NATIONAL TRANSPORTATION SAFETY BOARD
Vehicle Recorder Division
Washington, D.C. 20594

June 3, 2008

Video Study Report

NTSB Accident Number:
HWY07MH024

by Doug Brazy

A. ACCIDENT

Location: Minneapolis, MN
Date: August 1, 2007
Time: 1805 Central Daylight Time
Event: Collapse of I-35W Bridge

B. GROUP

N/A

C. SUMMARY

On Wednesday, August 1, 2007, about 6:05 p.m. central daylight time (CDT), the Interstate 35W (I-35W) highway bridge over the Mississippi River in Minneapolis, Minnesota, collapsed.

A nearby video surveillance camera located at the Lower Saint Anthony Falls Lock & Dam captured a portion of the collapse and recorded it to a digital video recorder (DVR). Agents from the Federal Bureau of Investigation retrieved the recorder, and forwarded it to the NTSB Vehicle Recorder Division in Washington, DC.

Overview of Observations from the Video Recording

The video surveillance system recording activated shortly after the collapse began. In the recording, the first region of the bridge that can be seen moving is the center section (span 7). The recording shows that, at the onset of the span 7 motion, two localized areas of deformation occurred:

- A “bend” or discontinuity in beam L9' / L11' West (W)[1] at node L10' W.
- A separation of deck stringer 14, the westernmost stringer, from the deck at node U11W.

Span 7 appears to have remained level about its longitudinal axis as it fell (that is, it did not tilt left or right), but did tilt north/south about its lateral axis. The north end of the span was higher than the south end as it fell. Span 7 collapsed completely into the river in slightly more than 3 seconds.

Pier 7 on the northern bank of the river appears to have remained stationary until after the collapse began.

Node L11W appears to have remained intact during the collapse. Of the five beam sections that met at node L11W, three are visible in the video. These three beams appear to have maintained their orientation relative to one another as span 7 collapsed.

Neither of the U10 nodes (east or west), which were located on the southern end of span 7, can be seen at any time during the collapse.

[1] See the Structural Investigation Group Chairman Factual Report for a description of the bridge and numbering system for the nodes of the deck truss portion of the bridge.

D. DETAILS OF INVESTIGATION

The video surveillance system had four cameras installed, one of which (camera #4) was located near the southern bank of the Mississippi river and pointed towards the northeast. A portion of the west side of the bridge can be seen in this camera's view. Figure 1 shows the approximate location and viewing angle (red lines) for camera #4. Figure 2 is an image recorded by the camera, approximately 8 minutes before the bridge collapsed.

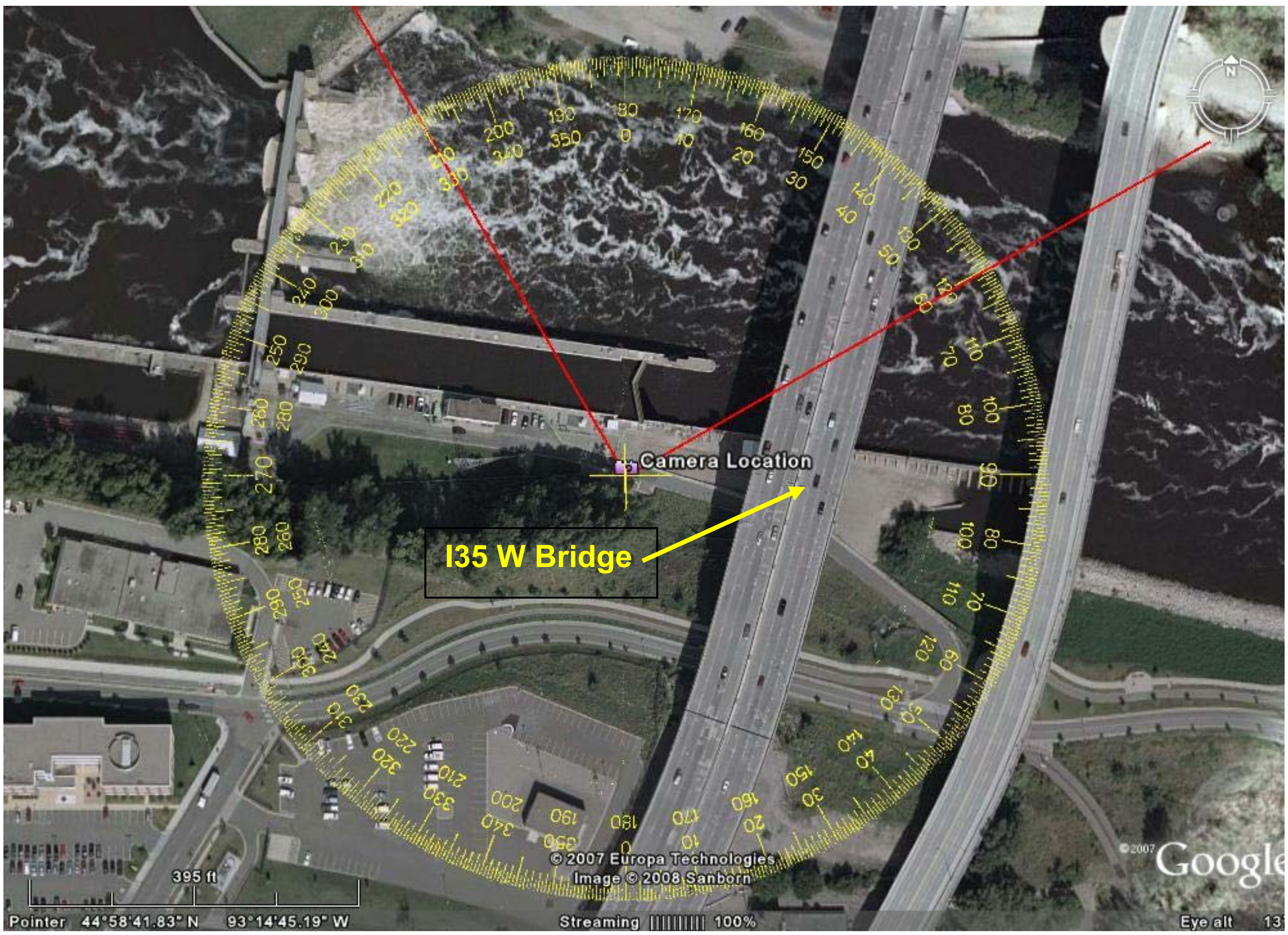

Figure 1. Surveillance camera #4 location.

Figure 2. View from surveillance camera #4 (at time 17:53:34 CDT).

The camera and recording system were always on and were operating continuously. However, recording activates only when the system's sensor detects motion activity within the camera's field of view.

The system recording "trigger" was activated just after the collapse began, and over about 10 seconds, captured 23 images of the span 7 and span 8 collapse sequence. Each of these images is presented in order starting on page 30 of this report.

Bridge Structure Visible in View

The primary structure visible in the video is the west truss of span 7, which is the span of the bridge that crossed over the river. Portions of the east truss are also visible behind the west truss. The lower nodes of the west truss are visible beginning at node L11W, which is partially visible, northward through node L9′W. The upper nodes are visible from U12W northward through U8′W. Some upper nodes north of U8′W can also be seen, though not as clearly. This means that the upper and lower nodes at 10′W and 11′W are present in the images. Most of the west side truss members are visible within this region. Most of pier 7 (northern river bank) can be seen, although a fence in the foreground obscures the western column of the pier. See Figure 3 through Figure 6.[2] “Prime” node labels (which are north of midspan node 14) are shown in yellow, while node 14 and southward are shown in red.

