The Quebec Bridge collapse: a preventable failure (part 1)

In the first of a two-part article, Sean Brady takes readers through the chain of events that led to the collapse during construction, with 75 deaths, of the Quebec Bridge.

A stark example of how technical and human factors can combine and cause failure is that of the Quebec Bridge, which collapsed twice during construction: the first time in 1907, resulting in the deaths of 75 workers; the second failure occurring in 1916 with a further 13 fatalities.

The Quebec Bridge was one of the world's most ambitious bridge engineering projects. It was overseen by one of the world's most celebrated bridge engineers and its collapse would reverberate through the construction industry for decades to come. Its aftermath would see the formation of the American Institute of Steel Construction and the American Association of State Highway Officials, and it would also give rise to the tradition of all graduating engineers in Canada receiving the Iron Ring, a ring worn on the pinkie finger of their working hand to remind them that, regardless of the sophistication of modern structural engineering, their fundamental duty is to prevent failure.

In Part 1 of this two-part article, we will examine the events that led to the first collapse of the iconic bridge. In the next issue, Part 2 will explore the complex interaction of human and technical factors that contributed to the catastrophe.

Crossing

While the idea of bridging the St Lawrence River had been around since the 1850s, it was only in the 1880s that interest gained momentum, culminating in the formation of the Quebec Bridge Company in 1887. The company's role was to plan and deliver the bridge, and the technical challenge was significant. At its narrowest point the St Lawrence River was 3.2km wide and up to 58m deep. The river was fast moving (as fast as 14km/h), had a tidal range of 5m and, during winter, ice became stuck in the channel and piled up to a height of 15m.

The team that would eventually deliver the structure first met at an American Society of Civil Engineers (ASCE) meeting in Quebec in 1897, where the Quebec Bridge Company's principal engineer, Edward Hoare, met the chief engineer from the Phoenix Bridge Company. Controversially, Phoenix offered to complete the initial design of the bridge for no fee, provided it was awarded the contract for the bridge's final design and construction. This is indeed what occurred, with the Phoenix Bridge Company's proposal selected from the six proposals submitted, being cited as the "best and cheapest"[1].

At the same ASCE meeting, these men would also meet the eminent bridge engineer, Theodore Cooper, who offered his services as a consultant. In time, Cooper would also be selected as the chief consultant for the project, overseeing all of its technical aspects.

Cooper's reputation as a bridge engineer was immense. He had been an inspector during the construction of the Eads Bridge at St Louis, which pioneered the use of steel in major bridges, and was assistant general manager of the Keystone Bridge Company before setting up his own consulting practice in New York in 1879. In addition to his practical expertise and experience, he made a significant academic contribution to bridge design. He developed a methodology for dealing with railway loads on bridges, and he wrote papers promoting the use of steel as a bridge material and prepared general specifications for iron and steel bridges. At approx. 60 years of age, Cooper felt the Quebec Bridge project would be the crowning achievement of his career[2].

There would be a number of interesting aspects to Cooper's engagement. Despite the fact he would be located in New York, over 800km from the site, he accepted the role of inspecting the steel fabrication and erection. He also insisted on maintaining full control of the project, and when it was suggested that his work should be subject to peer review, he refused, claiming, "this puts me in the position of a subordinate, which I cannot accept"[1]. Furthermore, the poor financial position of the project would result in Cooper agreeing to charge only half his usual fee, a decision that essentially cost him his ability to hire appropriate staff.

He did, however, hire Norman McLure as his on-site inspector, a decision that would have far-reaching consequences. Due to ill health, Cooper didn't actually visit the site after superstructure construction began, instead relying on the young McLure as his eyes and ears.

Inexperience constructing a bridge of this size was not, however, limited to McLure. Hoare had never worked on a bridge longer than 90m – hence his desire to retain Cooper as a consultant – and the Phoenix Bridge Company was also relatively inexperienced for a bridge of this scale. Worryingly, it had experienced a number of collapses during construction on previous projects.

Construction

Construction of the superstructure began in July 1905, with a significant technical issue manifesting itself early the following year. The steel members arriving on-site were heavier than expected. McLure brought the issue to Cooper's attention and a self-weight calculation error was identified.

