The METALLURGICAL HISTORY *of* MONTREAL BRIDGES

AN ONLINE SERIES

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PART 3
THE QUEBEC BRIDGE (1917) —
RECORD CANTILEVER IN NICKEL STEEL

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Abstract

Built in 1917, the Canadian-designed and built cantilever bridge near Quebec City still stands as the longest such span in the world. It was designed for both rail tracks and roadways; in later years, the roadways were expanded by removing one rail track. The first bridge attempted on the site collapsed in 1907 during construction; a thorough engineering enquiry showed that this collapse was due to poor design and not to any metallurgical failure. Completion of the new bridge, originally planned for 1916, was interrupted when the suspended mid-span fell due to failure of a cast hoisting saddle. A successful bridge was finally opened in 1917. This bridge was based on K member panels that reduced distortion when loaded, which facilitated construction. (The K design has been employed in the construction of several other bridges.) In terms of critical components, the K member panels included high-strength nickel steel. Because of limited rolling capability in the fledgling Canadian steel industry, most of the material for the new bridge was imported from the United States. In 1970, the Pierre Laporte suspension bridge (Canada's longest suspension bridge) was built along side the Quebec Bridge to serve as a six-lane auto-route.

Introduction

At the turn of the 20th century, Quebec City was isolated on the north shore of the St. Lawrence because significant populations and industrial centres were mainly located on the south shore, in Montreal and the Eastern Townships to the west, and in the Gaspé to the east. On just the other side of the St. Lawrence, rail lines extended from Montreal to both the Maritimes and the Gaspé. However, east of Montreal, road traffic of growing volume depended on ferries to cross the river. It was therefore decided to build a bridge at Quebec City. This bridge would need to be long and high in order to accommodate ocean ships bound for Montreal.

In this paper, issues surrounding construction of a bridge at Quebec City are explained thoroughly. The development of a cantilever design, which seemed the only solution at the time, is described. The collapse of the first attempted bridge and the resulting conclusions put forth by the Royal Commission of Enquiry are examined in detail to clarify design problems and the possibility of metallurgical defects. The advantages of the final Canadian K-panel design are then described in association with the use of high-strength steel. The importance of the Quebec Bridge to both future design development and to regional transport is considered.

Planning the Bridge

Because of the geographic intrusion of Maine, the rail lines from the Gaspé Peninsula and from both New Brunswick and Nova Scotia ran along the southern bank of the St. Lawrence, with terminals in Lévis (which is across the river from Quebec City). In the early 1900s, there were rail lines from Quebec City to Montreal, where there were two low-level bridges (*Ponts du Quebec,* 1975; McQueen, 2008a, 2008b), and the Great Northern line extended almost straight west. North of the river, there were prospects for lines to be built towards Chicoutimi, which was not yet of industrial significance, and for a line eastward along the north shore. Partly because Quebec was not an industrial city or a final destination for ocean shipping, none of the railways had compelling reasons for establishing a bridge in the region. Provincial or civic governments did not feel any great economic or electorate pressure to invest in one. It therefore fell to a consortium of local business leaders to provide a bridge that could prove profitable by tolling the various railroad companies and the public.

After several failed efforts to drum up sufficient capital, the Quebec Bridge and Railway Company (QBRC) was incorporated and began the task of selecting a bridge site (Quebec Bridge Enquiry Report, 1908; Steinman & Watson, 1957; Smith, 1964; Plowden, 1974; *Ponts du Quebec,* 1975; Middleton, 2001). The St. Lawrence River narrows between high cliffs to the west of Quebec City and then widens significantly to the east, with relatively low banks. At Isle d'Orleans, there are two somewhat narrower channels, but the banks are not very high. Because of the high frequency of large ship traffic, a high bridge was essential. It was decided that the optimum site would be from Chaudière

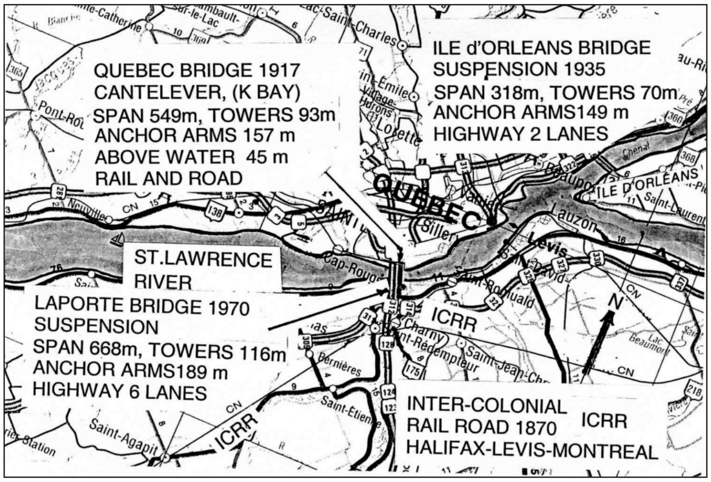

Fig. 1. The Quebec Bridge is on a site just to the west of Quebec City with high cliffs well suited for a span over the shipping channel. This is markedly different from the very wide low crossing of the Victoria Truss Bridge at Montreal that is about 230 kilometres up the river (McQueen, 2008a, 2008b). The Inter-Colonial RR (now CN) and also two more recent crossings of the river are marked.

