicates that the deck and stringers from node 12 south to node 8 separated from the main trusses, and that the deck and stringers from node 10 to node 8 transitioned to the north as the collapse progressed, resulting in the folded pattern in the postcollapse position.

5.3 South Fracture Area – Floor Trusses and Braces

FT 8 remained at least partially attached to the vertical members in the east and west main trusses but was significantly damaged during the later stages of the collapse by impact with the ground and pier 6.

As shown in figure 6, the portion of FT 9 between the main trusses (the central portion of the floor truss) was attached to vertical U9/L9E through the lower chord of the floor truss, and this vertical member had a severe bend to the south at a location slightly below the lower chord of the floor truss. As previously discussed, vertical U9/L9E was fractured from both the upper and lower nodes, and displaced toward the centerline of the pier. From its attachment to vertical U9/L9E, the central portion of FT 9 extended longitudinally north, bending down into the river. The central portion of FT 9 was separated from vertical U9/L9W through the gusset plate at the lower chord attachment and through a fracture in the floor truss upper chord at the upper chord of the west main truss.

The upper chord of FT 9 was deformed to the north in two lobes located on each side of center. Near its middle, the central portion of the upper chord of FT 9 had a corresponding slight bend to the south, consistent with this portion of the floor truss being restrained by the upper lateral brace members that attached to the south side of the upper chord as the stringers pulled adjacent portions of the upper chord to the north. Twisting deformation in the lower chord of FT9 adjacent to vertical U9/L9E was in the direction consistent with the upper chord of the floor truss being pulled northward by the deck stringers, causing rotation of the lower chord.

The central portion of FT 10 remained partially attached to portions of main truss verticals U10/L10 East and West through the floor truss's lower chord. The vertical members were found lying on the guide wall with their upper ends in the water and the central portion of FT 10 between the verticals almost directly below its position in the bridge, with the west vertical further south than the east vertical as shown in figure 7. Figure 7 also shows that the central portion of FT 10 was partially submerged in the river in the postcollapse position.

The upper chord of FT 10 had a deformation pattern similar to but more pronounced than the pattern found on the upper chord of FT 9. The pattern was consistent with the deck stringers pulling the upper chord northward, as the upper chord was restrained at the main trusses and by the upper lateral braces attaching to the south side of the upper chord (in the center). The upper chord of FT 10 was also fractured near node U10 East, and part of this fracture was brittle. See Section 7.1 for a more detailed description of this fracture.

FT 11 was heavily damaged and was recovered almost directly below its normal position in the truss. It was partially covered by the three folded layers of deck and stringers. Damage to FT 11 was consistent with crushing damage during the final stages of river impact.

Most of the lateral and sway brace members between nodes 8 and 11 were present in the jumble of members on the south bank of the river. Deformation associated with the upper lateral braces between FT 8 and FT 9 and between FT 9 and FT 10 was consistent with these braces resisting the northward movement of FT 9 and FT 10.

Sequence in the South Fracture Area

- The gusset plates connecting the U10 ends of diagonals L9/U10 East and West buckled and fractured, initiating the collapse.
- The diagonals translated to the west as the remaining portions of nodes U10 East and West displaced downward, with the west side plates passing to the west of the nodes and the east side plates passing through the center of the nodes.
- As nodes U10 East and West displaced downward, positive bending loads increased in the portion of the gusset plates remaining across the upper chord members of the nodes, and the plates fractured through the upper chord.
- Deck stringers above FT 10 initially moved downward with nodes U10 East and West, but began to resist downward displacement as the downward displacement increased.
- FT 10 became temporarily suspended from the deck stringers, and large compression loads developed between the upper ends of verticals U10/L10 East and West and the floor truss lower chord attachment location on these verticals as the northern portion of nodes U10 East and West continued to drop.
- The deck cracked and/or fractured above FT 10 and above FT 9 due to truss displacement.
- As the center portion of the truss continued to drop, the deck from FT 10 to FT 8 was pulled northward toward the river. Because the deck stringers were attached to FT 9 and FT 10, these floor trusses were pulled to the north, with load transfer through the upper lateral braces as the collapse continued.
- Tension loads in the lower chord, the lateral bracing, and the deck pulled the south portion of the deck truss northward and off piers 5 and 6, causing most of the bearing rollers at these piers to fall off the north sides of the piers.
- The deck and floor stringers were pulled off FT 8 because of the expansion joint at this location.
- Lower chord members L9/L10 East and West fractured adjacent to nodes L9 East and West from downward bending.
- Separation in the South Fracture Area was complete or nearly complete, and the south end of the center portion of the truss continued to fall toward the river.
- The deck sections from nodes 8 to 11 dropped into a folded shape, with the deck section between nodes 9 and 10 sandwiched between the deck sections between nodes 10 and 11 and the deck sections between nodes 8 and 9.