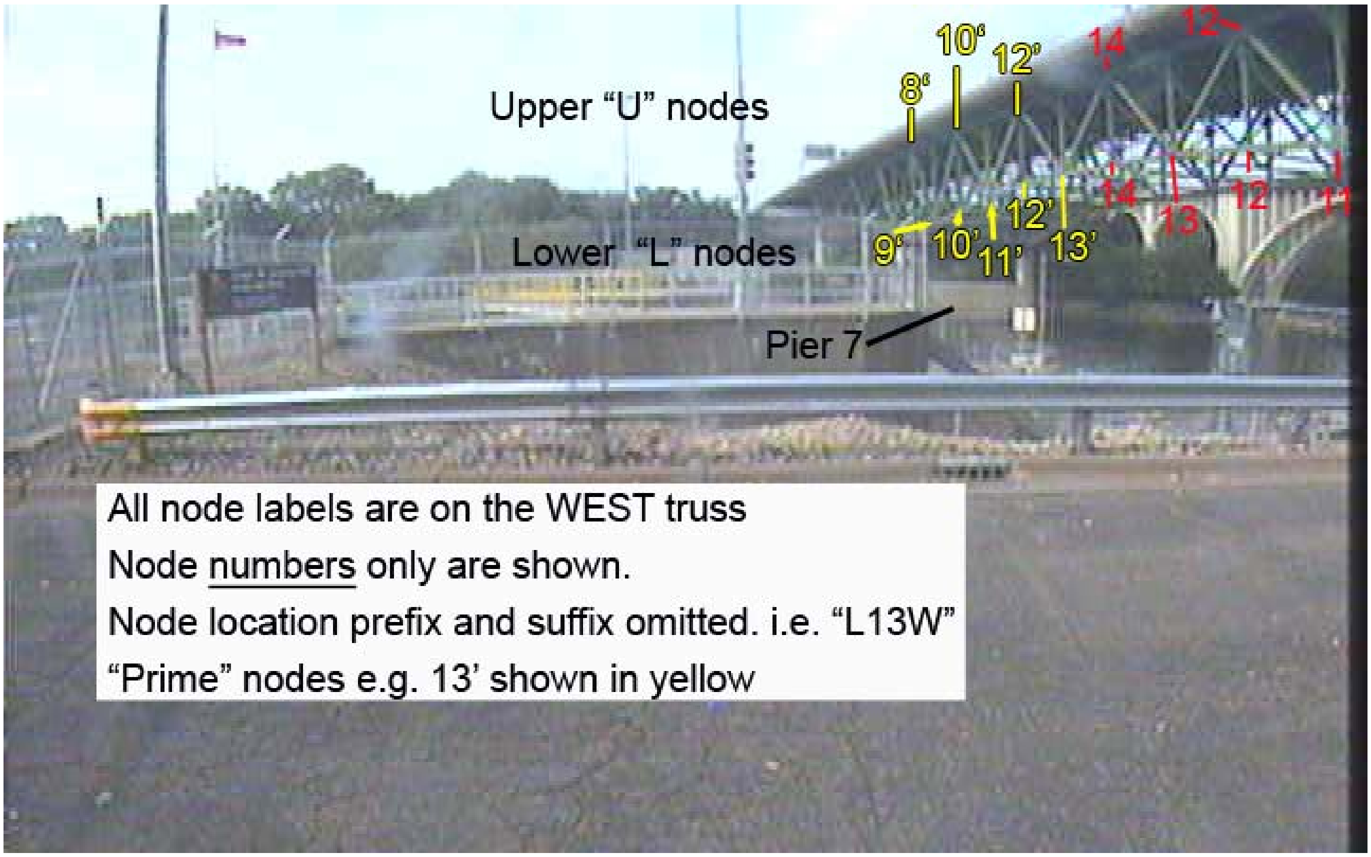

Figure 3 - West Truss Nodes

[2] Figures 3-6 all use the same image, recorded at 18:03:58 CDT, about 1 minute before the collapse.

Figure 4. West truss nodes (enlarged view).

A few of the lower nodes on the east truss can also be seen, including part of L13E northward through L8′E, as well as some of the truss members in this area.

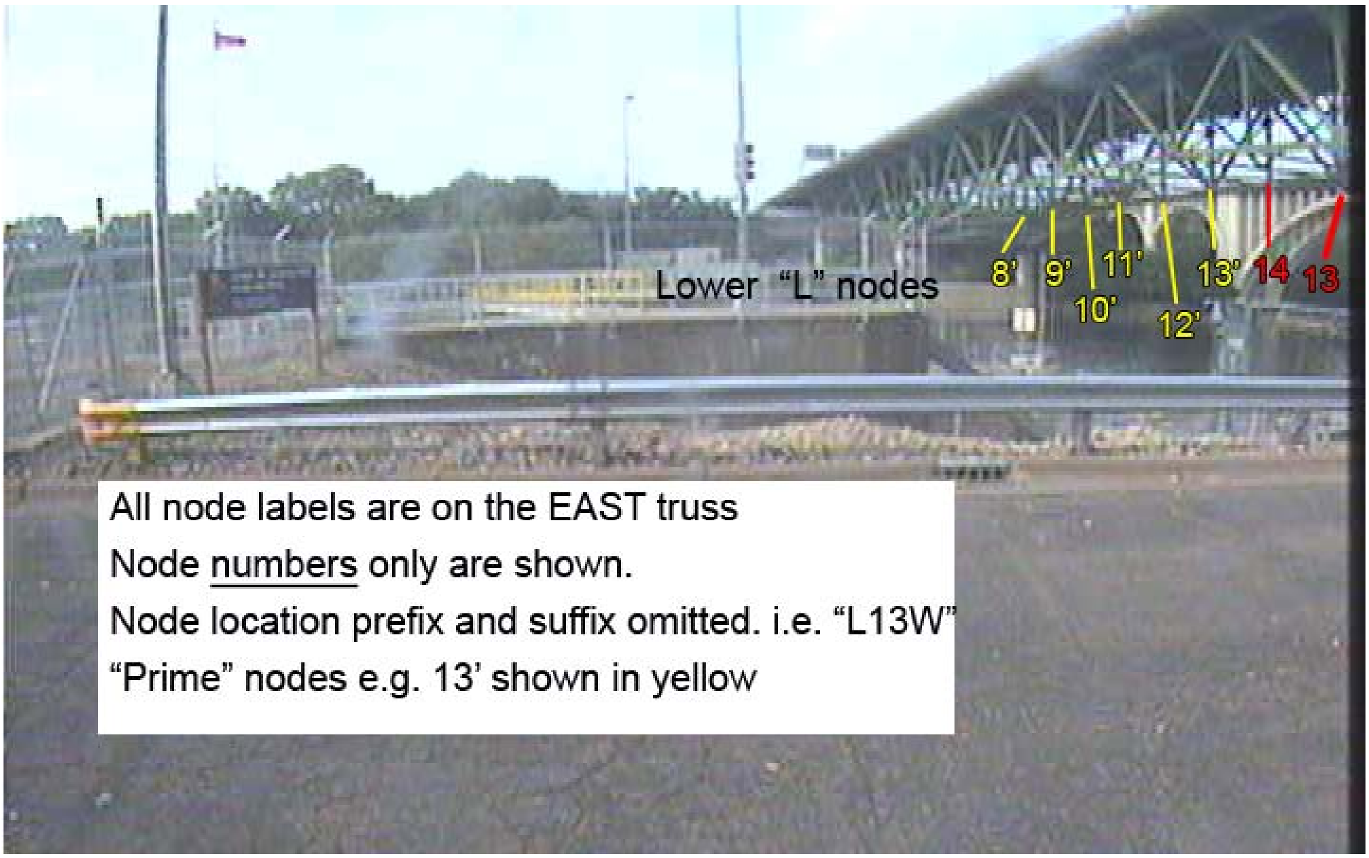

Figure 5. East truss nodes.

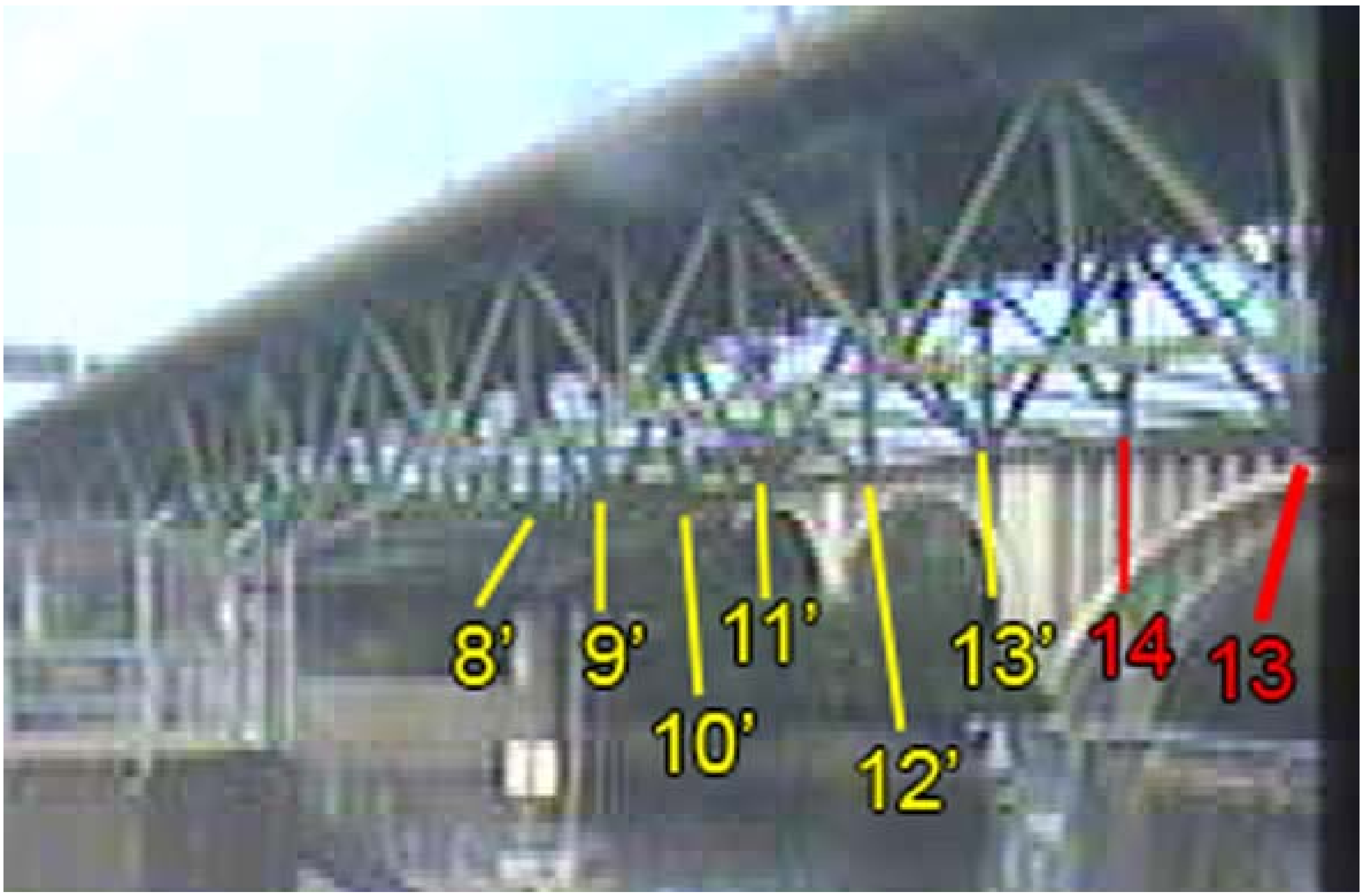

Figure 6. East truss nodes (enlarged view).