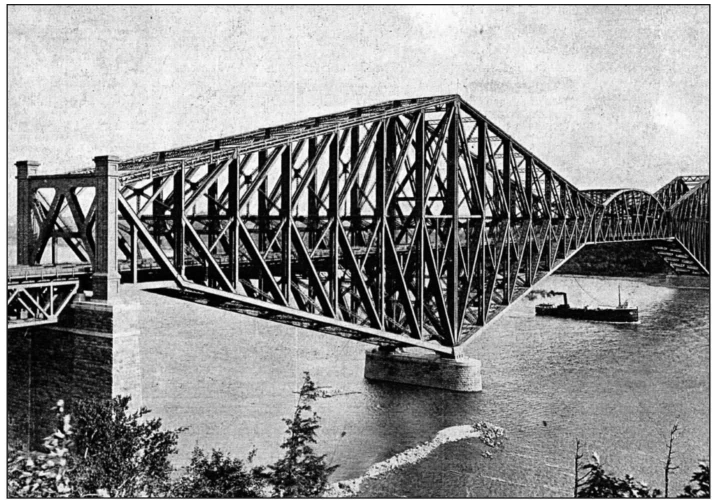

Fig. 2. The complete bridge viewed from the North Shore, emphasizing the straight lower girder chords (compression) and upper forged eyebars (tension). The K members in each bay minimized distortion and facilitated erection (Duggan, 1918; Middleton, 2001).

to Sainte-Foy (Fig. 1); it would be possible to transport equipment to both sides by rail. After a call for tenders, QBRC let the contract to the lowest bidder, Phoenix Bridge Co. of Pennsylvania, which had extensive experience and a good reputation. However, following the completion of preliminary designs for the specified live load that determined the overall structure for the dead weight and for the dimensions of the members, the project went into abeyance because of insufficient funds (Quebec Bridge Enquiry Report, 1908; Middleton, 2001). Normally, the next stage would have been the design of the bracing and splicing to rigidly tie together the compound beams that constitute individual members, as well as other stabilizing members. Then the dimensions of the members that carry the entire load would have been recalculated.

Developments in Bridge Design

Brief discussions of bridge evolution have been presented in the two prior papers of this series, the Victoria Box-Girder Bridge and the Victoria Truss Bridge (McQueen, 2008a, 2008b). Notably, as described in the discussion surrounding the Victoria Truss Bridge, the height of a truss must increase as the span and load increase; this proportional relationship places the maximum dead weight at the centre, which in itself requires a more substantial truss. One design that overcomes this challenge is the suspension bridge, in which the load is supported by the cables. Fortunately, after the introduction of steel, it became possible to produce wire (the strongest form of steel) and still retain suitable toughness. The use of many strands of wire overcame the potential for random defects. Such a bridge required a rigid deck that could absorb the vibrations of the live load and redistribute the weight along the cable. Thus, the price for sufficient rigidity, especially for railway bridges, was a heavy deck with large cables. Towers were needed to sustain the entire load and, hence, piers with substantial foundations were essential; these piers would require complex and dangerous pressurized caissons to descend into the river bottom. An example of a very successful bridge of the period is the Brooklyn Bridge (1883), which was built by the Roeblings and was 480 metres (or 1,596 feet) in length (Steinman & Watson, 1957; Smith, 1964; Plowden, 1974; Petroski, 1995).

The cantilever bridge has a structure that appears like a truss centred on the piers, so that the parts on each side balance each other (Fig. 2; Quebec Bridge Enquiry Report, 1908; Duggan, 1918; Steinman & Watson, 1957; Smith, 1964; Plowden, 1974; Ball, 1987; Petroski, 1995; Middleton, 2001). The trusses taper towards the centre of the span so the dead load is lightest there. The bridge is inherently stiffer than the suspension type, but tends to be much heavier; hence, it requires substantial central towers and piers, which can pose difficulties for construction. In a pattern opposite to the simple truss, the upper members are under tension and the lower members are under compression, so that a large cross-section is necessary to avoid buckling. The cantilever bridge also has the advantage that the main span, supported by the anchor span, can be extended across the river; this anchor span could either be built earlier on a construction framework or simultaneously in balance.

While this type of cantilever bridge had been introduced in 1867 for long span railroad bridges (greater than 120 metres), the first partly steel, a Canadian cantilever bridge (which was 151 metres or 495 feet in length) was built over the Niagara Gorge in 1883 by C.C. Schneider (Steinman & Watson, 1957; Smith, 1964; Plowden, 1974). The first all-steel bridges were of cantilever type; the first in the United States, built in 1879, ran 151 metres across the Missouri River and the first in Canada, built in 1886 by C.C. Schneider, crossed Siska Creek in the Fraser River Gorge, British Columbia (Plowden, 1974). In 1889, two record-breaking spans of 520 metres were constructed across the Forth estuary in Scotland (Quebec Bridge Enquiry Report, 1908; Duggan, 1918; Ball, 1987; Middleton, 2001). The twin spans were built outward from the land in both directions from double columns and piers, having tapered tubular members with a plate and rib construction. The Scottish bridges, designed by J. Fowler and B. Baker, were cut and shaped on site over a period of four years, with a work force of about 4,000 experienced shipbuilders under the most able direction of W. Arrol (Quebec Bridge Enquiry Report, 1908; Duggan, 1918; Ball, 1987; Middleton, 2001).

The steelwork design of cantilever bridges included the location of every rivet that, when driven hot, clinched the pieces together rigidly (Lemieux & Morentz, 1968; Fisher & Struik, 1974). This technique was explained and illustrated for a critical Quebec Bridge joint in the fabrication account of the Victoria Truss Bridge (McQueen, 2008b). Moreover, with the exception of the Forth Bridge described above, the common construction practice was to fabricate all the members in the shop to as large a size as permitted by the transport facilities. The plates were cut and bent into angles and clamped together, rivet holes were bored and the rivets were driven by C-shaped hydraulic presses that were supported on cranes (Fig. 3; Quebec Bridge Enquiry Report, 1908; Duggan, 1918; Middleton, 2001). All parts to be transported separately and joined in the field were assembled with splice plates and drilled with rivet holes to ensure proper alignment. Many large bays or assemblies were connected by pins (up to 60 centimetres in diameter); this meant that large holes had to be accurately milled and the parts had to be assembled to ensure proper fit. There were often problems of assembly on the bridges because of distortions caused by gravity on the bays that differed from the manner of support on the drilling or milling machines. Alignment of rivet holes was attained by using jacks or possibly waiting until further additions of components corrected the situation (Quebec Bridge Enquiry Report, 1908; Duggan, 1918; Middleton, 2001).

