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19TH CENTURY BRIDGE DESIGN IN CANADA:
A TECHNOLOGY IN TRANSITION

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Between 1880 and 1885, three cantilever railroad bridges were built all or partly in Canada. They spanned the Saint John River in New Brunswick, the Fraser River in British Columbia and the Niagara River between the state of New York and Ontario. These bridges, contemporary with the great Forth Bridge in Scotland, were followed in a few years by others including the Quebec Bridge. They represent an important transitional period not only in bridge design but also in technology in general. Some of the main factors causing this transition were:

1. The advent of steel rail resulting in heavier, faster trains requiring heavier, more rigid bridges;

2. Railroad lines were reaching out, crossing mountain ranges, international borders and river canyons that presented greater challenges to the bridge builder;

3. The marvellous properties of steel had been discovered and engineers were experimenting with its use in structures and machines;

4. Finally, a combination of the above three factors were instrumental in the evolution of detailed bridge design by (a) requiring greater speed in planning design and erection, (b) casting doubt upon the traditional system of pin connections in bridge construction, and (c) presenting new configurations which were made possible by the use of steel members.

These changes were more complex than they appear on the surface. This complexity is further confused by traditional histories of bridge building because the authors tend to oversimplify the changes. I often remind myself of the advice L.T.C. Rolt gives in his preface to *A Short History of Machine Tools* when he says

> the historian's desire for order always tempts him to oversimplify so as to make past events form a neat pattern. To some extent this is inevitable if history is to be written coherently. But it can lead

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> the reader into the error of supposing that the logical pattern created by the historian was evident to those taking part in the particular sequence of historical events he is recording.[1]

The more deeply I investigated these changes the more I discovered that they were not neat and orderly and that they presented real problems to bridge designers of the past and also to bridge historians of the present.

I will describe the main features of the three bridges in order to compare them (see Diagrams 1 and 2). I was originally attracted to the Saint John Bridge because it was such an unusual shape and because it was totally pin connected. It was also the first big contract for one of Canada's foremost bridge building companies -- Dominion Bridge Company Limited. I soon discovered that most of the original drawings were still available at the bridge company's office in Montreal.

The Saint John Bridge (see Diagram 3) was located over the reversing falls on the river at Saint John, New Brunswick, which was an obvious location for a cantilever bridge as the erection of false work over the river at that point was very difficult. The tenders were called for by the Saint John Bridge and Railway Extension Company, which became part of the New Brunswick Railway which, in turn, was leased to the CPR in 1889. The contract was awarded to the Dominion Bridge Company whose design for a cantilever bridge was prepared by Job Abbott, President and Chief Engineer of the Company, and countersigned by P.S. Archibald, Engineer for the customer and Chief Engineer for the Intercolonial Railway.[2]

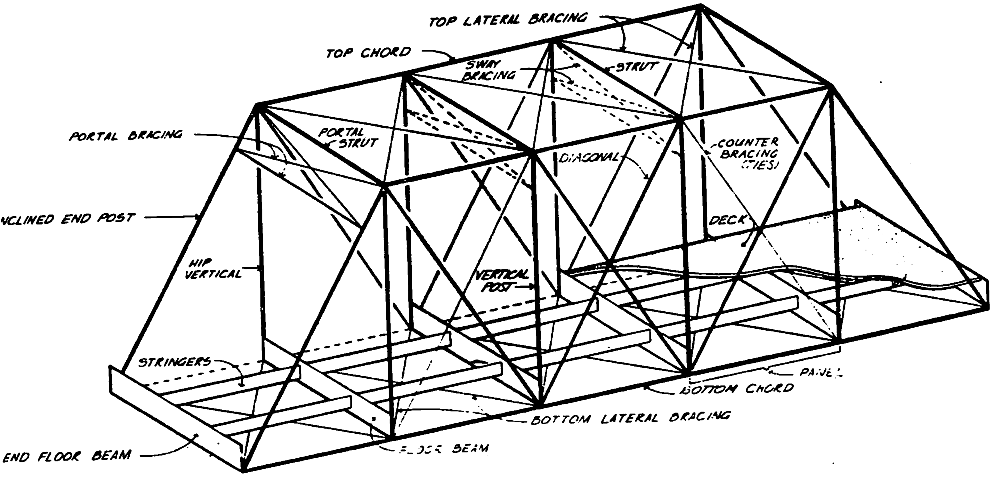
The original design called for an equal-arm cantilever but detailed examinations of the footings for the western pier caused the company to move the pier further westward and redesign the western cantilever to make it longer.[3] It would appear that time precluded the redesign of the whole bridge to make it symmetrical. The final design had a clear span of 477 feet. The drawings reveal other design features of the superstructure:

1. All members were prefabricated in the machine shops of Dominion Bridge where they were shop-riveted. Very little riveting was planned for the field and this was done on the shore for final assembly of such members as the lower chords on the bridge.

2. All panel points, braces and struts were pin connected. A few connections were riveted *in situ* in portions of the deck and in flooring members where the stress on the connections was minimal;

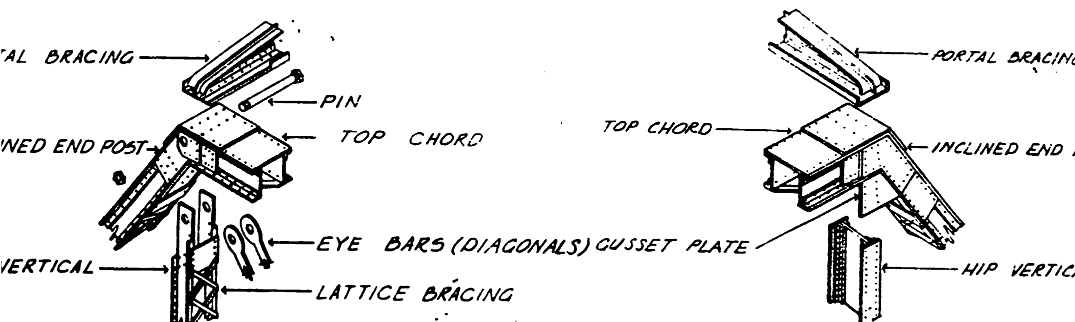
3. All members were made from steel provided mainly by the Steel Company of Scotland with some material from the Aachener Works in Germany;

Diagram #1



Bridge Features

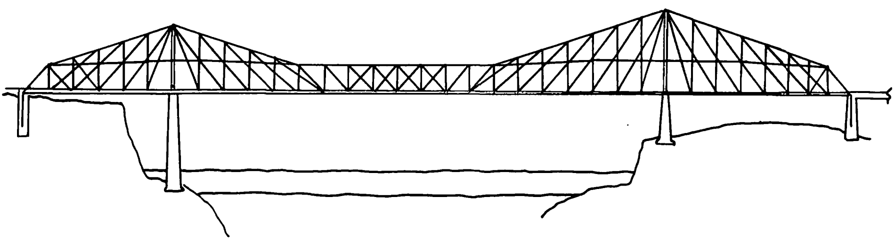
Diagram #2



PIN CONNECTION RIVETED CONNECTION

(Diagrams from Historic American Engineering Record)

Diagram #3



Saint John, NB, (1885), span 477 feet.

4. The shore arms were erected over false work. The river arms were erected by a traveller cantilevered out from the piers;

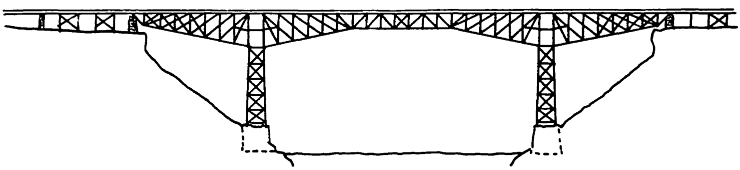
5. The suspended span was erected by making it temporarily rigid and cantilevered out from the main arms. The hinge was freed after the span was completed;