Bridge Structure NOT Visible in View

No elements of the bridge on the west truss south of vertical member U11/L11W, and no elements of the east truss south of L13E can be seen in the recording. This means that the U10 nodes (east or west) are also *not* visible. Further, none of the lower nodes on the west truss north of L9′W can be seen either. Some of the upper nodes on the west truss north of U8′W are visible, but are generally too far away to be resolved clearly.

Most of the upper nodes on the east truss that are visible in the view are too dark or blurred to be indentified, or they are obscured by the west truss.

Time Duration of the Collapse

The center span (span 7) of the deck truss portion of the bridge collapsed over a period of approximately 3 seconds. The first frame of video that shows motion of the span was recorded at 18:04:57 CDT.[3] Span 7 was in the water and presumably at rest by 18:05:00 (in the recording, it is obscured by dust/debris). However, the video system was configured to record based on scene-motion-sensing algorithms and did not record continuously. Consequently, the bridge actually started moving a short time before the recording activated, and the first image of the collapse sequence was recorded slightly after the motion began. The last image recorded *before* the collapse began was taken 59 seconds earlier, at 18:03:58.

After the collapse of span 7, a portion of span 8 north of node U8′ remained standing for another 4 seconds. This portion began to collapse at about 18:05:04. Immediately thereafter follows a 3-second gap in the recording. When the recording continue, this portion had finished collapsing, and no other portions of the remaining structure moved from this time forward. The recording continues for another 3 seconds until 18:05:10, when another gap in the recording occurs. This gap lasts 2:32 (2 minutes and 32 seconds), and the recording continues again at 18:07:42.[4] At this time, the airborne dust/debris had cleared, and the remaining northern end of

[3] All times in this report reflect the U.S. Naval Observatory clock, offset to central daylight time unless otherwise noted. Times specified with an appended letter "B" or "C" indicate a fractional sub-second time reference. See appendix A for more details on timing information.
[4] Time gaps in these types of recording systems are not uncommon. Gaps can occur when scene motion is below the motion detection threshold, or recording priority is set for other cameras in the system, or for other reasons. The cause of these particular gaps was not determined.

the bridge can be seen, as well as some portions of the bridge deck resting in and above the water line.

Table 1 lists the video segments surrounding the collapse.

Table 1. Video segments.

Video Segment	Begins (CDT)	Ends (CDT)	# of Frames
Precollapse Video (most recent contiguous segment before collapse)	18:03:55	18:03:58	10
Gap in recording	*18:03:58*	*18:04:57*	*(59 seconds)*
Collapse underway	18:04:57	18:05:04	21
Gap in recording	*18:05:04*	*18:05:07*	*(3 seconds)*
Postcollapse1	18:05:07	18:05:10	8
Gap in recording	*18:05:10*	*18:07:42*	*(2 min32 seconds)*
Postcollapse2	18:07:42	18:07:44	5

Collapse Symmetry of Span 7

The recording shows the large portion of span 7 falling into the river in a generally “flat” orientation with respect to the bridge deck. No side-to-side tilting or rolling about the span’s longitudinal axis is observed. However, as the span moved downward, a noticeable North-South “tilt” or “pitch” can be seen. The north end of the span remained higher than the south end as it fell. This is most easily noticed in the images recorded at 18:04:58.

Figure 7. North/south tilt as span 7 fell.

Figure 7 is the first of the three images recorded at timestamp 18:04:58. The white line represents a parallel to the horizon, at this location in the image. The white line was drawn on a precollapse image between nodes L12W and L12′W, which was assumed to represent a horizontal line in plane with the west truss, and parallel to the horizon. Figure 7 shows the difference between the outer (western) edge of the bridge deck and the white level horizontal line at 18:04:58, indicating a pitch or downward slope from north to south.

Localized Motion / Displacement

The video images were reviewed for any indication(s) of localized truss element motion or failure — that is, any relative displacement of a beam or other component that appeared to be separate from the uniform motion of the larger portions of span 7.

Initial Localized Motion/Displacement

Beam Section L9′ / L11′W[5]

In the first image of the collapse (at 18:04:57), a localized displacement can be seen in beam section L9′ / L11′W, at or just north of node L10′W. Figure 8 shows this area of the bridge before the collapse began.

Figure 8. Precollapse orientation of L9' / L11'W beam section.

[5] This section was one continuous beam between nodes L9’W and L11”W, passing through node L10’W. In other reports, such as the Structural Group Chairman Factual Report, this beam section may be referred to as L9’/L10’W and L10’ / L11’W.

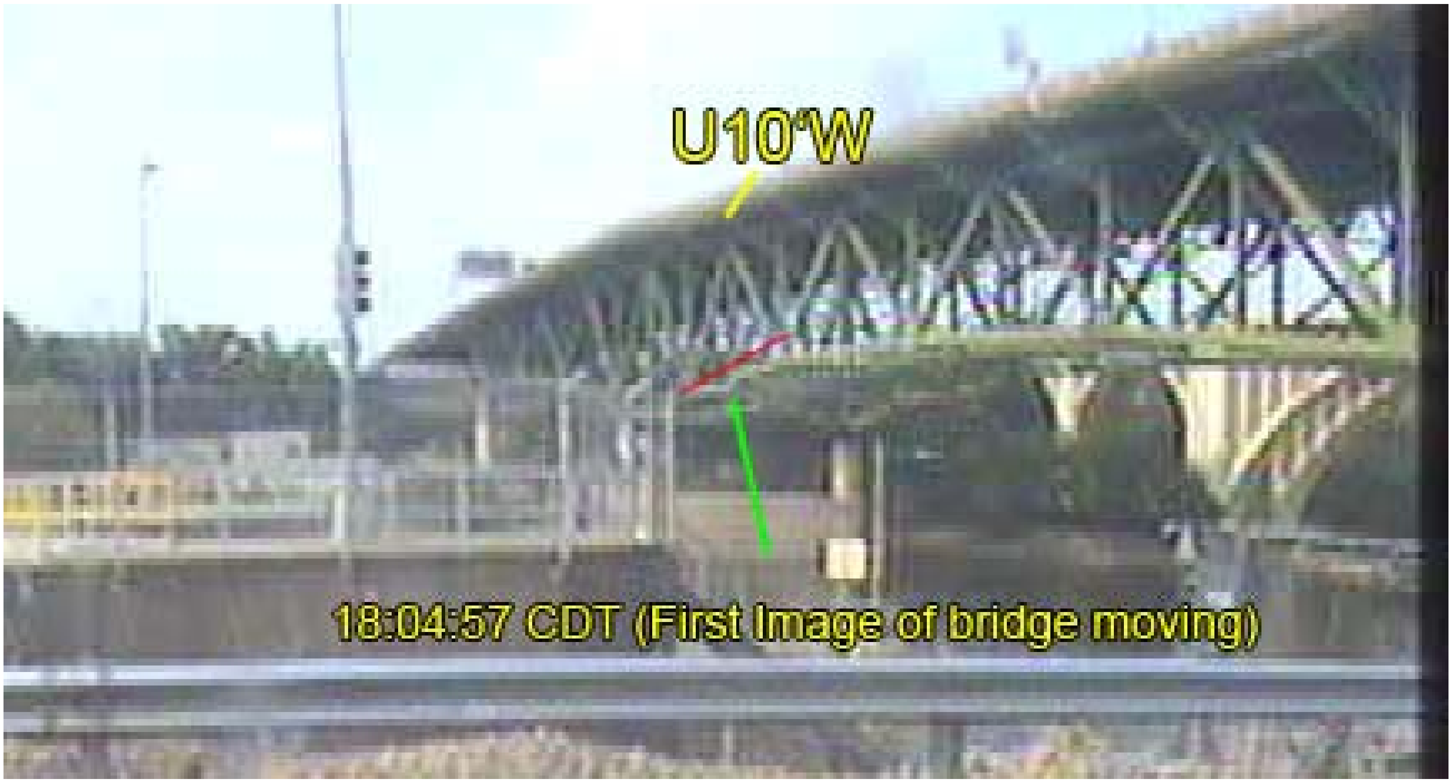

Figure 9. Discontinuity in L9' / L11'W beam section at node L10'W.

Figure 9 shows the first recorded image of the bridge moving. The red line shows the precollapse location/orientation of the entire beam section between nodes L9′W and L11′W. The green arrow points to the localized displacement that occurred after the bridge started moving, at or just north of node L10′W.