The Bridge that Collapsed

The first attempt at building a bridge near Quebec City was carried out by Phoenix Bridge Company of Pennsylvania, which had been contracted by a Quebec business consortium. The Phoenix Bridge Company design was completed by P.L. Slapzka and accepted by T. Cooper, who was a consulting engineer to the QBRC. Cooper had wide experience and a good reputation in railway bridges in the United States; however, being in poor health and close to retirement, he appointed a young and inexperienced engineer to represent him (Quebec Bridge Enquiry Report, 1908; Smith, 1964; Watson, 1975; Petroski, 1995; Middleton, 2001). Because the QBRC was not an operating railroad, it had a chief engineer with limited experience. The fabrication of the bridge components had proceeded without incident in Phoenixville, Pennsylvania, shops and all the steel had been tested to ensure that it met specifications. The bridge construction began on the south side of the St. Laurence River, so that, by August 1907, the anchor and main span arms were complete (Fig. 4); the main travelling crane was about to be dismantled and some work had started on the suspended span (Quebec Bridge Enquiry Report, 1908; Smith, 1964; Middleton, 2001).

Because of shape differences between the shop and under load, some of the joints had not completely closed upon initial erection; a crew was employed to fill in rivets as holes sagged into alignment. However, some points failed to fit properly and consideration was given to using jacks for closure. The workmen reported that some rivets had popped and the fit at some joints was getting worse (Quebec Bridge Enquiry Report, 1908; Smith, 1964; Middleton, 2001). The engineers on the site wired Cooper and Slapzka for instructions, but none were forthcoming so Cooper's representative decided to consult with him in person. On the morning of August 29, 1907, the bridge collapsed, dropping downwards and pulling the tower over so that the tension bars on one arm remained stretched out in alignment (Fig. 4). Unfortunately, 75 men were killed in the collapse and only 11 survived (Quebec Bridge Enquiry Report, 1908; Smith, 1964; Middleton, 2001).

Examination of the collapsed bridge showed that the lower chords near the central column had buckled after the reinforcements between the four girders popped off and that some girders had bent 180 degrees (Fig. 5; Quebec Bridge Enquiry Report, 1908; Smith, 1964; Middleton, 2001). Extensive examination of the wreckage indicated

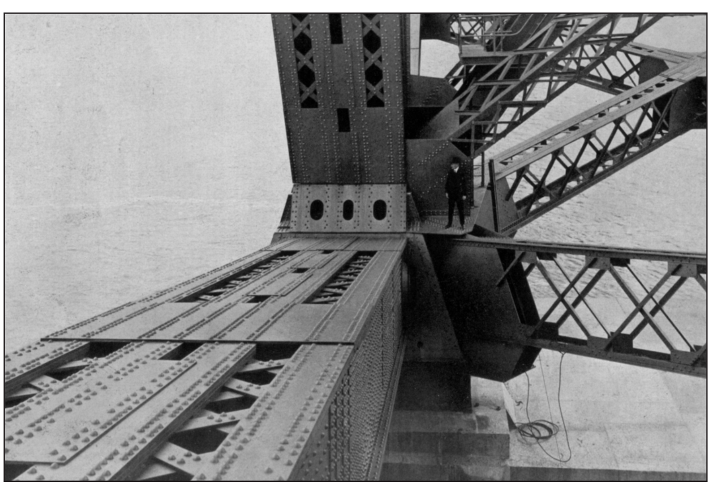

Fig. 3. The Quebec Bridge's main lower chord (which extends from the tower to the junction of the first and second bays) consists of four fabricated girders braced together with one longitudinal splice at the site. The significant role of the rivets is clear in their carefully designed arrays. This chord has about double the section of the slender one that failed on the Phoenix Bridge (Fig. 5; Duggan, 1918; Middleton, 2001).

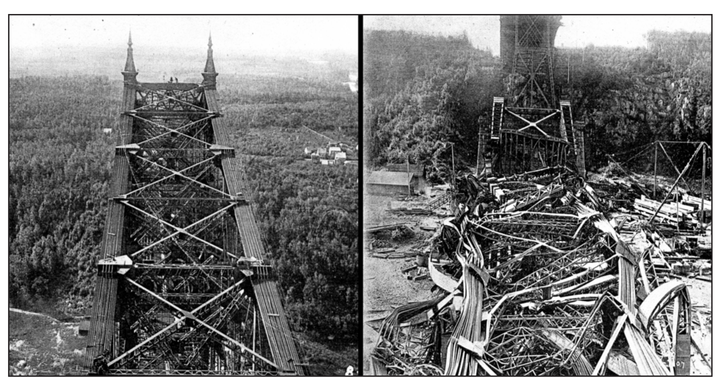

Fig. 4. General views of the south structure of the Phoenix Bridge at Quebec: a) cantilever from the construction crane at tip shortly before the collapse, and b) from pier afterwards. The tension eyebars of the anchor arm were stretched out when the tower was pulled over by the cantilever arm as the lower chords buckled (Quebec Bridge Enquiry Report, 1908).