6. The erection time for the structure was about three and one-half months from 9 April to 30 July 1885.

The Niagara River Bridge (see Diagram 4) is the best known of the three and was located near Roebling's well-known suspension bridge. The bridge was designed by the justly famous Charles Conrad Schneider[4] acting for the Central Bridge Works who were tendering on behalf of the Niagara River Bridge Company.[5] The contract was awarded on 11 April 1883 on the condition that the structure was completed by 1 December of the same year! The drawings reveal the configurations to be what we now consider as the classic cantilever design. It was a deck truss with equal-sized cantilevers giving a clear span of 470 feet. We also know that all the panelled points were pin connected. Field riveting was kept to an absolute minimum and that only on places of minimum stress. Although Schneider planned to use steel throughout, he found that he could not obtain enough in time and restricted its use to the compression members, the pins and to some of the main tension members. Wrought iron was used for the eye bars and cast iron was used for railings and decoration. The superstructure was erected in the amazing time of three weeks, being completed on 18 September.

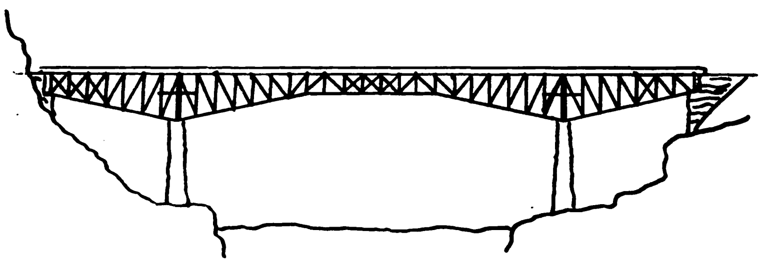
We know less about the details of the Fraser River Bridge[6] (see Diagram 5). It too was designed by Schneider for the CPR to span the rugged mountain canyon. Its configuration is also a classic cantilever deck truss with a clear span

Diagram #4



Niagara River, NY - Ont. (1883), span 470 feet.

Diagram #5



Fraser River, BC (1885?), span 316 feet.

of 316 feet. It is truly an international bridge as it was designed by a German-trained engineer for a Canadian company. The iron and steel members were fabricated in England, shipped by sea to Vancouver and erected by the San Francisco Bridge Company. All the panel points were pin connected. It was erected sometime between 1882 and 1886.

For comparison, we may look at two other cantilever bridges: the Forth Bridge, which is a multiple cantilever with 1710-foot spans constructed entirely of steel, riveted throughout and took seven years to erect, and the Quebec Bridge, a single span cantilever of 1800 feet, started in 1900, collapsed in 1907, redesigned and restarted in 1911. As it neared completion in 1914, the suspended span was dropped into the river. A new suspended span was connected successfully in 1917. The construction time for the final bridge was approximately three years. The final design called for

'K' trusses without multiple intersections and with all the panel points pin connected.

A close study of the available information on the first three bridges reveals some interesting facts. First of all, it was clear by the 1880s that the outstanding properties of steel were recognized by most engineers as illustrated by its use in Ead's St. Louis Bridge[7] and others. However, it was also recognized that good quality steel was not yet readily available at competitive prices. While Waddell states in his 1916 bridge text that, by 1895, the adoption of steel for bridges was practically universal,[8] Schneider writes in 1914 that good steel for bridge building was both difficult to obtain and expensive.[9] Many papers on bridge building, printed in engineering journals of the period, include descriptions of detailed tests carried out on the structural steel by the bridge companies. Obviously, they could not always rely upon their suppliers.

The problem faced by the metallurgists was to devise a process that would produce large quantities of structural steel that could withstand great forces in tension and compression. This involved producing a 'clean' steel or what Waddell calls 'purified' steel, *i.e.* steel with fewer impurities and more specific and more homogeneous carbon content to which could be added other metals such as manganese, nickel and chrome. It would also involve some kind of heat treatment that would improve the strength of the steel. Heat treatment was seldom used in structural steel in the 19th Century and therefore this type of high quality steel was not available in large quantities until at least the 1920s. There had been enough bridge disasters to make most engineers very cautious. This caution led most engineers to over-design their structures by adding extra members and by bracing compression members when they appeared to be too long and might buckle. These additional members actually produced a design that was beyond calculation or what is termed statically indeterminate. It is, therefore, somewhat puzzling to see the Saint John Bridge built entirely of steel until one discovers that three of the original seven stockholders of the Dominion Bridge Company were principals in the Steel Company of Scotland and were presumably anxious to see their companies prosper and to see steel adopted more widely.