Beam Sections L7′ / U8′W and L9′ / U10′W

In the first image of the bridge moving, the upper portion of beam L7′ / U8′W appears to have bent slightly, and the top end near U8′W seems to have moved slightly southward. (See the upper green arrow in Figure 10.) Similarly, beam L9′ / U10′W appears to have bent southward near the center (or slightly below the center) (lower green arrow in Figure 10).

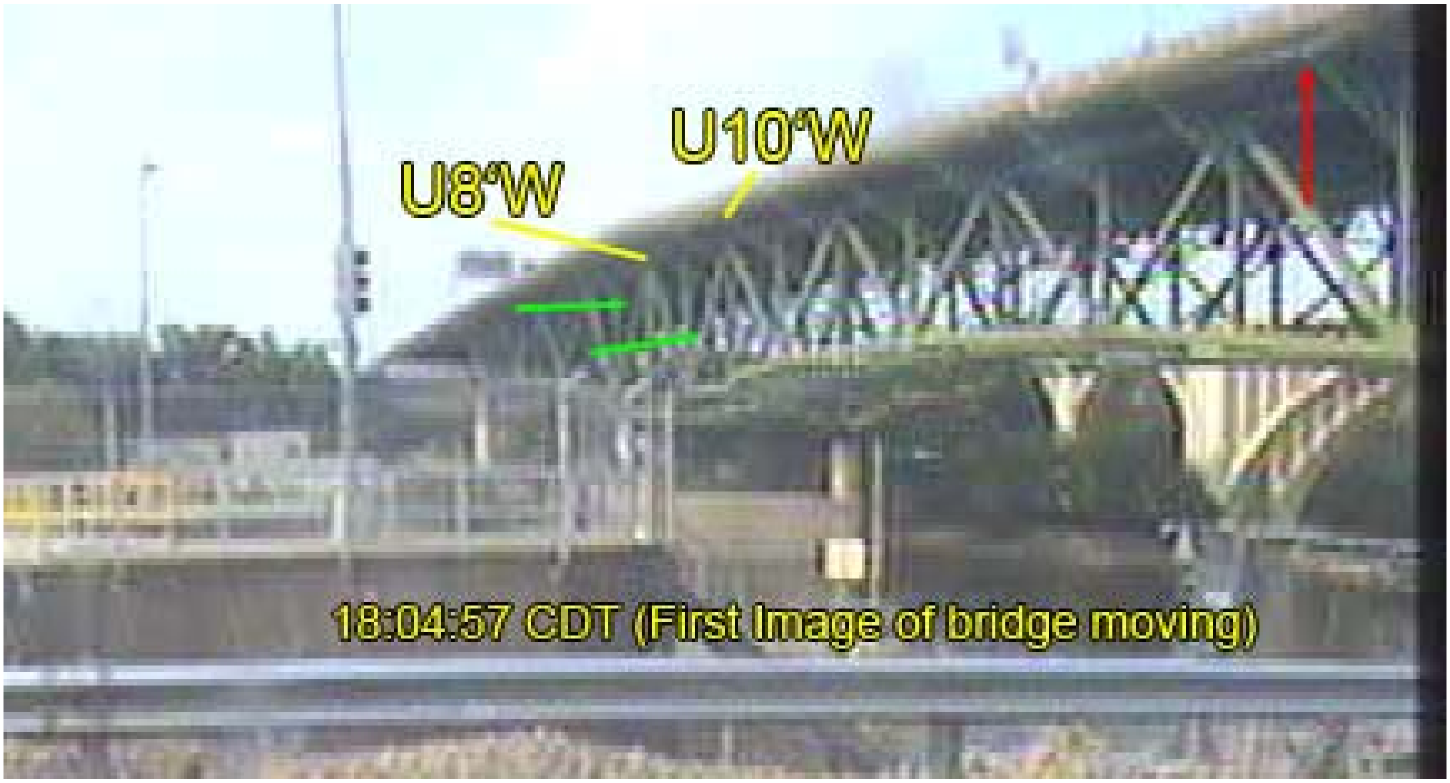

Figure 10. First image of bridge moving at 18:04:57 CDT.

Both of these apparent displacements can be seen when the 18:04:57 image is compared with the precollapse images. However, the motion seen at these locations may have been caused by artifacts introduced in the imaging process, such as distortion introduced during image acquisition or compression.[6]

According to the Structural Group Chairman's Factual Report for this investigation, the L7′ / U8′ beam was found to be intact after the collapse:

> The following members and nodes north of Node 8' were intact and were contained in the large intact portion of the truss that rotated to the north: L7'/L8' West, L7'/U8' West, U7 '/U8' West, U7'/L7' West, L7' West Node (West gusset and east gusset were bent west at lower chord member L6'-L7' from impact with ground), U7' West Node, U6'/L7' West, and U6'/U7' West.

[6] These displacements seem to be larger than other imaging system artifacts in this region that were present in the precollapse images. However, other lateral artifacts can be seen at the same vertical location in the image (for example, some lateral displacement can be seen on the pole to the left of the bridge at about the same vertical height in the image.).

Deck Stringer/ Deck at U11W Cantilever Diagonal

The westernmost deck stringer (stringer 14) appears to have separated from the bridge deck, where the cantilever diagonal met stringer 14 outboard of U11W (red arrow in Figure 10).

<u>Subsequent Localized Motion/Displacement</u>

Some localized displacements/motions of components were noted over the course of the collapse sequence, as described below.

L9′ / L11′W Beam Separates at L9′W After Bending

As the main portion of span 7 fell, some bending occurred at two locations in the L9' / L11' W beam. One bend occurred at L10′W, at or near the location of the discontinuity noted above in Figure 9. The other was at node L9′W where the beam bent downward, approximately 22 degrees before it fell away from node L9′W.

The *perceived* angle between vertical beam L9′ / U9' W and beam L9′ / L11′W, before the collapse, measured 60 degrees as noted in Figure 11 (yellow line 1 shows the precollapse location of L9' / L11 W).

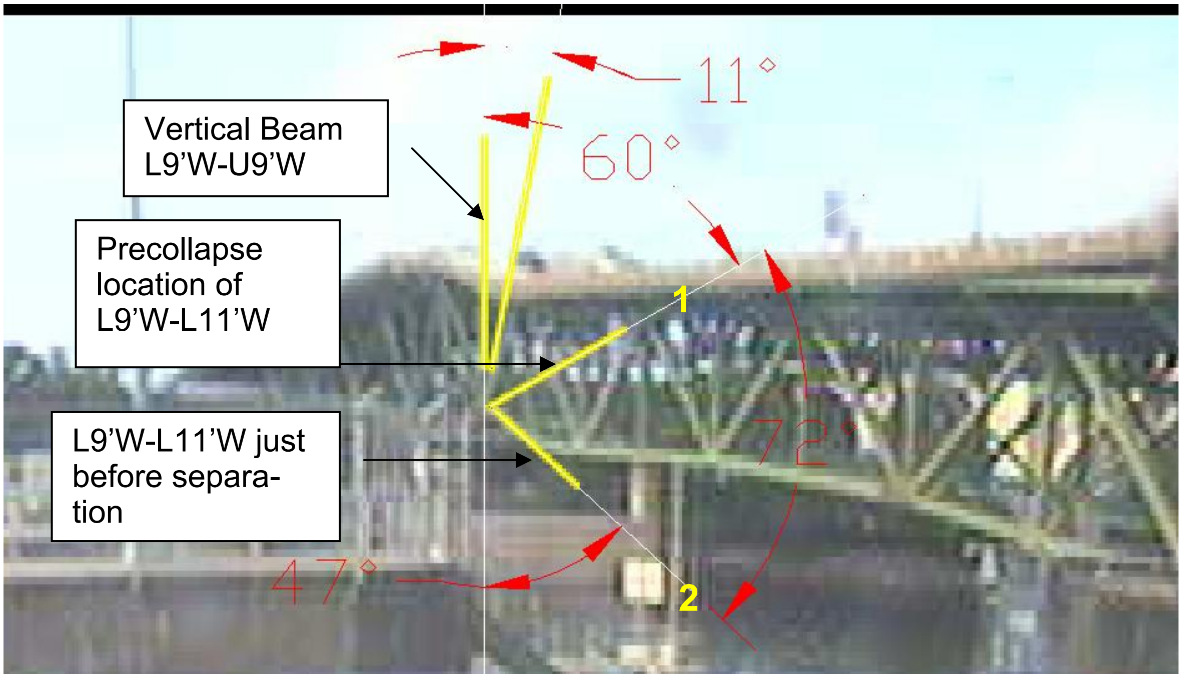

Figure 11. Perceived angles measured directly on the image.

After the collapse began (at 18:04:58 CDT, just before the beam separated from node L9′W, indicated by yellow line 2), the *perceived* angle between the L9′ / L11′W beam and the extended centerline of vertical beam L9′ / U9' W, measured 47 degrees.

These perceived angles were corrected for the oblique camera view using the following equation:

$$\alpha = \tan^{-1}\left[\frac{\tan(\alpha 1)}{\cos(\omega)}\right]$$

where α was the true angle between beams in degrees, $\alpha 1$ was the perceived angle measured from the image, and ω was the angle between the camera's sight line and a line perpendicular to the bridge truss.[7]

$\tan^{-1}$ [tan(60)/cos(75)] = 81.5 degrees

$\tan^{-1}$ [tan(47)/cos(75)] = 76.4 degrees

[7] See Appendix B for more information.