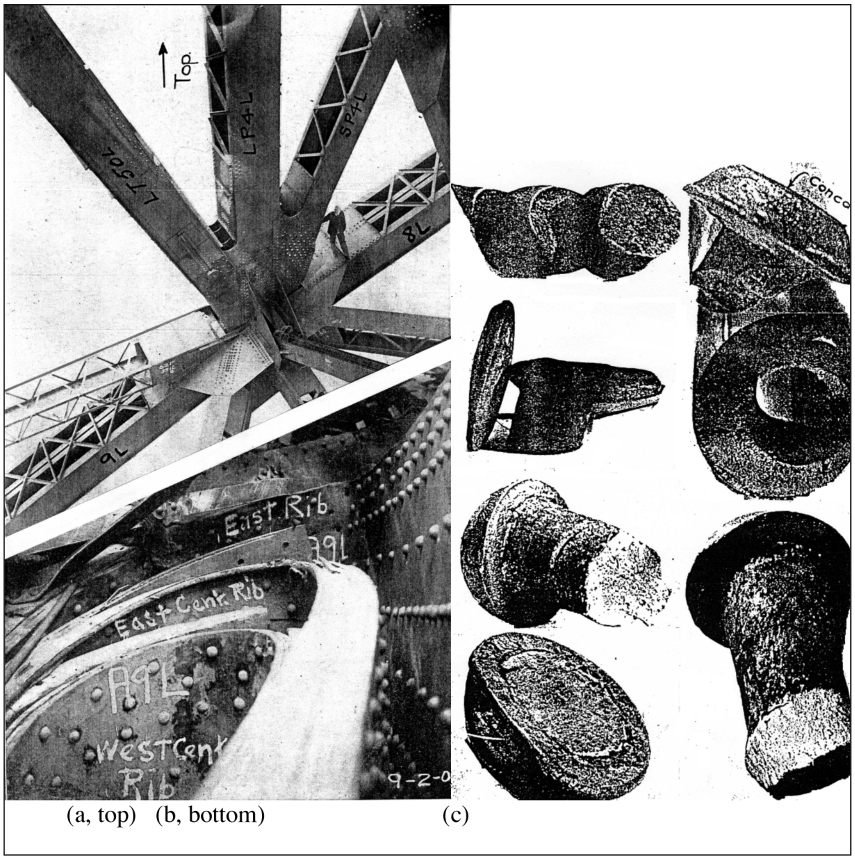

Fig. 5. a) The junction at the end of the first bay of the Phoenix cantilever, showing the lower chord 9L extending towards the tower at the pier; this is the one that buckled because it was 24 per cent below the minimum section required for the dead load (Quebec Bridge Enquiry Report, 1908); b) The girders, over a metre high, buckled and bent almost double, having popped off the rivets and the latticing that held the four of them together (Quebec Bridge Enquiry Report, 1908); c) Rivets from the collapsed Phoenix Bridge failed by ductile tension, lateral plastic shear or the shank pulling out of the head, leaving a holed rim (Quebec Bridge Enquiry Report, 1908).

that much of the distortion had occurred when the rapidly dropping members hit the ground. Many broken rivets were found, some with ductile tensile failure of the shank, some sheared between plates and some with the shank sheared out of the head, leaving a hole (Fig. 5). There were no brittle failures in any components, although many components had failed in a ductile manner. Only one eyebar had broken, resulting from the impact that had torn the head from the 30 centimetre pin, which itself was bent (Quebec Bridge Enquiry Report, 1908; Middleton, 2001). Brittle failure was a possibility in an age where the steel transition temperature might be above 10 degrees Celcius (as has been recently observed in specimens from the Titanic; Felkins, Leighly, & Jankovic, 1998); however, this type of failure was unlikely in warm August.

A board of engineers, appointed by the Royal Commission, was set up to investigate the collapse; this board included H.E. Vautelet, a CPR bridge engineer; M. Fitzmaurice, a Forth Bridge engineer; and R. Modjeski, an experienced American bridge engineer (Quebec Bridge Enquiry Report, 1908; Middleton, 2001). They commissioned a series of mechanical tests on bridge components, which confirmed the high metallurgical quality of the components. The largest mechanical test was a compression test performed on a one-third scale model of the main chord, which buckled with failure of rivets and loss of bracing under the load expected below (Quebec Bridge Enquiry Report, 1908; Smith, 1964; Middleton, 2001). C.C. Schneider, one of the leading cantilever designers, recalculated the load carrying capacity of the design and showed that the chords were 25 per cent and the tension bars were 15 per cent below requirements (Schneider, 1908). The design submitted by Slapzka to Cooper had not included revised bracing or taken into account the added weight. Cooper had accepted the design and later refused to make changes that would increase the weight because, apparently, he wanted to retain a slender appearance. His failure to visit the site and to pay close attention to messages resulted in overlooking the warning signs. The report by the Royal Commission (Quebec Bridge Enquiry Report, 1908), headed by J. Galbraith who was the first Dean of Engineering at the University of Toronto, placed the principal blame on Cooper, who later died in seclusion. The report clarified that the theory of bridge design, the method of construction and the materials were not at fault. The inadequacy of the Phoenix design meant that all the steel fabricated for the north cantilever (approximately 36,000 tons) had to be scrapped.

The Ministry of Railways and Canals, which had taken over the enterprise from the QBRC and regulated liability payments with the insurance and the Phoenix Bridge Company, instructed an enlarged Board of Engineers to call tenders for new designs. The board rejected a design by Vautelet, who then resigned from the board, and accepted one submitted by the St. Lawrence Bridge Company (G.H. Duggan, chief engineer), which had been formed from the Dominion Bridge Company in Montreal (under P. Johnson) and the Canadian Bridge Company, under F.C. McMath; (Quebec Bridge Enquiry Report, 1908; Middleton, 2001). The latter was a Canadian subsidiary of U.S. Steel that was located just south of Windsor, Ontario (Warren, 2001). The board was reconstituted to oversee the development of the design and its application in the construction; the new board consisted of R. Modjeski, C.C. Schneider and C.N. Monsarratt, a Canadian bridge designer (Quebec Bridge Enquiry Report, 1908; Middleton, 2001).

Steel Imports: Infancy of Canadian Industry

As mentioned above, the quality of the steel in the collapsed bridge was high (Table 1). The plates had been hot rolled from open-hearth steel at Carnegie Steel (in Pittsburgh), which was already a division of U.S. Steel, established in 1901 (Duggan, 1918; *Making, Shaping and Treating of Steel,* 1957; Watson, 1975; Warren, 1973, 2001). The eyebars for the tension chords had also been rolled

Table 1. Properties of wrought iron and structural steel (utilization* standards)**

	Yield		Ultimate		Ductility %	Allowed
	ksi	MPa	ksi	MPa	Elongation	ksi
Wrought iron						
Bar, single	28	192	48	330	25	
Double refined	31	213	52	358	28	11 ‡ – 16 **
Plate <1> ‡‡	27	186	48	330	14	(1913-1966) **
Mild steel <2> ‡, #, ‡‡‡	35	240	62 ‡‡‡	425	20	21 #,**
Low alloy < 0.25C	51	350	92	630	18	30
High yield S.	51	350	70	480	18	30
Ni steel ‡	50	345				31 ‡
T1 quench, tempered	88	605	112	770	15	44
Low C rivet	40	275	60	415	25%	ASTM **
Mn steel rivet	56	385	76	523	20%	36,42,242 **

* Utilization:

‡ Quebec Bridge: Ni Steel 52 kt, mild steel <2> 20 kt;

‡‡ Victoria Tube: <1> 9 kt;

Victoria Truss: <2> 22 kt;

‡‡‡ Forth Bridge: <2> 35 kt.