6.0 SUBSEQUENT DAMAGE PATTERNS

6.1 Description of the Damage in the North Fracture Area of the Deck Truss

The deck truss remained relatively intact south of nodes U10′ East and West (in the central portion that fell into the river) and in the rigid body portion that rotated north on pier 7. Thus, the North Fracture Area was located north of nodes 10′ and south of nodes U8′ and L9′. Figure 22 shows an overall view of the main truss members in the North Fracture Area in the postcollapse position.

6.1.1 North Fracture Area - Main Trusses

In the North Fracture Area, the main truss elements that were found to be separated from their nodes, fractured, or deformed are listed in the following table. The table also includes deformation to lower chord members L10′/L11′ East and West that was outside the fracture area as defined above.

Table 3: North Fracture Area Damage Summary

Member	Description
Diagonals L9′/U10′ East and West	Separated from nodes U10′ East and West through the gusset plates, bent or fractured close to nodes L9′ East and West
Upper Chord Members U9′/U10′ East and West	Separated from nodes U10′ East and West through the gusset plates, bent adjacent to node U8′ East and West
Vertical Members U10′/L10′ East and West	Compression deformation and fractures in the upper portion of the members above the attachment location for the lower chord of FT 10′ and bowing deformation in the lower portions of the members
Lower Chord Members L9′/L10′ East and West	Fractured in bending adjacent to nodes L9′ East and West
Lower Chord Members L10′/11′ East and West	Compression buckling adjacent to nodes L11′
Vertical Members U9′/L9′ East and West	Fractured at lower end, separated or nearly separated from nodes U9′ through the gusset plates, bent below the floor truss

As previously discussed, the video recording clearly shows that the North Fracture Area was secondary to the South Fracture Area. Nevertheless, a general description of the types of fractures found and the sequence of damage in the North Fracture Area is provided in this section for completeness. As indicated in the table above, the locations and types of fractures and damage in the main trusses from the North Fracture Area were very symmetrical laterally (east to west). The main differences in symmetry were that (1) the L9′W end of diagonal L9′/U10′W was fractured from severe bending adjacent to the node, and the main portion of this diagonal was recovered from the river under other structural members, while the L9′E end of diagonal L9′/U10′E was severely bent but not fractured and remained attached to node L9′ East, and (2) vertical U9′/L9′W completely separated from the main truss at both ends, while the corresponding vertical on the east truss remained minimally attached at node L9′ East.

Nodes U10′ East and West

The gusset plates at nodes U10′ East and West were fractured and deformed in a manner very similar to the gusset plates at nodes U10 East and West, with the fractures releasing the L9′/U10′ East and West diagonals and the upper chords U9′/U10′ East and West from the nodes. The remaining portions of the gusset plates did not totally fracture, and the upper end of vertical U10′/L10′, the U10′ ends of diagonal U10′/L11′, and upper chords U10′/U11′ remained connected to each other through at least one of the gusset plates on both the east and west main trusses.

Damage patterns on the gusset plates around the U10′ ends of diagonals L9′/U10′ East and West indicated that (1) the gusset plates buckled and bent in the portion of the plate between the diagonal and the upper chord and fractured mostly under tension loading in the portion of the plate between the diagonal and the U10′/L10′ vertical, (2) the diagonals displaced to the inside of the bridge (east for diagonal L9′/U10′W and west for diagonal L9′/U10′E) relative to the remainder of the nodes, and (3) the remainder of the nodes then displaced downward into the diagonals.

The deformation and fracture patterns in the node U10′ gusset plates associated with the upper ends of the L9′/U10′ diagonals indicate that the diagonals translated to the inside of the bridge relative to the remainder of the nodes. Pieces associated with the remainder of the nodes and FT 10′ contained multiple impact marks from being struck by the upper ends of the diagonals. Figure 23 shows the fractured and deformed west gusset plate on the U10′ East end of diagonal L9′/U10′ East. (Note that for orientation purposes, figure 23 is shown below figure 24.)

The fractures through the portions of the node U10′ gusset plates on the upper chord were very similar to the corresponding fractures in the node U10 gusset plates, with separation primarily through the first row of rivets north of the node centerline. Examination of these fracture areas showed that between each rivet hole, the gusset plate was elongated in a direction slightly offset from horizontal, with the angle gradually increasing from nearly horizontal at the lowest hole to more skewed (down and to the north) at the upper hole. Figure 24 shows the fracture through the west gusset plate of node U10′ East on upper chord member U9′/U10′ East. (Compare to the left photograph in figure 15.) Similar to the node U10 gusset plates, the fractures in the U10′ gusset plates in the area of the upper chord fractured primarily under horizontal tension loads in the lower portion of the fracture and under more shear loads in the upper portion of the fracture, with the direction of shear indicating that the structure on the south side of the fracture was moving down relative to the structure on the north side of the fracture. Figure 25 shows the remainder of node U10′ West (the southern portion) in its postcollapse position. The fracture through the portion of the west gusset plate on the upper chord is indicated.

