KSI: Kinzua Site Investigation

The Forensic Study of the July 21, 2003, Collapse of the Kinzua Viaduct

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As professional engineers, we often design and build structures, such as the Kinzua Viaduct, albeit seldom of its magnitude. However, rarely does the opportunity arise to step outside the purely quantitative realm of design codes and material properties to conduct an investigation in the manner of a detective or private investigator.

The Kinzua Viaduct — October 2004

On August 12, 2003, the Board of Inquiry (Board), a group of structural engineers, material engineers, meteorological scientists, and government engineers, proceeded to the "scene of the crime," minus the chalk line and yellow tape, to conduct a one-day forensic investigation into the tragic collapse of this historic structure.

The case file — On the afternoon of July 21, 2003, a wide range of severe weather moved into western Pennsylvania along a north-by-northwest track, spawning widespread thunderstorms and several tornadoes. At approximately 3:20 p.m. local time, a Class F-1 tornado touched down immediately east of the Kinzua Viaduct, a structure listed on the National Register of Historic Places and designated as a Civil Engineering Landmark.

The victim — The 301-foot-tall, 2,053-foot-long, Kinzua Viaduct — an engineering landmark and the jewel of the Pennsylvania State Park system.

The scene — Kinzua State Park is located approximately six miles east of Mt. Jewett, PA, in McKean County in north central Pennsylvania. This is approximately 17 miles south of the New York-Pennsylvania border.

Investigation Procedures

As with any investigation, certain questions surrounding the structural failure of this bridge had to be answered through both evidence gathered at the site and laboratory analysis. Aerial photography of the collapse and existing blueprints of the viaduct were provided by the state and used to determine exactly what transpired.

Laboratory analysis of failed structural components revealed the mechanics of the collapse on a microscopic level. The Board was able to answer the "what," the "when," the "how," and the "to what degree or extent" through a series of forensic markers that were reveled during the site investigation and the weeks of critical examination that followed.

These markers were order markers, direction markers, separation markers, and fracture markers, and each played its own role in the determination of the exact cause of the collapse. Additionally, eyewitness testimony from workers who were present at the site on the fateful day was crucial in corroboration of the reconstructed failure sequence, which was uncovered by the Board.

Order Markers

Using aerial and site photography, engineers were able to piece together the exact collapse sequence as it occurred on July 21, 2003. Analogous to the collecting of fingerprints at a crime scene, inversion of the debris clusters at the site was performed using a physical compatibility approach. Logically, the towers or other members lying on top of the pile would have collapsed last. Using this reverse progression, the failure sequence was reconstructed, and a series of four distinct collapse "episodes" was determined to have occurred during a 30-second time period. This assumption was confirmed by eyewitness testimony. The site superintendent of a crew performing rehabilitation work that day said, "…I heard four or five loud booms."

Direction Markers

The direction of both tree trunk debris and the collapsed towers at the Kinzua site led the forensic team to determine that the direction of wind and, ultimately, a structural "weak link" were responsible for the bridge's collapse. By viewing aerial photography of the site, two distinct paths of wind attack were evident. First, tangential winds emanating directly from the tornado's vortex impinged the structure from the east. Next, strong inflow winds, which fed the tornado, attacked the structure from the south. These two separate wind events, with estimated speeds of up to 100 mph, occurred nearly simultaneously, differing from the common practice of structural design with regards to wind design.

From the existing bridge construction drawings, it is evident that the designer assumed the west to be the predominant wind direction and, consequently, fitted the structure with fixed bearings at the western side of the structure and nested roller bearings on the eastern side. As the wind barraged the structure from the east, these fixed western bearings acted as hinges, about which the structure rotated and toppled. Further investigation revealed that more than 75 percent of the eastern roller bearings were deteriorated and offered no resistance to the excessive uplift forces.

Separation Markers

Site examination of the bearings and anchor bolts of the Kinzua Viaduct revealed that many of these elements had failed or had been critically damaged many years prior to the structure's collapse. In fact, it is estimated that up to 75 percent of the anchor bolts were deteriorated and should have been attributed with a substantially reduced capacity or zero capacity during analysis.

Existing 1901 construction drawings indicated that all of the anchor bolts were reused from a wrought iron structure that had been originally built at the exact same geometric configuration in 1882. Roller-bearing collar-coupling assemblies were constructed to attach the new structure to these existing bolts, as they were too short for the newer design. By examining these collar-coupling assemblies at the site, it was evident that they were all corroded, and many were critically fractured previous to July 2003. The site observation that failure occurred at this interface at every failed tower confirmed two things — the Board's theory of the mechanism of collapse, and the assumption of the anchor bolts as the structural system's weak link.

Fracture Markers

As indicated, it was evident from the site investigation that deteriorated anchor bolts had resulted in the Kinzua Viaduct's inability to withstand the violent winds of the extreme storm event. What was not apparent was what had caused the reduction in the capacity of these structural elements.

Subsequent to the field view, the Board performed a series of laboratory metallurgical tests on the anchor bolts and collar-coupling assemblies. What was observed was a series of distensions in the crystalline iron structure of the elements indicating not only tensile overstress, but also evidence of excessive cyclical fatigue stresses. These markers indicated that the majority of the structural damage to these elements had occurred, not during the storm event, but during the previous 102 years, under the constant cyclical loading of wind and trains.


Fractured collar-coupling assembly


Aerial photography of the Kinzua site was crucial in determining the cause and order of collapse

Conclusion

With the evidence collected and documented, and all questions answered, the Board prepared a report of its findings to the bridge's owner, the Pennsylvania Department of Conservation of Natural Resources (DCNR). The report summarizes the meteorological, metallurgical, and engineering evidence and provides collapse diagrams, back-calculation of wind loading, summaries of eyewitness testimony, and even a computer-generated animation of the collapse. This report is available online at http://www.dcnr.state.pa.us/info/kinzuabridgereport/kinzua.html.

Therefore, the final piece of the puzzle can be fit into place:

The culprit — The Kinzua Viaduct was unable to withstand the 94 mph winds of the extreme mesocyclonic storm event at the site due to a series of hidden fractures in the structure's collar-coupling assemblies and anchor bolts in its bearings. Fatigue most likely incapacitated these elements years before the tornado, which ultimately caused the historic railroad viaduct's demise. ■

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