** Standards: ksi = kilo pounds per square inch; MPa = mega Pascals; kt = kilo tons

there, but had then been upset, pierced, annealed and bored at the American Bridge Company in Pennsylvania (a subsidiary of U.S. Steel). The pins, which were as large as 60 centimetres in diameter, were cast and forged at the Bethlehem Steel Gun Plant, in Midvale, Pennsylvania. The lighter steel angles (used for latticing) were produced at Phoenix Iron Work, Pennsylvania. The decision to source this work from the United States was expected from a bridge company with a fabrication shop in the United States (Quebec Bridge Enquiry Report, 1908; Duggan, 1918; *Making, Shaping and Treating of Steel,* 1957). Unlike the design of the collapsed bridge, the new bridge was fabricated by two bridge shops in Canada, one near Montreal and the other near Windsor on the Detroit River (Duggan, 1918). However, the American sources of steel plates, eyebars and pins for the new bridge remained the same because they provided the specified quality at competitive prices and because they had the metallurgical know-how and modern equipment. The lighter latticing steel may have come from Canadian sources.

The first large-scale production of steel in Canada appears to be a foundry in New Glasgow, Nova Scotia; this foundry was associated with Ferrona Iron Works, which had operated a coke blast furnace from 1890 to 1902 (Inwood, 1989; Williams, 1989). In 1901 and 1904, two steel mills were established in Sydney, Nova Scotia, which was a suitable port for receiving raw materials and dispatching product. Coal for coking was available from nearby mines and iron ore was available from a mine on Bell Island, Newfoundland. These mills later merged to become Dominion Iron and Steel Company, before further reorganization in 1929. The high silicon and phosphorous content in Bell Island ore and sulphur content in Cape Breton coal required production in open-heath furnaces with successive and basic slag treatments (Williams, 1989). The plant concentrated on rails, producing 0.8 million tons of steel in 1911. It never invested in plate or structural production facilities.

As was the cases with the construction of the previous bridges on the St. Lawrence, the development of the Canadian primary metallurgical industry lagged behind in the installation of basic infrastructure. In 1901, Algoma Steel was founded at Sault Ste. Marie, Ontario, and utilized ore from a mine at Wawa, Ontario (Williams, 1989). Algoma, like the Sydney mills, concentrated on a single hot working process because the industry did not grow out of iron works and, therefore, had no experience with various mechanical shaping processes. Given the continued expansion of the railroads during the first two decades of the 20th century, rails were a significant commodity in Canada. Furthermore, it was important that the mills be able to earn a profit to warrant the investment. Algoma successfully beat off the competition of U.S. Steel, which had mills in Gary Indiana and later in Duluth (Warren, 2001). Between 1905 and 1915, Algoma Steel produced 2 million tons of rails.

In 1910, Stelco, the Steel Company of Canada, was created by amalgamating several industries, including Hamilton Steel and Iron and Montreal Rolling Mills. By 1918, Stelco production had grown to a half million tons per year (Kilbourn, 1960; Williams, 1989). In 1912, Dofasco, Dominion Foundry and Steel Company started producing about 30,000 tons per year of castings and expanded to 300,000 tons in 1918, but had no rolling mills until 1928 (Kilbourn, 1960). In the period of construction of the Quebec Bridge, the Canadian steel industry was still in its birth stage, whereas the two giants among the many producers in the United States had merged into the largest steel company in the world; it also had the most advanced technology in every type of product (Fisher, 1963; Warren, 1973).

Design of the Bridge

Though the principal aim of the Quebec Bridge design was to complete a structure that could stand up and carry projected traffic for decades to come, there were a variety of significant parameters that had to be factored into the design. One such parameter was the need to develop a simpler structure with less distortion during erection; this was especially important because it was one of the factors that had contributed to the inability to recognize the development of buckling in the collapsed bridge (Quebec Bridge Enquiry Report, 1908). The proposed K shape of members inside panels of equal length allowed each bay to be erected with all of the rivets driven before proceeding (Figs. 2 and 6; Quebec Bridge Enquiry Report, 1908; Duggan, 1918; Smith, 1964; Plowden, 1974; Middleton, 2001). Moreover, the travelling crane could be simpler and lighter when it was riding forward on the bridge deck of the preceding bay. The K truss was also easier to machine and fabricate, with less stringent tolerances. Incidentally, it was due to these considerations that Vautelet's design was rejected, even though the chief engineer was to be G.H. Duggan, who had a great deal of experience with Dominion Bridge (Quebec Bridge Enquiry Report, 1908; Duggan, 1918).

The bridge was to be built by the normal North American procedure that had become the world standard (The Quebec Bridge, 1917; Duggan, 1918; Middleton, 2001). As explained above, the components were fabricated in the shops. The workforce assigned to this task did not exceed 500 persons. The field erection, which was restricted to six months per year for each of the three years of construction, required about 200 workers, including six gangs of riveters.