The initial design span of the bridge was 488m. However, in 1900, after completion of the tender process, Cooper increased this span length by 61m to 549m. There were sound technical reasons for the change, including that an increased span resulted in piers being closer to the shore, with a subsequent reduction in construction depth. There is speculation, however, that an altogether more human desire contributed to Cooper's decision[3]. The initial span of 488m was shorter than the 521m span of the Forth Bridge in Scotland, which was completed in 1890. Increasing the span length of the Quebec Bridge to 549m would make it the longest cantilever bridge in the world – as it

Figure 1
Quebec Bridge prior to collapse

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remains today.

Whatever the reason, it was discovered that the Phoenix Bridge Company had carried out the self-weight calculations for the final design based on the initial proposed length of 488m and had not updated its self-weight calculations for the revised length. The actual bridge would weigh 325MN, as opposed to the initial calculated weight of 276MN, an increase of 18%[1]. Cooper would assess that the calculation error increased the stresses in the bridge by 7%, yet he concluded that the design was adequate and construction could proceed[1].

However, evidence that the design may not have been adequate began to present itself in June 1907, 23 months into construction of the superstructure. McLure identified that a number of the bridge's compression members had mid-point deflections – they were bowing. This bowing was most pronounced in the compression members on either side of the bridge piers (known as A8L and A9L). These members carried some of the largest compression loads in the bridge. In early June, it was found that member A9L had a bow of 1–2mm, but later that month these deflections had grown to 19mm. McLure notified both Cooper and the Phoenix Design Company's chief engineer.

Phoenix was of the view that this bowing was pre-existing and present when the members left the fabrication shop, thus being unrelated to in-service stresses. McLure disagreed: he was convinced the bowing had only appeared after the member was installed, a view supported by the fabrication shop. Cooper appears to have been confused by the bowing – the possibility that the bridge was overstressed was simply not considered[1]. He believed that the bowing may have been present prior to installation, but also speculated that these members may have been impacted by other members being lifted into position during construction. He asked McLure to check for evidence of such impacts. McLure found none and the cause remained unresolved.

But by late August 1907, there was no doubt that an issue existed. In the space of two weeks the bow in the A9L member had increased from 19mm to 57mm[1]. With the southern cantilever arm suspended 223m over the St Lawrence River (Figure 1), the scene was set for catastrophe.

Collapse

On 27 August 1907, a foreman noticed the significant bowing and immediately suspended construction. McLure sent a message to Cooper advising him that construction was suspended until Cooper reviewed the matter. The following day, McLure caught the 1pm train to New York to discuss the matter personally with Cooper. When Cooper arrived at his office at 11am the following morning, 29 August, McLure was waiting for him. They had a discussion and Cooper sent a message to the Phoenix Bridge Company in nearby Phoenixville stating that no further load was to be added to the bridge until he had resolved the situation.

McLure was then to travel to Phoenixville to meet the Phoenix Design Company that evening. He assured Cooper he would send the same 'cease construction' message to the bridge site, but he didn't, and the site remained unaware of Cooper's wishes.

While both Cooper and McLure proceeded on the basis that work had been suspended on the site since 27 August, this was not the case. Unknown to them, the same foreman changed his mind and recommenced work the next morning – the same day McLure caught the train to New York. He changed his mind because prolonged delays or stoppages would result in a 'decrease in morale' on-site, with the risk of workers leaving the project. He also proceeded on assurances from Phoenix, which still appeared convinced that the member bowing had occurred prior to installation.

Cooper's message to cease construction would arrive at the office in Phoenixville at 1:15pm on 29 August. It was ignored; the principal engineer was out. He returned at 3pm and, despite being aware that work was still proceeding on-site, simply waited for McLure to arrive that evening at 5:15pm. They discussed the issue, then decided to make a decision the following morning.

The decision came too late. At 5:30pm that evening, while the meeting in Phoenixville was wrapping up, the critical A9L member buckled, initiating the progressive collapse of the 17 000t southern arm of the bridge into the St Lawrence River. The bridge took 15 seconds to collapse and was heard over 10km away in Quebec City. Only 11 of the 86 workers on the bridge at the time would survive, with a number of bodies never being recovered.

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