As can be seen in figure 25 for the west gusset plate at node U10′ West, the remaining portions of the gusset plates on nodes U10′ remained intact and contained much less distortion than the corresponding portions of the gusset plates on nodes U10.

With continued downward displacement of the center portion of the deck truss, the upper chords north of nodes U10′ were bent down, with eventual negative bending deformation in the upper chord members adjacent to nodes U8′, as can be seen in figure 22. The lack of significant bending deformation in the upper chord adjacent to nodes U9′ indicates that verticals U9′/L9′ East and West were separated from the trusses or bent before the upper chord members from U8′ to U10′ were pushed downward.

Vertical Members U10′/L10′ East and West

Verticals U10′/L10′ were both bent/buckled in several locations, including directly below nodes U10′, below the lower chord of FT 10′, just below the mid strut attachment location, and above the node L10′ gusset plates. A portion of vertical U10′/L10′ West is also visible in figure 25. Arrows “2” and “3” in this figure indicate the bending/buckling damage adjacent to node U10′ West and below the lower chord of the floor truss. Although this vertical contained significant damage in the area below node U10′ West (area indicated by arrow “2” in figure 25), this area remained at least partially intact throughout the collapse, unlike the corresponding portions of the U10/L10 verticals in the South Fracture Area.

Lower Chord Members L9′/L10′ East and West

Lower chord members L9′/L10′ East and West were both fractured in negative bending adjacent to nodes L9′ East and West, consistent with downward motion of the center portion of the deck truss. These fractures were very similar to the fractures in the corresponding members in the South Fracture Area (L9/L10 East and West). Lower chord L9′/L10′ West also had a compression buckle 15 feet north of node L10′ West.

Lower Chord Members L10′/L11′ East and West

Lower chord members L10′/L11′ East and West had large compression buckling areas adjacent to nodes L11′, as shown in figures 26 and 27. In the compression buckling areas, the upper and lower cover plates were partially fractured from the side plates, and the side plates formed a large “S” shape, with deformation primarily in the horizontal plane. Lower chord member L10′/L11′ also had compression buckling adjacent to node L10′ East.

The compression deformation to lower chord members L10′/L11′ East and West and L9′/L10′W was consistent with high compression loads generated in the lower chord as the south end of the center portion of the deck truss displaced toward the river.

Vertical Members U9′/L9′ East and West

Vertical members U9′/L9′ East and West were damaged and fractured in very similar manners, except for the lower end of U9′/L9′E, which remained partially attached to node L9′ East, while the corresponding area on U9′/L9′W was completely fractured from node L9′ West.

Both of these members contained bending deformation just below the lower chord of FT 9′ (with the area of the bending deformation displaced to the north) and severe bending damage at the upper and lower ends. The damage on these two members was similar to the damage on vertical U9/L9E from the South Fracture Area.

6.1.2 North Fracture Area – Deck and Stringers

The deck and stringers above the North Fracture Area collapsed without the folding associated with the deck and stringers above the South Fracture Area and were located almost directly below their position in the bridge. This indicates that the deck and stringers became separated from FT 8′ (the deck stringers south of the expansion joint at nodes 8′ were only resting on FT 8′) and that the main truss structure between nodes 8′ and 10′ fractured and separated, allowing the deck to drop nearly vertically downward.

6.1.3 North Fracture Area – Floor Trusses and Braces

Most of FT 10′ was found in the river substantially intact. FT 10′ between verticals U10′/L10′ East and West was bowed northward consistent with restraint being provided by the upper lateral system between U9′ East and West and the upper lateral attachment point on the north side of the center of FT 10′.

The top chord of FT 9′ between the primary truss verticals to which it was attached was bowed southward consistent with the deck stringers pulling on the chord southward toward the river after the upper lateral brace became separated from the north side of the center of the floor truss.