The main chords of the bridge were composed of four girders (laced together) and weighed 380 tons (Fig. 3); the chord was divided into four parts, each comprised of two half-length girders to permit transport and lifting on site. As each bay moved further from the pier, the bottom chords were reduced in sections by making the girders smaller and transmitting the forces between bays through pinned connections (Fig. 6). The tension eyebars were also reduced in sections at each pinned joint. After erection, the free end of the cantilever arm (which was 177 metres in length) drooped by 20 metres due to the elastic strain of the compression chords and tension bars (Duggan, 1918). The addition of the suspended centre span (which was 195 metres in length and weighed 5,000 tons) caused a further 24 metre drop in the tip of the cantilever; however, the lower chords remained straight, which also reduced the wind loading. The two frames remained vertical (to simplify erection) rather than slanted inward from a wide base; this required more lateral bracing to withstand wind loads (The Quebec Bridge, 1917; Duggan, 1918).

The new bridge was considerably heavier than the one that had collapsed because of the greater anti-buckling cross-section of the chords (Figs. 3 and 6) and the tension bars required to take that weight. The old piers did not have a sufficient underpinning and a plan to enlarge them proved unfeasible. Therefore, two completely new piers were built a short distance upstream, with one pier further out in the river to shorten the span. The cut stones from the old piers were used in the construction of the new ones (Quebec Bridge Enquiry Report, 1908; Duggan, 1918). The caisson construction on one pier was successful, but the second suffered endless problems due to large glacial rocks in the sediment. Thus, the second pier had to be relocated shoreward, which augmented the span.

The designed weight of the Quebec Bridge was more than double that of the Forth Bridge in Scotland (1889), which had a similar span and carrying capacity (Fig. 7), because the circular cross-sections of the Forth Bridge (Fig. 6) provided the greatest buckling resistance for the least mass per unit length. In addition, the inward taper of the Forth Bridge's principal structures (which increased with height and towards the span centre) further reduced the weight. However, neither of these advantages could be utilized for the Quebec Bridge because of the need to erect the bridge in a six-month season for fieldwork and the lack of a large band of skilled shipyard workers (The Quebec Bridge, 1917; Duggan, 1918). These comments about weight are made after high-strength Ni steel had been specified for 70 per cent of the structure; this will be discussed in the next section.

This account cannot close without mention of the final mishap in 1916, when the suspended span fell during hoisting into position from barges. The span was supported at each end on a beam and two eye-bar chains to hydraulic jacks on each cantilever arm. To equalize stresses on the span, each

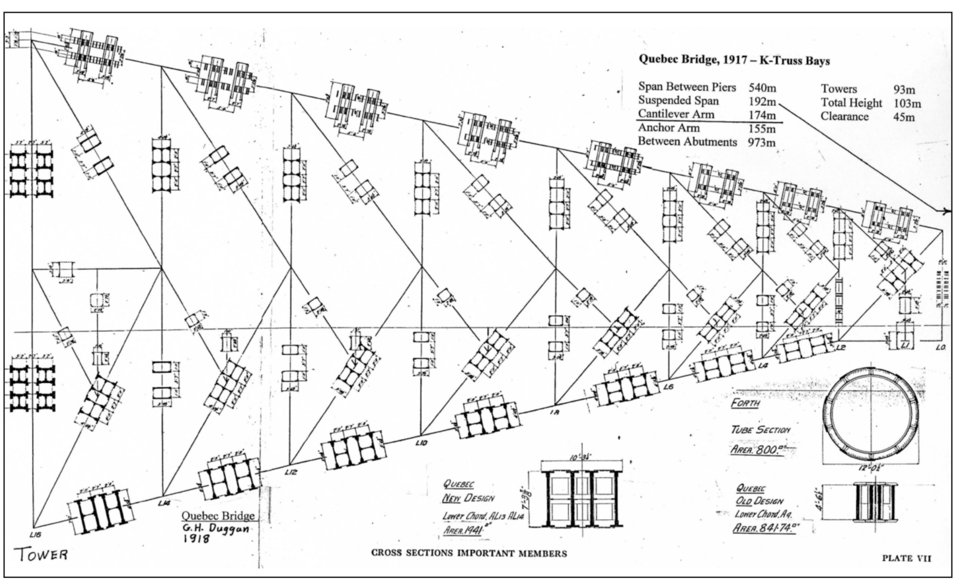

Fig. 6. In the cantilever arms (156 metres in length) of the Quebec Bridge, the dimensions and shape of members are reduced in section in each bay as they gets closer to the tip, thus carrying less dead load. The inserts compare the sections of the compressive chords next to the towers for the Forth Bridge and the Phoenix span that collapsed (Duggan, 1918).

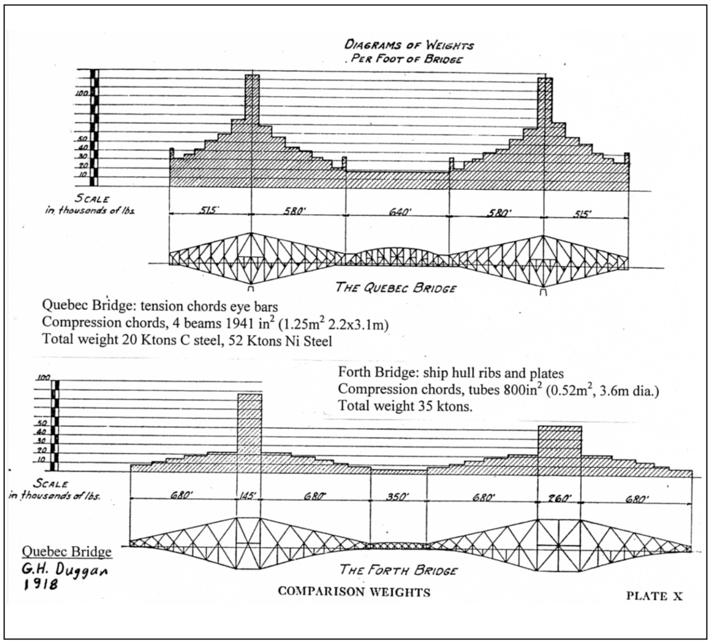

Fig. 7. Exhibiting the K structure of each bay, the section of the Quebec Bridge has 91 metre-long towers and banks 45 metres above the water. The dimensions amount to total span of 547 metres (1,800 feet) and a length of 985 metres. This diagram shows a comparison of dimensions and weights of the Quebec Bridge (which as plate I section girders) and the Forth Bridge of similar span (which has sheet and rib circular members; Duggan, 1918).