The detailed discussions to be found in many issues of engineering journals about the advantages of pin-connected trusses over rigid-riveted trusses are also interesting. It appears that European engineers favoured riveted joints and Americans, including most Canadians, stoutly defended pin connections. The argument has many facets but, from the North American point of view, it seems to centre on the fact that pin connections theoretically allow only axial stresses in a member; therefore, the member would be subjected only to tension or compression and never to torsion or sheer as found in a rigid-riveted joint. They also refer to riveted connections as joints causing 'ambiguous stress,' while arguing that pin-connected joints avoid secondary stresses caused by thermal expansion and contraction. They allow that pin connections are much easier to erect but claim that this is only of minor importance. There is no doubt that a pin-connected joint does indeed create only tension or compression in a member, and the speed of erection is dramatically demonstrated by comparing the Niagara Bridge and the Forth Bridge, even allowing for size.

The argument against pin connection was strong and became stronger. Pin connections permitted excessive vibrations which, in time, caused excessive wear, extra maintenance and sometimes failure. And it was clear that, as time passed, more and more bridges were riveted throughout and pin connections eventually became obsolete proving the structural superiority of rigid connections, providing that riveting is done properly. Therefore, examining the argument with the benefit of hindsight, one may assume that the real reason for advocating pin connections was not for structural efficiency but for ease of erection. This merits closer examination of the technology involved.

Using pin connections means assembling the members and inserting the pin much like building with a Meccano set. This avoided riveting in the field as neither bolting nor welding were practical at this time. Even riveting was difficult. Stationary powered riveters were used in every shop but were very heavy and cumbersome and, therefore, field riveting had to be done by hand. Hand riveting was not good enough for these structures unless the riveters were highly skilled and not hurried. Poor riveting was inconsistent and did not provide the clamping action that was such an important advantage in modern high strength bolts. The rivets in the old Victoria Tubular Bridge were constantly being sheared off and driven out by the action of the iron plates under stress with the result that a special crew of riveters was on duty full time to replace them. Apparently, European bridge builders had skilled riveters and more time for erection. C.C. Schneider, having been trained in Europe, would have been cognizant of this practice yet specified pin connections when practicing in North America.

In time, bridge engineers began to find alternatives to pin connections (field riveting) by constructing larger members in the shop or by partial assembly on a site adjacent to the bridge. These larger sections would then be erected by raising whole spans from water level. Eventually, spans were end-launched onto the piers. This avoided pin connections and minimized hand riveting but involved far greater risks. In 1889, the seventeen-span Coteau Bridge was erected over the St. Lawrence River. Thirteen of the seventeen 217-foot spans were assembled by riveting on shore and floated into position.

We know that bridge companies were very competitive and would have had to trim costs at every opportunity without endangering their product or their reputation. We also know that North American bridge sites were often remote and rugged, making erection procedures very important. Yet the tender to the customer would have to emphasize the utility and longevity of the bridge as the customer would consider the erection problems relatively unimportant. No doubt the bridge companies were unwilling to admit that rigid connections were more difficult and more expensive.

The third aspect of bridge building that I would like to discuss examines the very important changes in truss design. It is a recognized principle in truss design that a truss must be divided into triangular panels if it is to be statically determinate. It is also essential that a truss may only be loaded at the panel points or joints so that the stress is transmitted to the members along their axes. If a member is loaded at any other location it will bend and the triangle becomes a polygon and thus indeterminate. The tendency of earlier bridge designers to create multiple intersecting members created statically indeterminate trusses. Multiple intersections evolved from the old lattice trusses and were slow to disappear. Whenever an engineer distrusted his design or the material, he added another member. Or in railway bridges, if he needed greater support and more panel points, he added members.