Therefore, the angle through which the L9′ / L11′W beam moved from its original position to its last position before it separated from node 9′W was:

$$180 - 81.5 - 76.4 = 22.1 \text{ degrees}$$

assuming the angular rotation was all downward, in the same vertical plane as the precollapse truss.

Pier 7 Motion

Pier 7 is visible up until time 18:04:58_C, which was about 1⅔ seconds after the first image of the collapse was recorded. Up until this time, no motion of pier 7 is observed. Thereafter, pier 7 is completely obscured by bridge structure and dust/debris until 18:07:23. At this time, it appears that the east column of pier 7 was slightly displaced eastward (towards the right of the camera view), as compared to its precollapse position.

Regions of Rigid Body Motion

Rigid body regions of motion were considered to be relatively large sections of the bridge or groups of components that appeared to move together as one unit during the collapse sequence.

Node L11W (Southernmost Visible Node)

A portion of node L11W is visible in the video. Most of the vertical beam L11 / U11 W can be seen, as well as beam sections north of this node (that is, beams L11 / L12 W and L11 / U12 W). Beams L11 / L10 W and L11 / U10W are not visible in the video.

As the bridge fell, the L11 W node and all visible beam sections entering it appear to have remained intact, and to have maintained their positions relative to one another. Staff verified these positions by overlaying reference lines along the visible beams that meet at L11 W in a precollapse image, and transposing those lines (in the same orientation) to each of the images recorded during the collapse. The reference lines indicated that all three visible beams at L11W maintained the same orientation. Also, these elements appear to have fallen together as one contiguous unit along with the truss section northward of L11W as described below. The L11/U11 beam appears to be bowed in the image recorded at 18:04:58. Figure 12 shows several sequential images (enlarged 200% and cropped) that show the area around L11W during the collapse. After time 18:04:57_C, the node is obscured by items in the foreground of the view.

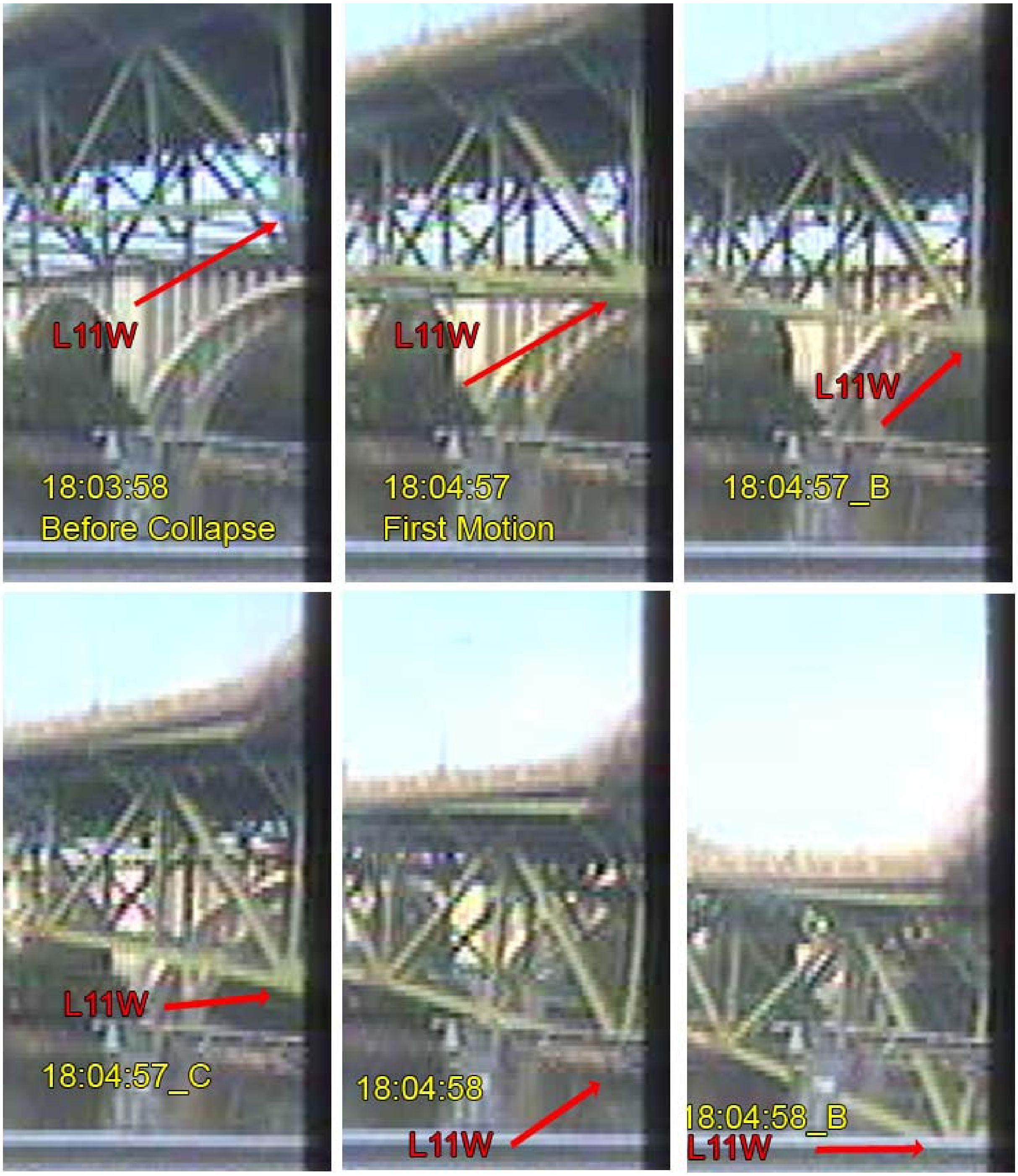

Figure 12. Sequential images of region surrounding node L11W.

West Truss, Lower Nodes L11′W, to L11W, Upper Nodes U10′W to U12W

Other than the localized motion / displacement objects noted above, all of the visible elements on the west truss (nodes, beams, etc.) in this region appear to have moved together as span 7 collapsed into the river.

Bridge Deck: U8′W Southward to U10′W

The first discontinuity or bend in the deck line can be seen in the first image of the collapse (18:04:57), just north of where the cantilever diagonal intersected stringer 14, outboard of node U10′W. The bend occurred at the red arrow in Figure 13.

Figure 13. "Bend" in deckline north of U10'W.

As the collapse progressed, a break in the deck line at U8′W occurred, creating a deck region that appears to have moved as a rigid body between U8′W and U10′W. See Figure 14.

Figure 14. Bridge deck between U8'W and U10'W.

Bridge Deck: Main Center Portion Between U10′W and U11W Southward

The solid green line in Figure 15 outlines the bridge deck from U10′W to U12W.[8] U12W is the southernmost longitudinal visual reference that can be positively identified along the deck-line at the time of this image.

The large portion of span 7 that appears to have fallen as one contiguous segment (at the deck level) extended from U10′W (left end of solid green line) to the south beyond U12W, ending at the right end of the *dotted* green line. The precise location of the right end of the dotted green line (southernmost end of the contiguous deck section) could not be determined. However, it appears to have been just south of U11W.