corner rested on a saddle with crossed pivots consisting of three cast semicircular channels and two forged pins (Fig. 8; Quebec Bridge Enquiry Report, 1908; Schneider, 1908; Smith, 1964). Crossed channels of the middle casting fractured in such a way that the supporting beam was pushed out from under the span; it twisted and fell into the river (killing 16 men), where it remains in a deep channel. None of the eyebars broke, but some were extended considerably by plastic deformation. The bridge itself recoiled upwards, injuring a number of workers but suffering no damage. Despite the shortage of materials imposed by World War I, Carnegie Steel was able to roll the needed plates to rebuild the span. A year later, the final hoisting was accomplished as originally planned (Fig. 9), but with bearings fashioned from lead plates (The Quebec Bridge, 1917; Duggan, 1918 Smith, 1964).

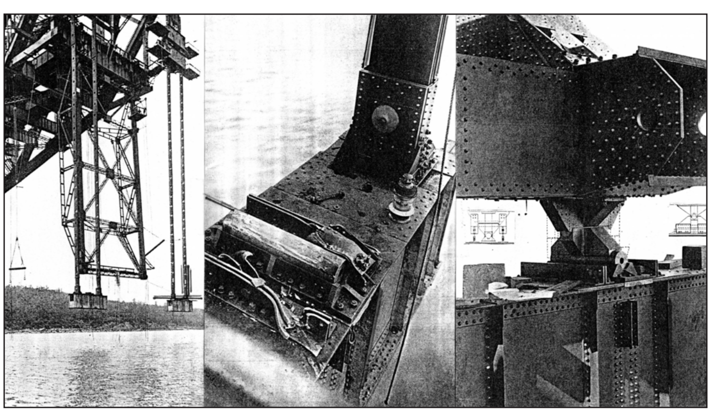

Fig. 8. The lifting system for the suspended span: a) a guiding frame and two yoke beams, with eyebar chains that pass through the jacking mechanisms; b) the support saddle that broke and slid out from under the span corner; and c) the complete saddle with two round bearings at right angles with an intermediate cast component that fractured (Duggan, 1918).

High-Strength Nickel Steel

Dating as far back as ancient times, iron alloyed with nickel in meteorites has been known for its improved properties, though without knowledge of the cause. M. Faraday experimented with nickel, chromium and tungsten steels in 1819, but did not commercialize these experiments (Fisher, 1963; Tylecote, 1992; Habashi, 1994). In 1871, R.F. Mushet produced chromium-tungsten steels for metal cutting that were considered outstanding for the decade. Chromium-steels were produced after 1865 for superior hardness and were used for naval armor and for projectiles; sometimes nickel was also included to raise the properties. In 1882, R. Hadfield patented 13 per cent manganese steel and put it into production; this steel hardens from deformation in service. During the 1904 to 1914 construction of the Panama Canal, manganese steel provided wear-resistance for buckets of steam shovels, dredges, plow blades and crushers of rock (Gatun Locks, the world's then biggest concrete structure; Bennett, 1915; Fisher, 1963). Nickel steels were produced after 1885 and, because of their toughness, were favoured for high-caliber artillery; later, nickel steels were selected by the worlds' major navies for armor plate (Fisher, 1963; Habashi, 1994).

Nickel additions constituted the first high-strength low-alloy steels to attain application in general engineering. In 1900, simple nickel steels had 90 per cent of the hot-rolled, high-strength market, but, by 1915, this share had fallen to 30 per cent; nickel-chromium alloys accounted for 30 per cent of the steel market and chromium (either alone or with vanadium) accounted for another 35 per cent (Yeo & Miller, 1965). The major source of nickel was in Sudbury, Ontario. In 1903, the International Nickel Company published a book describing the advantages of nickel steel in bridges (Yeo & Miller, 1965). Low alloy nickel steels are not in the category endowed with improved hardenability for machine applications that in 1911 were standardized to 11 grades by the auto industry and over 1935-1940, were reduced to 100

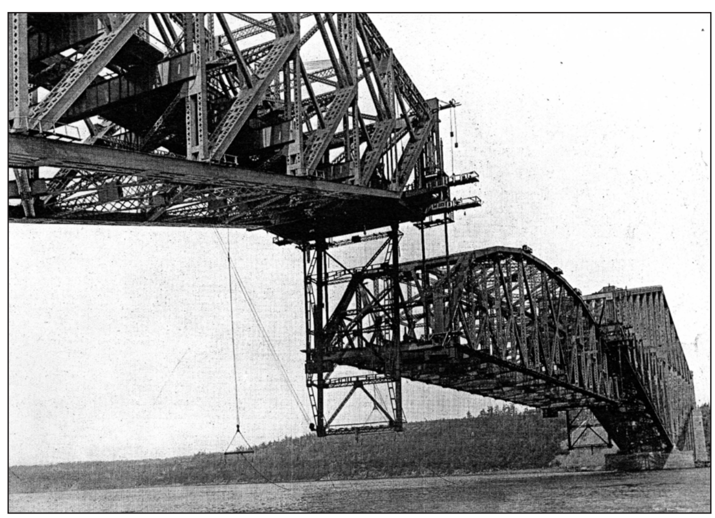

Fig. 9. The suspended truss has been jacked partly into position to complete the centre span of the Quebec Bridge. The four corners of the truss (at the base chords in tension) are connected by forged pins into vertical tension eyebar hangers that are in turn pinned into the ends of the upper tension chords of the cantilever. The temporary frames hanging down at each end were to prevent swaying from the wind.

specifications from 4,000 by the Society of Automotive Engineers and the American Iron and Steel Industry (Yeo & Miller, 1965). For massive bridge components where quenching and tempering were out of the question, the strengthening arose from the effect of nickel's transformation to pearlite during normalizing (i.e. air-cooling).