Sequence in the North Fracture Area

- Compression buckling developed in the lower chords of the main truss between L11′ and L9′ directly following failure of the U10 nodes. In addition, the gusset plates connecting the U10′ ends of diagonals L9′/U10′ East and West buckled and fractured, allowing the remaining portions of nodes U10′ East and West to displace downward through the diagonals.
- In addition, both diagonals translated toward the centerline of the bridge as they penetrated nodes U10′ East and West, with the west side plate of diagonal L9′/U10′W and the east side plate of L9′/U10′E passing through the center of the nodes.
- As nodes U10′ East and West dropped, positive bending loads increased in the portion of the gusset plates remaining across the upper chord members of the nodes, and the plates fractured through the upper chord.
- Vertical compression loading on verticals U9′/L9′ East and West, coupled with bending forces induced in these verticals by the lower chord of FT 9′, initiated bending of these verticals below the lower chord of FT 9′ and corresponding complete or partial bending fractures in the upper and lower ends of these verticals.
- Upper chord members from nodes U8′ to U10′ were then unsupported at nodes U9′ and U10′, and these members bent down adjacent nodes U8′.

- As the center portion of the truss continued to drop, the deck sections from FT 10′ to FT 8′ were pulled and dropped toward the river. The deck stringers were pulled off FT 8′ because of the expansion joint at this location. Because the deck stringers were attached to FT 9′, this floor truss was pulled to the south, with forces transferred through the upper lateral braces, as the collapse continued.
- Lower chord members L9′/L10′ East and West fractured adjacent to nodes L9′ East and West from downward bending.
- Separation in the North Fracture Area was then complete or nearly complete, and the center portion of the truss fell into the river, with the south end of the center portion preceding the north end.

6.2 Description of the Damage to the South Portion of the Deck Truss

The deck and floor stringers north of the expansion joint at node U8 separated at this node and remained attached to the portion of the structure that fell into the river. The deck and stringers south of this node remained approximately in position relative to the upper chords of the truss. All of nodes U8 and L8 East and West (at pier 6) remained with the south portion of the truss.

Nodes L1 were found north of pier 5, and nodes L8 were found north of pier 6, indicating that, in general, the entire south portion of the truss had displaced several feet north toward the river. Associated with this movement, the lower surface of lower chord members L7/L8 East and West contained impact and scraping damage from contact with the bearing components and concrete of pier 6. Figure 28 shows the impact and scraping damage on the lower surface of lower chord member L7/L8W. Similar damage was noted to the lower surface of lower chord member L7/L8E, as shown in figure 29, and loading associated with this damage was severe enough that this lower chord member was partially fractured approximately at mid-length, near the southern terminus of the damage (see figure 30). In addition, the member was totally separated from node L7 East (through shearing of the rivets between the member side plates and the gusset plates, as shown in figure 31) and from node L8 East (through fracture of one of the side plates and shearing of the remaining rivets between the side plates and the gusset plates). The presence of the scraping damage on the lower surfaces of lower chords L7/L8E and L7/L8W indicates that the southern portion of the truss shifted to the north before the structure above these members toppled to the east.

The bearing rollers at piers 5 and 6 fell on the north side of the piers (except for one roller that remained on pier 5 West and one roller that was found on the south side of pier 5 East). It would be expected that the northern and center rollers in any set of bearings would be dropped off the north side of the pier as the superstructure above was translated to the north. However, with a sufficient amount of translation to the north, the upper bearing casting would be expected to drop off the north side of the pier before the southern roller in any set of bearings would drop off the pier, thereby potentially leaving the southern bearing on top of the pier in a position where it could then be pushed off the south side of the pier during a later stage of the collapse. The wear pattern associated with the bearings indicated that the rollers moved over a range of approximately 5 inches relative to the pier at pier 5 and over a range of

approximately 2 ½ inches relative to the pier at pier 6. Postcollapse survey measurements indicated that piers 5 and 6 did not exhibit any settlement or displacement.[5]

The upper chords of the main trusses in the southern portion of the deck truss were intact from node 8 to node 1. (The upper chords of the east and west trusses were fractured between nodes 1 and 0, on the south side of node 1.) The lower chord of the west truss was fractured between nodes L2 and L3 West, and the lower chord of the east truss was fractured adjacent to node L1 East.

Also, as previously discussed, each end of lower chord member L7/L8E separated from nodes L7 and L8 East, primarily through shearing of the gusset plate rivets. There was no evidence that damage was more severe on the east side of this member (see figure 29), suggesting that the main trusses above this area toppled to the east after lower chord member L7/L8E failed.

Most of the main truss members and nodes south of pier 6 contained compression or bending damage consistent with ground impact. The mating fracture areas in the lower chord were displaced apart, indicating continued translation to the north after the fractures were created in the lower chords.

The floor trusses from node 8 southward remained at least partially attached to the nodes on the east and west main trusses. The sway braces and lateral braces between nodes 0 and 8 showed no evidence of primary failure.

It was also noted that the superstructure of the center portion of the deck truss (between the South and North Fracture Areas) was located almost directly below its original position, as discussed below, which is consistent with the South Fracture Area occurring before nodes 4 through 8 toppled to the east.