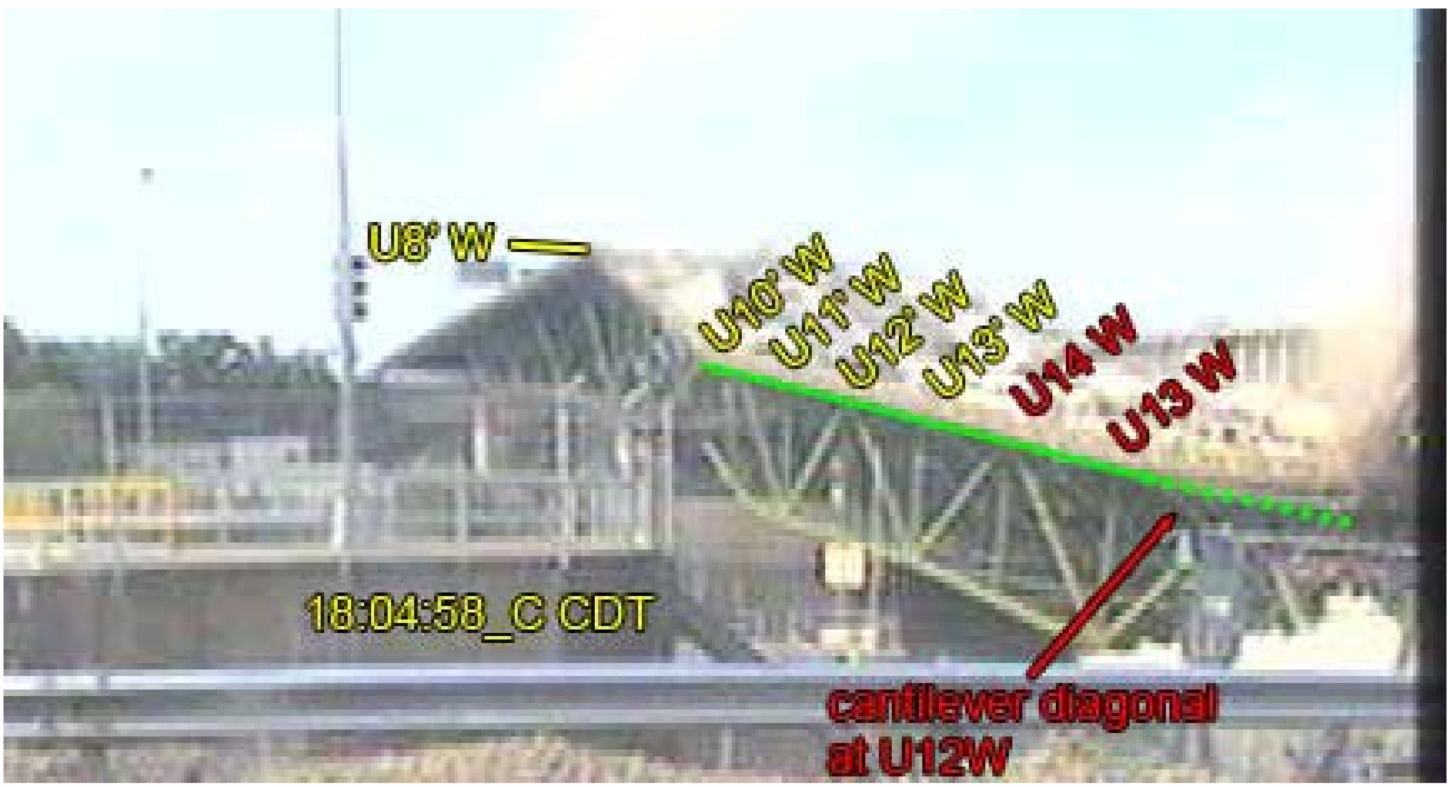

Figure 15 - Bridge deck between U10'W and U12W

[8] The green line(s) were drawn to show the outer edge of the bridge deck at the U10'W and U12W node locations, while maintaining the approximate perspective of the view. This was done by locating the ends of the solid green line at the intersections of the cantilever diagonals at the westernmost deck stringer, at nodes U10'W and U12W.

Bridge Deck: South of U11W

The red arrow in Figure 16 shows the portion of bridge deck south of node U11W, angling downward. Dust and debris partially obscure the view of the deck.

Figure 16. Bridge deck south of node U11W.

Observations of the East Truss

Once the motion began, most of the east truss was too obscured to determine any localized or rigid body motion on any of the truss elements. However, a beam section between L8' / L9' E (extending southward from pier 7) appears to have remained stationary during the first two video images of the collapse (18:04:57, 18:04:57_B). This beam was obscured by the west truss after this time. As noted previously, the collapse of span 7 generally appeared to show no rotation about the longitudinal axis of the bridge.

Apparent "Airborne Feature" in the Video

In the first few frames showing the collapse, a dark region can be seen above the bridge deckline. This artifact gives an illusion that dust or smoke might have been rising from the bridge deck in the early stages of the collapse. However, this artifact was actually fixed with respect to the camera view (it did not move), and was present throughout the recording (both before and after the collapse). This artifact is consistent with some type of contamination on the lens, the camera housing, or elsewhere in the imaging system. See Figure 17.

Figure 17. Imaging system artifact.

Figure 18. Imaging system artifact.

In Figure 18 (about 8 minutes before the collapse), this artifact is in exactly the same location as it was in Figure 17. The artifact appears lighter in color where the background is the dark bridge deck, and darker in color where the background is the lighter colored sky. After the bridge moves downward, the entire artifact appears dark in contrast with the sky.

Archived Video Reviewed

Staff also reviewed the recording from camera #4 from the period before the collapse and visually scanned the video segment from midnight, July 25, 2007, up until the collapse. The only activity noted was the presence of what appear to be two or three people walking on the lower members of the west truss between nodes L12W and L12′W, between 9:00 a.m. and 9:20 a.m. on the morning of the accident (8/1/08). According to a telephone interview with a representative from Killmer Electric, two workers were in the area that morning, and were assigned to remove spray disks from the anti-icing system on the bridge. In addition, two employees of the City of St. Paul indicated that they were also working on the spray disk removal. The City of St. Paul employees indicated that another employee of Progressive Contractors, Inc., was also under the bridge inspecting some concrete areas. All five of these employees were using one snooper truck in the course of their duties.

No trucks are visible on the west side of the bridge at this time. If these workers had been operating on the east side (from the outside northbound lanes that were closed to traffic), the truck would have been obscured by the bridge deck in the recording. From the camera's vantage point, operations of the snooper arm/bucket below the east rail of the bridge deck might appear as movement on the lower members of the west truss.

Due to the distance from the camera, the activity is difficult to discern in a single still image. Figure 19 shows the area of the activity, and one of the persons or (objects) appears to be moving along the lower members of the west truss.

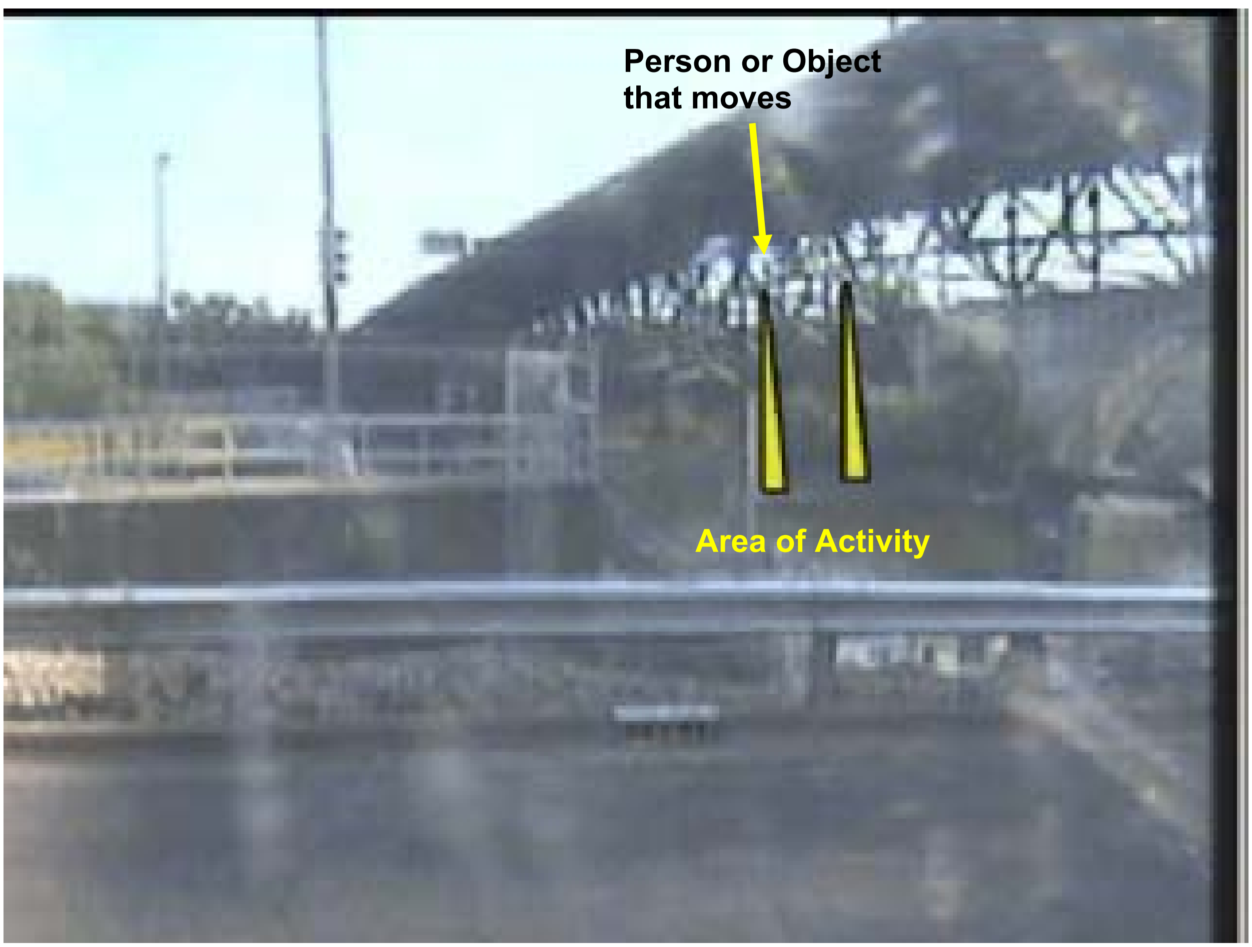

Figure 19. Location of activity between 09:00 and 09:20 on 8/1/2008.

Other Cameras

Video from the other three cameras recorded by this DVR were also reviewed for relevant information. None of the other three cameras had a view of the bridge before the accident. Camera #3 was located just west of camera #4 looking east along Cedar Avenue South, which ran underneath span 6 on the south bank of the river. At 18:11:34, well after the bridge had collapsed, camera 3 was triggered to record. Some bridge structure can be seen in the upper left corner of the camera view. The last recorded image before this time was taken about 13 minutes earlier, before the collapse began, at 17:58:27. See Figure 20 and Figure 21. The image of a pedestrian visible in Figure 21 was redacted with the black rectangle.