Nickel steel (in the range of up to 3 per cent nickel) lowers the initial transformation on cooling and the eutectoid temperature by about 20 degrees Celsius per 1 per cent nickel, also lowering the nose (temperature of minimum time) for isothermal or continuous cooling transformation (Hall, 1954; Gillett, 1948; Johnson, 1949; Yeo & Miller, 1965). For steel of up to 3.5 per cent nickel content, martensite does not form on air cooling. Lower formation temperature for pearlite produces a finer lamellar mixture of ferrite and Fe_3C that has much greater strength than does a plain steel of similar carbon content. Nickel also reduces the eutectoid composition by up to 0.4 per cent carbon, which means that, for a given carbon content, the volume of pearlite is larger; this also raises the strength. In addition, the nickel atoms (which are relatively insoluble in Fe_3C) end up in the ferrite and, thus, cause considerable strengthening. Fortunately, these strengthening features are additive but do not reduce the toughness because of the structural refinement associated with the reduced transformation temperature (Yeo & Miller, 1965).

For the new Quebec Bridge, a decision was made to use high-strength nickel stell for 70 per cent of the structure. As a result, the design strength of nickel steel in the bridge was raised to 213 megapascals (31 kilo pounds per square inch) compared to 152 megapascals (22 kilo pounds per square inch) for carbon steel, at a cost factor of 2.5 (The Quebec Bridge, 1917; Duggan, 1918; Middleton, 2001). For modern structural steel, the allowed stress is 300 megapascals (43 kilo pounds per square inch) ASTM A514 (Gillett, 1948; for such a steel (1.4 nickel, 0.9 copper, 0.2 molybdenum and 0.2 carbon), the yield strength is 400 megapsacals (57 kilo pounds per square inch) with 36 per cent elongation, compared to about 1,150 megapascals with 15 per cent elongation for quench and tempered 4340 steel (0.8 nickel, 1.8 copper, 0.3 molybdenum and 0.42 carbon; Gillett, 1948; Yeo & Miller, 1965).

Consequences of the Bridge

The new Quebec Bridge design was a great success because of its ease of shop and field construction. The fourth bridge across the St. Lawrence and the first solely road bridge was the Jacques Cartier cantilever span, designed by C.N. Monsarratt to have a K panel design and be 330 metres in length. The Jacques Cartier Bridge was built in 1929 across the Montreal harbour by Dominion Bridge; the steel used in its construction was produced at Algoma, which began heavy rolling in about 1921 (*Ponts du Quebec,* 1975). The Howrath Bridge in Calcutta was built in 1945 with a span of 450 metres and was the third longest cantilever bridge; it carried both road and light rail traffic.

Since the construction of the Quebec Bridge, the cantilever design has been used in more than a dozen bridges with spans longer than 300 metres. However, suspension construction was used for bridges with longer spans because suspension bridges had a much more economical use of materials to build them for highway traffic and even for railway use with sufficiently rigid decks.

The Quebec Bridge was never used to its full potential as a railway bridge because it was not an essential part of any one network, but was instead an interconnection between several rail lines that crossed at other places (*Ponts du Quebec,* 1975; Middleton, 2001; McQueen, 2008a, 2008b). Due to near bankruptcy of the Grand Trunk and other aforementioned railways, they were nationalized as the Canadian National Railway and reorganized in about 1924. The Quebec Bridge became part of the system, although it remained under the direction of the National Harbor Board. Since 1917, no other railway bridges have been built across the St. Lawrence; there remain only three, including the Victoria Truss Bridge and the CPR Bridge at LaSalle (McQueen, 2008a, 2008b; *Ponts du Quebec,* 1975).

The Quebec Bridge is currently used for passenger service between Montreal and Quebec City, which represents one segment of the rapid transit corridor that stretches westward to Windsor. As part of the privatization of CNR in about 1995, the Quebec Bridge was turned over completely to CNR with a grant for refurbishing. The CNR bridge group constructed a computer model and, upon recalculation, proved that the bridge could sustain all the expected modern loading (Sweeney & Oommen, 1996). Thorough inspection resulted in replacement of some minor elements and led to added protection against salt spray, especially near the roadway (Sweeney & Oommen, 1996).

As automobile use grew, the demand for roadways on the Quebec Bridge also expanded. Therefore, in 1929, the single lane was changed to two lanes by removing one of the rail tracks. This road became very congested, so a parallel six-lane highway bridge was built in 1970; the Pierre Laporte suspension bridge has a span of 668 metres, which is the longest in Canada (*Ponts du Quebec,* 1975). There is no bridge to the east of Quebec City, except for the suspension bridge which has a span of 318 metres and runs to Ile d'Orleans across a narrow non-shipping channel (*Ponts du Quebec,* 1975). During the period between 1995 and 2000, the CNR, in cooperation with the Quebec government, refurbished the bridge and applied a modern corrosion-resistant coating. Furthermore, extensive lighting was added as a tourist attraction (Sweeney & Oommen, 1996).

Conclusion

The challenge of crossing the ocean-shipping channel of the St. Lawrence at Quebec City was resolved by means of a cantilever design that remains the world's longest. Because of inattention to detail by the Phoenix Bridge designer and the consulting engineers, the first attempted bridge was not strong enough and collapsed before completion. The final design, led by Dominion Bridge engineers, utilized a new K bracing in each bay that simplified both fabrication and field erection, as well as reduced dead-load distortion; this approach was then replicated in several long-span cantilevers. The steel plates were rolled from open-hearth melts by Carnegie Steel Mills because the Canadian steel industry was in its infancy and did not have suitable hot rolling facilities. The use of nickel steel greatly reduced the weight of the bridge because it allowed for 50 per cent greater strength (compared to similar carbon steel) due to the increased volume of refined pearlite. There is no bridge crossing the shipping channel eastward, down-river from Quebec; therefore, the Quebec Bridge served as a vital rail and road link until a parallel suspension highway bridge was built in 1970.

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