Sequence in the South Portion of the Deck Truss

- As the South Fracture Area developed, the south portion of the deck truss was pulled toward the river; nodes L1 East and West were pulled northward off pier 5, and nodes L8 East and West were pulled northward off pier 6.
- The northernmost span of the south approach lost its support at node U0 as the south portion of the truss was pulled northward, allowing the north end of this span to fall to the ground.
- The south portion of the truss fell to the ground north of pier 5.
- Lower chord member L7/L8 East partially fractured near its center and fractured from nodes L7 and L8 East, allowing the east side of this portion of the truss to begin to topple to the east while lower chord member L7/L8 West remained on top of pier 6.
- Twisting damage associated with the toppling structure extended from nodes 8 back to nodes 4 East and West as the structure continued to fall to the ground.

[5] See appendix 2 of the Structural Investigation Group Chairman Factual Report for information on the piers and bearings.

- Deformations south of nodes 4 resulted from ground impact and impact with pier 5 as the truss fell following its translation to the north.

6.3 Description of the Damage to the Center Portion of the Deck Truss

In the postcollapse position, the center portion of the truss (between the South and North Fracture Areas) was relatively flat and impacted the river almost directly below its original position. The video recording shows that the center portion of the deck truss remained relatively flat as it dropped, and that the south end of the center portion preceded the north end of the center portion. Also, many of the vehicles on the inner northbound lanes remained in their respective lanes. These features indicate that the east and west main trusses in the South Fracture Area fractured about the same time and before the fractures in the North Fracture Area, and the center portion of the bridge dropped into the river with minimal lateral roll and with the south end preceding the north end. Figure 3 shows that the center portion of the deck truss was located almost directly below its original position, with multiple vehicles still on the deck.

The main truss upper chord members from nodes 12 to 12′ remained intact and above the water (see figure 3), with the floor trusses at these nodes at least partially attached and supporting the deck stringers and deck. Furthermore, the video recording does not show any type of failure or deformation occurring in the lower chords between nodes L13 East and L12′ East and between nodes L11 West and L12′ West.

Sequence in the Center Portion of the Deck Truss

- Fracture of the main trusses in the South Fracture Area allowed the south end of the center portion of the deck truss to begin to fall toward the river.
- The main trusses in the North Fracture Area fractured, and the center portion of the deck truss dropped into the river with minimal lateral roll and with the south end preceding the north end.

6.4 Description of the Damage to the North Portion of the Deck Truss

An overall view of the north portion of the deck truss after the collapse can be seen in figure 32.

Pier 7 (the fixed bearing location) hinged about the top of the pier footing, resulting in a tilt toward the river of more than 9°. Survey measurements and monitoring showed no movement of the pier after the accident. The video recording shows no evidence that pier 7 displaced prior to the collapse.

The pier 8 columns hinged about a section approximately 3 ½ feet above the top of the footings near the location where the dowel bars terminated. These columns were tilted southward an amount similar to the tilt in pier 7.

A large portion of the deck truss above and north of pier 7 rotated to the north as a rigid body, as shown in figure 22. This rigid body included the deck and upper chord from node U8′

to node U6′, the lower chord from node L9′ to node L7′, and the diagonals between these nodes. Nodes L8′ East and West were in contact with the north side of the upper end of the pier 7 columns in the postcollapse position (see node L8′E in figure 33). The video recording clearly shows that the rigid body portion of the deck truss initially remained in position (that is, it did not rotate) as the center span dropped into the water. The rigid body portion can be seen later in the recording, after the water splash cleared, and by that time, the rigid body portion had rotated to the north.

Between this rigid body portion and pier 8, the deck truss collapsed nearly straight downward and experienced severe vertical compression deformation. In this area, the upper chord and upper nodes generally were displaced 18 to 25 feet to the north relative to the lower chord and lower nodes. Fractures in the gusset plates at nodes U2′ East and West separated the upper chords at these locations.

The main trusses, deck stringers, and deck at node U1′ (above pier 8) were bent down over the pier, as shown in figure 34. The deck had fractured at this bend location, but the stringers were still intact and had severe bending and deformation. Nodes L1′ were on the ground, resting against the north face of pier 8. Node U1′ West remained on top of the pier and is visible in figure 34. Node U1′ East was trapped near the top of the pier on the north side. The upper chord of FT 1′ was on top of or on the north side of the pier, and the lower chord of this floor truss was on the south side of the pier. A visible portion of the upper chord of FT 1′ is indicated in figure 34. Nodes U0′ East and West were on the north side of the pier. Based on the postcollapse position of FT 1′ and the main truss above pier 8, the truss collapsed across the pier without significant movement of the truss relative to the top of the pier. As the portion of the truss south of pier 8 dropped, this pier would have been pulled to the south, consistent with the partial fractures in this pier and its tilt to the south.