Figure 20. Camera #3 view at 17:58:27.

Figure 21. Camera #3 view at 18:11:34.

Complete Sequence of Recorded Video Images from 18:03:58 to 18:05:07 CDT

The following images represent the complete sequence of recorded video images from 18:03:58 to 18:05:07. The images were enlarged by 125% and cropped to the upper right corner. All times are central daylight time.

18:03:58 (before collapse).

18:04:57 (first image recorded of the collapse).

18:04:57_B

18:04:57_C

18:04:58

18:04:58_B

18:04:58_C

18:04:59

18:04:59_B

18:04:59_C

18:05:00

18:05:00_B

18:05:00_C

18:05:01

18:05:01_B

18:05:01_C

18:05:02

18:05:02_B

18:05:02_C

18:05:03

18:05:03_B

18:05:03_C

Note: A gap in the recording of approximately 3 seconds occurred here.

18:05:07

Note: some ghosting of previous image is present; cause is unknown.

18:05:07_B

Note: only two images were recorded at time 18:05:07.

18:05:08

18:05:08_B

18:05:08_C

18:05:09

18:05:09_B

18:05:09_C

Note: a gap in the recording of approximately 2 minutes, 32 seconds occurs here.

18:07:42

All of these images are available individually in digital format, along with two short digital video clips, in the public docket for this accident investigation. See the separate cover titled Digital Video Recording Images - HWY07MH024.

Doug Brazy
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NTSB Vehicle Recorder Division

APPENDIX A

Digital Video Recording System and Image Information

General Information

The digital video recorder (DVR) was a multiple camera security video system, which recorded video signals from (what appeared to be) analog cameras. The system was motion activated, such that when the recorder itself detected changes in the view from the camera, recording began. Recording continued as long as the system sensed motion, and then stopped 2 seconds after motion was not sensed. The recorder retained system date, time (to the nearest 1 second), and camera name for every image recorded.

Timing and Conversion to USNO CDT Reference

The DVR system clock was 199 seconds (3min 19 seconds) behind the U.S. Naval Observatory (USNO) clock. Times in this report reflect the USNO time reference, which was offset for central daylight time by adding 199 seconds to the DVR recorded time for any given image.

The DVR recorded time to the nearest whole second, although it typically recorded images three times every second. As a result, three consecutive images all had the same timestamp. Since the precise subsecond time of each image was not known, images in this report were labeled with a “B” or “C” appended to the timestamp, to represent the second and third images in a 1-second sequence. For example:

18:04:57	1st image with timestamp 18:04:57
18:04:57_B	2nd image with timestamp 18:04:57
18:04:57_C	3rd image with timestamp 18:04:57

Frame Rate

Although the precise frame rates for this system could not be determined, examination of the images from camera 4 yielded a rate of approximately 3 images per second.

DVR Specifications and Settings

DVR Make/Model/Serial Number:
Dedicated Micros / Digital Sprite 2 Model # DS2AC DX16C-600GB/ S/N MT052717N018

Recovered System Settings
[Record Schedule]
(Day):
Standard PPS 006
Event PPS 006
Event Active ....Activity
Event Mode ....Interleave
Recorded File Size 16KB
Max Recording Time ....--:--
Main Storage (protected) 2GB (0%)
Event Storage ....553 GB
Earliest Recording ....8/02/2007 (Standard Recording Type)[9]
Earliest Event ....12/13/2005 (Event-Based Recording – Motion Activated)

[Advanced Record Schedule]
Update Rates per Camera
(Day)
Average (secs)..............0.33
Low (secs).....................1.00
STD (secs)....................0.50
High (secs)....................0.25

[9] This system was not configured to record using the standard recording type, which is time-based. It was instead set up for event-based recording. This earliest standard recording was recorded after the accident.

[Activity Camera Setup]
(All cameras indicate the following)
Detection.............ON
Sensitivity............Outdoor Low
Activity Grid – Setup (All elements in the motion sensing grid were active; no areas were excluded from motion detection.)
Activity test...........Walk Test

[Activity Setup]
Pre-Activity.......................00min 00 sec
Post-Activity ....00min 02 sec
Auto Copy........................No
Relays (edit menu)
Extended Relay................Off
Activity Display.................No
Activity Buzzer..................No

Image Processing

Manufacturer-supplied software was used to connect to the DVR through an Ethernet connection and to download recordings from the unit's hard disk drive. The recordings were downloaded in the native manufacturer's proprietary file format. These proprietary files can be viewed (and single images exported from them) on a PC computer using another software viewing program provided by the manufacturer. All 31 images recorded between 18:03:58 and 18:07:42 (spanning the collapse) were exported one at a time in Windows .BMP format. Several other images before and after this time were also exported for reference. The export program yields images with pixel dimensions of 720 x 448, although the DVR records images at only a 720 x 224 pixel size. It appears that this DVR digitizes and records approximately half the analog NTSC video frame (called a video field), which is every other NTSC scan line visible on a typical television monitor.[10] Field-based recordings are common in multi-camera surveillance systems. Presumably, the viewer/export utility expands the recorded digital image to 720 x 448 pixels when exporting an image, in order to preserve the aspect ratio of the image.

[10] 720 x 224 is approximately 1 NTSC video field. A digitized full NTSC video *field* is typically considered to be 720 x 240 pixels.

The exported images were loaded into individual layers in an image-viewing program so that they could be examined. This process allowed staff to compare the images easily by choosing which layer to view on top, while all of the images remained in exactly the same location on the screen. Reference lines and annotations were added as new layers that could be toggled on or off, which was useful when comparing the previous locations of beams, nodes, and other components with their locations in subsequent images.

All Images in this report were exported from the analysis-viewing program at their original pixel size of 720 x 448, with a resolution parameter of 72 pixels per inch. Unless otherwise specified, the images were enlarged 125% and cropped to the upper right corner of the image by the same amount in each figure.

Angular measurements were made by importing images into a computer-aided drafting (CAD) application. Reference lines were constructed by tracing over any elements of interest in the image, and angles were measured between reference lines using the CAD application.

APPENDIX B

Beam L9′ / L11′W Angle Calculation

The camera's view of the bridge truss was at an oblique angle, which caused angles between truss members to appear larger or smaller than the true angle between them. Given the angle between the camera's sight line and the plane of the bridge truss, an equation was derived to transpose angles measured in the plane of the image to their true angles.

In order to estimate the swept angle of the L9' / L11' beam, the following correction was derived.

Correction Equation Derivation

Determine the angle from the camera to the area of interest, relative to an orthogonal view.[11] See Figure 22 below.

- Measure true heading of bridge centerline in Google Earth (white line - 015 deg true).
- Measure true heading of a line from camera to area of interest[12] (red line - 030 deg true).
- Camera sight line is 75 degrees (angle "B") from an orthogonal view (green line is orthogonal to bridge truss plane) [90-(30-15)].

[11] For an orthogonal view, the viewing axis sight line would be oriented 90 degrees to the plane of the truss. An ideal orthogonal view would not require this correction. The amount of correction required is proportional to the difference between the camera's sight line angle and the ideal 90-degree orthogonal angle.

[12] The west column on pier 7 was chosen as a reference to scribe the red line. Since this column is not visible in the Google Earth Image, the line was scribed through the west edge of the bridge at the northern shoreline.

