Structural Integrity: designing against failure

Reconstructing the collapse

Tom Leech
We determined the sequence of events where the collapse in three distinct episodes. Let me describe those episodes. During the first episode, as the tornado touched down and moved in a northerly direction, leading edge winds affected the structure. The first group of towers occurred a separation failure at their base and were displaced a little to the west and were held momentarily in an upright, uh, position by the rails that were still attached to the towers. The next group of towers as the tornado moved northward were affected by the leading edge winds, separated at the base and toppled in a westerly direction, followed by the northern most section of towers which similarly fell in a westerly direction. Finally, as the inflow winds attacked the structure, the southerly group of towers then collapsed in a northerly direction.

Francesca Hunt (narrator)
The booms which were heard were almost certainly the sound of each group of towers hitting the ground. But the bridge was designed to resist lateral tornado- strength winds of up to 100 miles per hour, so what caused the towers to collapse?

Eugene Comoss
In the structural design of the towers, the load was transmitted from the deck down through the tower legs to the pedestal bases and the tower legs were fastened to the pedestals by, uh, use of an anchor bolt that was embedded in the pedestals and then bolted to the tower legs.

Francesca Hunt (narrator)
In the pedestal bases higher up on the flanks of the gorge the original base bolts from the 1882 bridge were of sufficient length to bolt the towers down. But this wasn't so down at the bottom of the gorge where the towers failed, where the bolts had been modified.

Eugene Comoss
In the towers that failed, anchor bolts similar to this anchor bolt was the principal cause of failure. Uh, the reason for the failure was the method, the designers of the 1900 reconstruction chose to fasten the towers to the, uh, 1882 pedestals. In…in their fastening, they extended the anchor bolt by approximately six inches and then fastened that six inch extension to the original anchor bolts by use of shims and a coupling.

Francesca Hunt (narrator)
So the weakest link in the load path occurred where the bolts were lengthened.
To the original bolt embedded in the base, spacing shims were added and then a wrought iron collar, or coupling, was attached. Into this the additional length of bolt, required for tying-down the new towers, was screwed into place. These joints were unprotected, water percolated into the collars leading to corrosion fatigue as the rust expanded – resulting in vertical cracking. Evidence recorded by the inquiry, shows the degree of the corrosion suffered by the collars. Cracks like this weren't safety critical because the base of a tower will have been held down by gravity but they became the weakest link with very high lateral wind-loads.

Tom Leech
There's an interesting comparison between the collapse of the Kinzua Viaduct and the Tay Bridge collapse. Both bridges exhibited the same four forensic markers. Another interesting fact observed from the historical photographs are the towers on either side of the collapse.

Both towers reveal clear evidence of a high degree of oscillation that occurred during the collapse cycle.

Francesca Hunt (narrator)
At the Tay Bridge, each of the towers which fell collapsed in winds much lighter than those that hit the Kinzua viaduct. Originally they looked like this. Being a vertical column, it has considerably less lateral stability than an inclined tower such as the towers at Kinzua. It's a top heavy structure because the wrought iron deck weighed nearly 4 times as much as the towers. The use of cast iron lugs to connect struts and tie bars to the columns was wrong, because they cracked when strained cyclically. The way the lugs must have behaved when the towers oscillated can be contrasted, at Kinzua, by the strength of the riveted joints which kept each fallen tower pretty much intact.

Tom Leech
Let's consider the collapse of one individual tower. As the leading edge winds affected the tower, the tower immediately started to vibrate at its natural frequency. As the tower was attacked by the wind, the wind increased in intensity, the tower vibrated more and when a sufficient wind speed was generated, the towers experienced a separation failure at the base on the windward side. The tower then became airborne and collapsed in the direction of the wind, and experienced large scale fractures and deformation upon impact.

Francesca Hunt (narrator)
Conversely, at the Tay Bridge, the towers fell down, more like a house of cards.
Tie-bars, both upwind and downwind, were seen to have failed in the towers still standing. The inference has to be that the tie bars failed as the result of the fracture of the brittle cast iron connecting lugs. This is what's surmised happened in the collapse cycle, once a high girder tower started to oscillate the weakest links in the load path became the lugs. As the oscillations grew in amplitude, the lugs failed in succession. Struts, also held by lugs, similarly failed ….until the tower separated into two…. which then collapsed together, with some toppling, into the estuary. The remains of the old bridge, just the piers, were left in place and in fact they are still visible today running alongside the replacement Tay Rail Bridge

(Voices off: What's actually going to happen at the end of the tower? Well, right now…)

Francesca
Kinzua's not going to be replaced, but there's an ongoing debate about its future ….

Linda
One of the ideas that had been presented was also using maybe a laser light show to recreate the structure visually at night. Is that going to be possible?

Eugene
Well, actually when the idea was initially proposed we thought it was a little far out but since then we've had ……

Francesca Hunt (narrator)
Whatever plans win the day, in one way or another, the viaduct will be preserved as a tribute to an engineering masterpiece – albeit one that met its match when the forces of nature exposed the weakest link in the viaduct's redesign. But the forensic investigation hasn't just answered questions about what happened at Kinzua and Tay; in terms of the dynamic oscillations that both those bridges experienced. More importantly, the findings from any disaster have to be made known as widely as possible so that remedial action can be taken to prevent similar catastrophes.

Tom Leech
Trestle bridges, such as the Kinzua Viaduct, with such a high height and a relatively narrow base, are what we've termed wind susceptible structures, and these are at risk certainly from high wind events. We have made many public presentations on this topic, and as a result of these presentations we have been contacted by owners of other structures enquiring to the manner of collapse and what these folks need to do with their structures.

Francesca Hunt (narrator)
So, clearly, trestle bridges have to be continually inspected and maintained throughout their lives – but, on open structures like these, any corrosion is at least visible to inspection and so can be treated. But solid mono block structures, or concrete towers, rely on internal steel reinforcing bars. And yet corrosion in the steel reinforcing bars is the weakest link within concrete structures too. Any corrosion damage which occurs is not apparent at all and may only be seen if a bridge cracks - due to the internal pressure of the expansion of corroding metal – at which point a bridge may be doomed. At Mingo creek the new road bridge spans an existing trestle in a dramatic juxtaposition of old and new technology. What lessons have gone into the construction of the new bridge with regard to minimising corrosion and particularly the problems associated with drainage, further exacerbated here, by the need to add highly corrosive salt to the road in winter?

Tom Leech
There's a wonderful contrast between this new interstate class structure and the existing viaduct structure. I was the principal designer for the new structure. My design team took corrosion into account in the following manner. All the structural elements are weathering steel in tight patina forms that protects the steel from corrosion. We look carefully at the joints, especially at the bearings. We take the expansion joints and extend them to the very ends of the structure to prohibit the salt penetration.

Francesca Hunt (narrator)
The work of the design engineer today is crucial to the integrity of any structure but especially bridges and other structures exposed to the external environment. It's only by careful consideration of the detailed design of the safety critical joints that the long term integrity of structures, such as these, will be assured for their users.