As the deck truss south of pier 8 dropped to the ground, the portion of the truss north of pier 7 began to rotate to the north. The damage to the truss extended southward from pier 8 toward pier 7 as this portion of the truss continued to rotate to the north until only the rigid body portion of the truss remained relatively undamaged. A progression of the damage from the north to the south in this area is also consistent with the postcollapse position of the upper chords being north of the corresponding lower chords. Also, tilting of pier 7 to the south is consistent with southward forces exerted on the north side of the pier during this portion of the collapse.

The bearing rollers at pier 8 showed evidence of movement over a distance of 2½ inches, similar to the amount of movement for the rollers in pier 6. The bearing rollers at pier 8 came off the south side of the pier (except for one roller found on the north side of pier 8 West).

Sequence in the North Portion of the Truss

- The truss collapsed over pier 8, and the pier was pulled to the south by the collapsed structure as the collapse continued.

- The south end of the north approach span lost its support as the structure collapsed over pier 8, allowing the north approach span to fall to the ground.
- The truss south of pier 8 dropped to the ground, and the portion of the truss north of pier 7 began to rotate northward.
- Damage spread southward toward pier 7 until only the rigid body portion remained relatively undamaged.
- Pier 8 was pulled to the south as extensive ground impact occurred between piers 7 and 8.
- Pier 7 was pushed to the south as the rigid body portion rotated to the north (upper chord hinged near nodes U6′) and impacted the ground.

7.0 DISCUSSION OF ALTERNATE THEORIES

As part of the evaluation of the sequence of collapse, numerous alternate theories of initiating or contributing conditions were considered, including fracture of a floor truss member, failure of welds in floor truss or main truss members, corrosion damage, pre-existing cracks, and movement of the piers. These particular theories are discussed in some detail below. All proposed alternate theories considered were determined improbable due to significant inconsistencies with the physical evidence and/or their inconsequential effects on the structural integrity of the bridge. That is, these theories were not supported by physical evidence, were inconsistent with other documented deformations or fractures, and/or could not have initiated a complete collapse.

7.1 Fracture of a Floor Truss Member

In consideration of the possibility that the collapse of the bridge could have initiated from a tension or compression failure[6] of a member within a floor truss, the floor trusses reconstructed at Bohemian Flats were examined for these conditions, and neither was found.

One fracture of interest was found in the upper chord of FT 10, which was fractured 5.5 feet west of the centerline of node U10 East, as shown in figure 35. Through the lower half of the chord, the fracture was largely flat, consistent with a brittle fracture region, and contained a chevron pattern, indicating that the fracture initiated in a weld between the lower flange of the upper chord and the gusset plate for floor truss node FT10U10. The two lower photographs in figure 35 show closer views of the origin area. Through the upper half of the chord, the fracture was on a slant plane, consistent with a ductile fracture region. The upper flange of the upper chord in areas adjacent to the fracture was deformed upward, indicating that bending forces were present in the upper chord as the fracture progressed.

Examination of the underside of the upper chord's lower flange in the area between the fracture and node U10 East revealed deformation and impact marks associated with the west side plate of diagonal L9/U10E. The fracture in the upper chord of FT 10 was therefore consistent with forces applied during the impact of the L9/U10E diagonal into the floor truss.

[6] A member fractured under tension-only loads would have minimum bending deformation, and a slender member subjected to compression-only loads would be expected to buckle approximately at the mid-point of the length.

7.2 Failure of Welds in Floor Truss or Main Truss Members

The Structures Investigation Group Chairman Factual Report documents examples of less than ideal welds associated with several of the floor truss members. Notable among these examples were welds between the east cantilevered portion of the upper chord of FT10 and the cantilever diagonals.[7] Both of the diagonals supporting this cantilever were relatively undamaged but had separated from the upper chord at least partially at the interface between the weld and the surface of the gusset plate, indicating lack of fusion. Because the two most eastern lanes were closed to traffic at the time of the accident, there was no live load on the deck above this location. Also, there was no evidence of an early collapse of the cantilevered portions of the floor trusses.