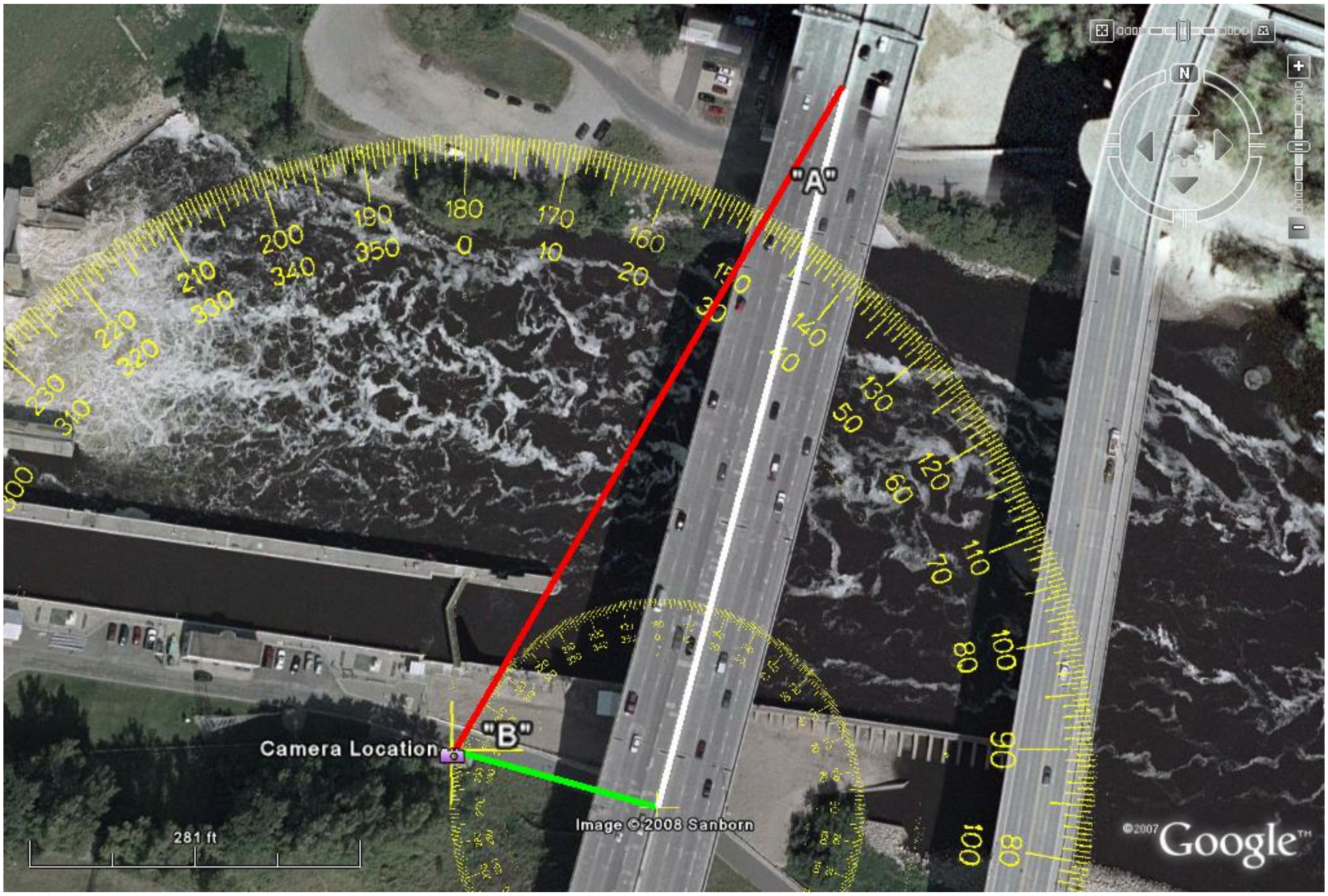

Figure 22. Camera angle.

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With this estimate of the camera angle, staff were able to transpose measurements taken directly from the images of the bridge truss from the plane of the camera's image sensor into the plane of the bridge truss, as described below. This provided a correction from the perceived angle as seen in the image, to a true angle between truss members.

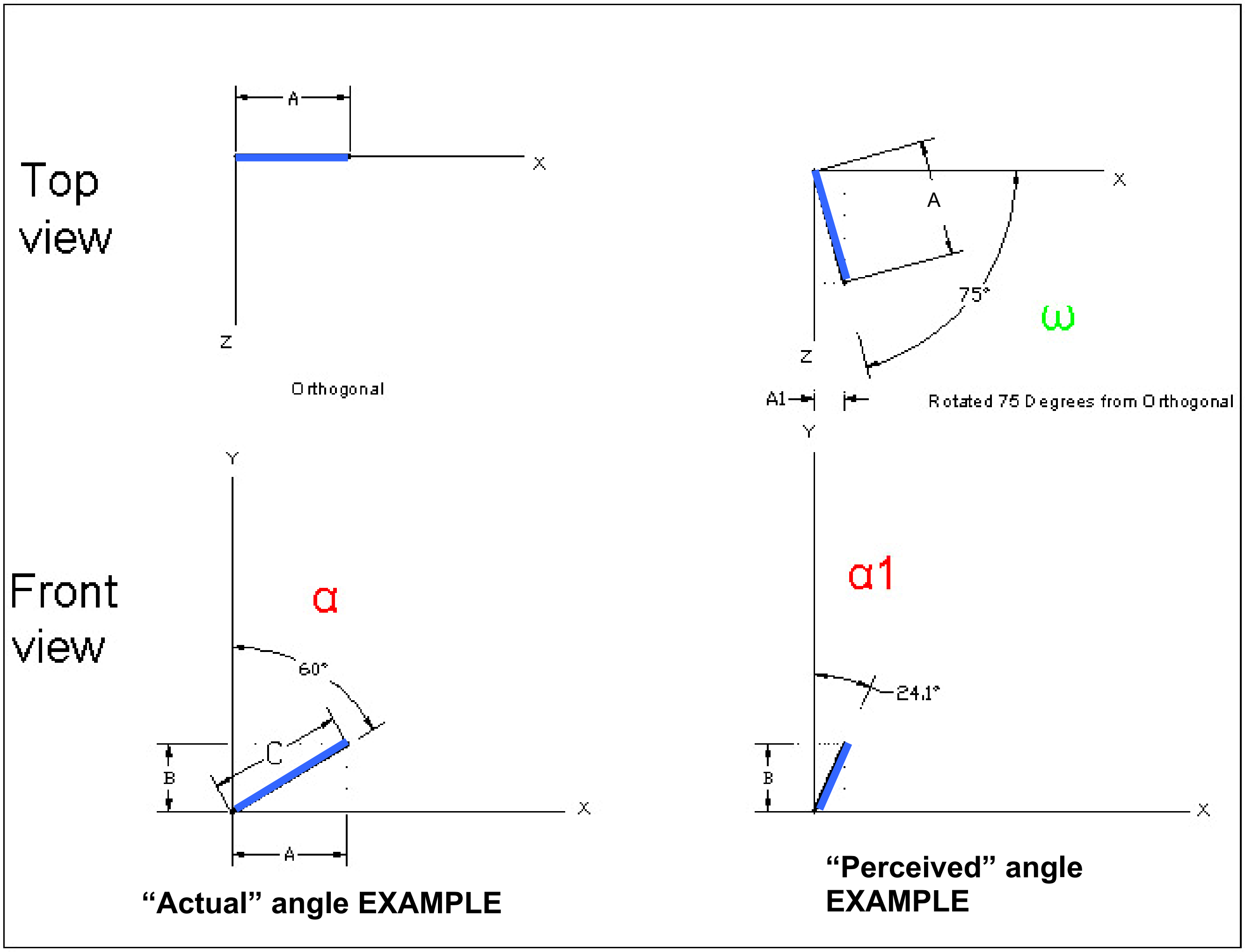

Figure 23. Perceived angle correction.

The lower left "front view" in Figure 23 shows a blue line in the XY plane at a true 60-degree angle to the Y-axis (angle α), as viewed orthogonally. In this view, a direct measurement of α would yield its true angle of 60 degrees. (If the camera angle had been 90 degrees to the bridge truss, a true 60-degree angle between two truss members would measure as 60 degrees on the image.) The upper left top view shows the orientation of the blue line as viewed from directly above (looking down the Y-axis at the XZ plane).

The lower right graphic in Figure 23 shows how the same true 60-degree angle would appear if the blue line were rotated about the Y-axis toward the camera by 75 degrees. This would represent the orientation of the surveillance camera as it viewed the bridge truss. In this view, a direct measurement of the angle between the blue line and the vertical Y-axis would be 24.14 degrees. This direct measurement can be corrected to the true angle using Equation 1:

$$\alpha = \tan^{-1}\left[\frac{\tan(\alpha 1)}{\cos(\omega)}\right] \qquad \text{(equation 1)}$$

Equation 1 can be derived from Figure 23 as follows:

tan (α) = (A)/(B) [lower left graphic] (equation 2)

A = A1 / cos(ω) [upper right graphic] (equation 3)

A1 = tan (α1) * B [lower right graphic] (equation 4)

Substituting equation 4 into equation 3:

$$A = \frac{\tan(\alpha 1) * B}{\cos(\omega)} \qquad \text{(equation 5)}$$

Substituting equation 5 into equation 2:

$$\tan(\alpha) = \left[\frac{\tan(\alpha 1) * B}{\cos(\omega)}\right] \Big/ B$$

solving for **α** yields equation 1:

$$\alpha = \tan^{-1}\left[\frac{\tan(\alpha 1)}{\cos(\omega)}\right]$$

Applying the example angle values shown on the right side of Figure 23:

$\alpha 1$ = 24.14 degrees

ω = 75 degrees

The true angle on the left side of Figure 23 can be computed:

$$\alpha = \tan^{-1}\left[\frac{\tan(24.14)}{\cos(75)}\right]$$

α = 60 degrees

This method corrects only the horizontal component of the camera's sight line to the plane of the bridge truss. The camera was located at a lower elevation than the area of interest of the bridge truss; however, the elevation angle was small compared to the horizontal angle and was assumed to have a negligible effect. To check this assumption, as well as the logic and derivation of the horizontal correction, staff measured a known angle between two beams on the bridge truss and then corrected using Equation 1. The angle between vertical beam 9′ and the nearest south diagonal L9′ / U10′W was used for this check because it was easily computed from drawing measurements and was near the area of interest.

From the Deck Truss Span Stress Sheet drawing, the L9′ / U9′W vertical beam length is known to have been 51.3 feet. The horizontal U9′ / U10′W beam was 38 feet. These measurements yield a true angle of 36.5 degrees between the 9′ vertical beam and beam L9′ / U10′ [$\tan^{-1}$ (38/51.3)].

> Measure the perceived angle between these two beams as seen in a precollapse image (11 deg).
> Plug into equation 1
> $\tan^{-1}$ [tan(11)/cos(75)] = 36.9 degrees

The computed angle compares favorably (within ½ degree) with the actual angle.