The practice of using multiple intersections continued for some time because the engineer did not trust his steel members. When describing the construction of the Niagara Bridge, Schneider says 'It was also decided to use a double system of diagonals although the writer does not ordinarily advocate double intersection. It was done however, in this case to have an intermediate support for the posts some of which are very long.'[10] The posts he referred to were compression members for which steel was specified. An examination of the design drawings for the Saint John Bridge reveals that the designer used multiple intersections and, in order to calculate the force on each member, had to ignore some of the connections. Therefore, the Fraser River Bridge with the simple triangular panels in its trusses is Schneider's purest design and deserves to be considered for this and other reasons as the first truly-modern cantilever. The 'K' trusses of the Quebec Bridge avoid multiple intersections and yet provide sufficient points for loading.

An examination of these bridges reveals that the transition from iron to steel in bridge construction in North America was much more complex than it appears on the surface. The development of the steel rail did not signal a corresponding change in construction materials as the rail was only subjected to compressive forces. Good steel had been available for centuries in small quantities for tools and machines but large quantities of high quality steel, able to withstand large tensile forces, were not universally available at a price competitive with wrought iron until after World War I. This shortage of good, inexpensive structural steel was also experienced in the building construction and shipbuilding fields as well.

This study also highlights the problem faced by the bridge engineer who knew that pin-connected bridges were not really as structurally sound as riveted bridges but was forced to defend the practice because he knew they were cheaper and easier to build. He also knew that cantilever bridges were not as rigid as ordinary truss bridges or continuous span bridges and that pin-connected cantilevers were even worse, yet they were the only possible solution over certain obstacles during this period in North America. One observer notes

> under test loads the centre span of the St. John cantilever 477' span - deflected 4 inches, the Niagara cantilever, 470' span deflected about 6½ inches after making allowance for compression of steel piers.
>
> These deflections are excessive and under loads at high speed might produce serious and unknown strains.[11]

A few engineers advocated all-riveted structures but they had difficulty competing in the market place.

An examination of the discussions printed in the transactions of the Canadian Society of Civil Engineers and the American Society of Civil Engineers also indicates that these comparatively small bridges had a greater effect on cantilever bridge design in North America than the Firth of Forth Bridge. These bridges were cheap, quick to erect and eventually satisfied the designer's urge for precision in calculations. Interestingly, Schneider's cantilever design is still the cheapest and most efficient design for spans of between 800 and 1500 feet although all the connections would now be bolted or welded. We do have different aesthetic criteria today and the high trusses on a bridge or the belching smokestack are no longer welcome signs of industrial progress.

Another item of interest to students of Canadian history is the founding of the Dominion Bridge Company by an American immigrant. This company's success was gratifying. Its shops at Lachine were frequently cited at the turn of the century as one of the most complete bridge fabricating shops on the continent. Job Abbott returned to the USA to work and eventually to die, but the company lived on and today has acquired several subsidiaries in the USA and Europe, an interesting reversal of the trend.

NOTES

1. L.T.C. Rolt, *A Short History of Machine Tools* (Cambridge, Mass., 1965), iv.

2. Plowden states that P.S. Archibald assisted Abbott as Chief Engineer for the CPR and that the bridge was ordered by the CPR. In fact, the CPR was not involved with this bridge until five years later. D. Plowden, *Bridges, The Spans of North America* (New York, 1974), 139.

3. Most of the detail on this bridge comes from two unsigned articles in *Engineering* (London), 38 (24 Sept. 1886), 327-8 and (15 Oct. 1886), 393-4 and from the original drawings in possession of the Dominion Bridge Co. in Montreal.

4. C.C. Schneider described the design and erection of this bridge in three articles: *ibid.* (5 March 1886), 224-6, (12 March), 246-8, and (2 April), 324-6.

5. The Niagara River Bridge Company was part of the Canada Southern Railroad which was a subsidiary of the New York Central Railroad.

6. An illustration appears, without text, in *ibid.*, (5 Sept. 1884), 226.

7. Structurally Ead's bridge was a series of arches in which the steel is mostly in compression. Therefore this was still not a real test of all the properties of steel.

8. J.A.L. Waddell, *Bridge Engineering* (New York, 1916), 28.

9. Letter, C.C. Schneider to the Dominion Bridge Co., 7 July 1914. Dominion Bridge Company, Montreal.

10. Schneider, *Engineering* (5 March 1886), 225.

11. C.F. Findlay, 'Cantilever Bridges,' *Transactions of the Canadian Society of Civil Engineers* 3 (1889), 86.