In several locations, fractures were found along longitudinal welds in main truss members. For example, in both upper chord members U10/U11 East and West, the upper cover plate was fractured from the side plates for 10 feet north of nodes U10 East and West. At both of these locations, there was no evidence of inadequate welding, and the fractures were consistent with the collapse sequence presented. Diagonals L9/U10 East and West had fractures in or near the longitudinal welds in the areas associated with the bending deformations near the L9 ends of these members. These areas were eliminated from consideration as possible initiating events for two reasons: (1) an initial compression failure at these locations would have greatly reduced the compression load pushing these members into nodes U10, and (2) the deformations associated with the L9 ends of these diagonals were consistent with a lateral deflection and subsequent downward bending, indicating that the initial failure occurred at the U10 ends that were then free to rotate. Because the bending deformation and longitudinal weld fractures in diagonal L9/U10E were located slightly above node L9, it is possible that less than ideal weld quality influenced the localization of the damage once bending loads were introduced as a result of failure at the U10E end of the member. Other examples of fracture in or near longitudinal welds include lower chord members L10′/L11′E and L11′/L12′W, each of which had compression buckling damage as shown in figures 26 and 27. At both of these locations, there was no evidence of inadequate welding, and the compression buckling at these locations was consistent with large loads generated after separation in the South Fracture Area.

No evidence was found that weld conditions in any of the major structural members contributed to the initiation of the collapse.

7.3 Corrosion Damage in the Gusset Plates at Nodes L11 East and West

As discussed in Section 5 of this report, the fracture and deformation patterns found in the South Fracture Area were consistent with initiation of the collapse sequence at nodes U10 West and East. However, the partial loss of section associated with the corrosion damage in the gusset plates at nodes L11 East and West was also investigated as a possible initiator of the failure.

[7] See Structural Investigation Group Chairman Factual Report, appendix 1, page 1-54.

Five primary truss members were connected at main truss nodes L11 East and West: lower chord members L10/L11 and L11/L12, tension diagonal[8] U10/L11, compression diagonal L11/U12, and vertical U11/L11. The vertical member applied compression loads to nodes L11. As documented in Materials Laboratory Report No. 08-031, the node L11 gusset plates were generally intact in the area of the lower chord but had multiple fracture locations in areas above the lower chord. For complete documentation of the fracture locations and damage patterns on the gusset plates at nodes L11, see Materials Laboratory Report No. 08-031.

Three sources of information were considered in regard to the possibility of initial failure at nodes L11: the video recording, fracture and damage patterns at nodes L11, and finite element analysis. As discussed in the remainder of this section, there is no evidence that the corrosion found in the gusset plates at nodes L11 contributed to the initiation of the collapse of the truss.

Video Recording

The video recording clearly shows members L11/L12W, L11/U12W, and U11/L11W, and that node L11 West remained intact well after multiple other fractures occurred in the South Fracture Area. Therefore, the collapse sequence clearly did not initiate with this node. Although node L11 East was not visible in the video recording, an initial failure at node L11 East associated with intact structure at node L11 West would have produced significant rolling of the truss main span as the structure fell. The video recording showed that the center portion of the deck truss fell into the river in a generally level orientation, without lateral roll about the span's longitudinal axis. Therefore, the video recording does not support an initial failure at nodes L11.

Fracture and Deformation Patterns

Fracture and deformation patterns will be discussed in regard to three potential initiating events associated with gusset plate failure: (1) the gusset plates around the L11 end of tension diagonal U10/L11 could fracture under tension loading, pulling the diagonal out of the node; (2) the gusset plates around the L11 end of compression diagonal L11/U12 could fail, pushing the diagonal into the node; and (3) the compression diagonal L11/U12 and vertical member U11/L11 together could be pushed into the node, with gusset plate failure around the ends of these members. Overall documentation of nodes L11 is contained in the Structural Group Chairman Factual Report, and further documentation of the fracture and deformation patterns associated with these nodes is contained in Materials Laboratory Report No. 08-031.

Tension failure of the gusset plates around the L11 end of the tension diagonals: The reports cited above indicate that neither of the tension diagonals

[8] The diagonals at nodes L11 leading to nodes U10 are described as tension diagonals because these members always carry tension loads. Similarly, the diagonals at nodes L11 leading to node U12 are described as compression diagonals because these members always carry compression loads. See figures 5 and 6 in the Structural Investigation Group Chairman Factual Report for a summary of the loading condition for all the members of the main trusses.

(U10/L11 East and West) pulled from the nodes in tension. Instead, fractures of the gusset plates around these diagonals contained evidence of bending, consistent with compression loading at the time of failure, and the lower ends of these members appeared to slightly penetrate the nodes and then fold on top of the lower chord members L10/L11 East and West after translating to the side. The physical damage documented was consistent with and most likely the result of impact of the bridge with the river or riverbed.

Failure of the gusset plates around the L11 end of the compression diagonals: The gusset plates around the L11 ends of compression diagonals L11/U12 East and West contained significant deformation, fracture, and damage, consistent with these members penetrating through or around nodes L11 East and West. If this damage had been the initial failure, the main truss segment between nodes 11 and 12 would have been unstable, with nodes U12 and L12 dropping relative to nodes U11 and L11. This relative motion would have introduced large in-plane negative bending loads into the portions of the ½-inch gusset plates attached to lower chord members L10/L11 and L11/L12. However, these gusset plates did not fracture in the area of the lower chords, indicating that bending loads associated with initial failure of the gusset plates around the L11 end of the compression diagonals did not occur.

Compression diagonal L11/U12 and vertical member U11/L11 pushed into the node: Because both the compression diagonal and the vertical member at nodes L11 East and West are loaded in compression, the fracture and deformation patterns at these nodes were evaluated in regard to this mechanism. If this damage had been the initial failure, the main truss segment bounded by nodes U10, U12, L12 and L11 would have been unstable, with nodes U12 and L12 dropping relative to nodes U10 and L11. This relative motion would have introduced large in-plane negative bending loads into the portions of the ½-inch gusset plates attached to the lower chord members L10/L11 and L11/L12, similar to the bending loads that would have been generated if only the compression diagonal had penetrated the node. However, these gusset plates did not fracture in the area of the lower chords, indicating that bending loads associated with initial failure of the gusset plates around the L11 end of the compression diagonal and vertical did not occur. Furthermore, it was noted that the east gusset plate at node L11 East was not fractured in the area between the vertical member and the tension diagonal, confirming that this failure mode did not occur at node L11 East. In addition, if nodes U12 and L12 had dropped relative to nodes U10 and L11, negative bending loads would have resulted in the upper chord through nodes U10. As discussed in section 5.1, the portions of the U10 gusset plates attached to the upper chord members failed under positive bending loads, not negative bending loads.

Summary of Fracture and Deformation Patterns: The preceding discussion clearly shows that none of the initiating failure modes proposed for nodes L11 was consistent with the observed fracture and deformation patterns.

> Furthermore, all of the fracture and deformation patterns were consistent with damage expected during impact of the intact nodes with the river bed.

Finite Element Analysis

Finite element analysis[9] of the load and stress conditions in the gusset plates at nodes L11 East and West was conducted using the measurements of the reduced thickness of the plates due to corrosion[10]. This analysis showed that the gusset plates at nodes L11, even in the presence of the corrosion, were subjected to less stress than the gusset plates at nodes U10.

7.4 Pre-existing Cracking

As mentioned in earlier sections of this report, cracks of various lengths had been noted in the bridge, primarily in the approach spans, but also including two cracked tack welds in the deck truss spans. The July 2006 URS draft report "Fatigue Evaluation and Redundancy Analysis, Bridge No. 9340 I-35W Over Mississippi River" indicated that

> there was a crack noted in the tack weld inside the box on member U21-U22 (U7′-U6′) approximately 2 feet north of joint U21 (U7′). There was another crack noted at joint U14 at the upper lateral stringer connection starting at a tack weld.

The overall pattern of the collapse is consistent with initiation of the collapse at U10W in the South Fracture Area of the deck truss portion of the bridge, an area not associated with any of the previously noted pre-existing cracks. There is no evidence that any of these pre-existing cracks contributed to the initiation of the collapse of the structure or significantly affected the pattern of the collapse.

All fractures in the portions of the deck truss laid out at the Bohemian Flats were examined in detail for areas of fatigue cracking. None were found. In particular, the fractures in the gusset plates at nodes U10 East and West were typical of ductile overstress tension, shear, bending, and buckling fractures consistent with the loading on the plates, and there was no evidence that these plates had any detectable defects or cracking prior to the collapse.

7.5 Movement of Piers

As previously discussed, postcollapse survey measurements indicated that piers 5 and 6 did not exhibit any settlement or displacement. This fact, coupled with the location of the roller wear marks approximately in the center of the contact plates at piers 5, 6, and 8 establishes that piers 7 and 8 did not have significant longitudinal movement relative to piers 5 and 6 before the accident. Thus, the roller wear marks show that there was minimal pre-collapse movement of the piers. In addition, the presence of the roller wear marks showed that the deck truss was moving relative to piers 5, 6 and 8 in response to thermal contraction and expansion, thereby limiting the amount of longitudinal force applied to the top of any pier.

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[9] See FHWA report on the finite element analysis and Modeling Group Chairman Final Report.
[10] See appendix 3 of the Structural Investigation Group Chairman Factual Report.

Postcollapse evaluation of damaged piers 7 and 8 showed that the tilted postcollapse position of these piers occurred because of separations above the bases of the piers. Pier 7 (the fixed bearing location) hinged about the top of the pier footing, and the pier 8 columns had fractured concrete at the top ends of the footing dowel bars (approximately 3 ½ feet above the top of the footings). There was no evidence that the bases of these pier shifted.

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