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THE LESSON OF THE QUEBEC BRIDGE

Wilfred G. Lockett[1]

'Where no precedent exists the successful engineer is he who makes the fewest mistakes.'[2]

INTRODUCTION

For most of history technological man has conceived, designed and built his pyramids, aqueducts, temples, cathedrals and bridges on the basis of divine inspiration, common sense and a considerable reliance on experience and precedent. The materials of construction have been generally those found in nature--stone, timber and vegetable fibre, supplemented by man-made bricks and mortar and fastenings of iron. Learning has been largely by trial and error and the transmission of accumulated knowledge has been through imitation and apprenticeship. Occasional texts have appeared, of which Vitruvius's *De Architectura* and Villard de Honnecourt's *Sketchbook* are notable examples.

The completion in 1779 of a cast-iron bridge across the river Severn at Coalbrooke Dale in England heralded a new era. Cast iron soon gave way to wrought iron with its greater and more predictable tensile strength, and by the latter half of the 19th century the inventions of Bessemer and Siemens had made steel available in quantity to the construction industry, facilitating such engineering feats as the Brooklyn bridge in New York and the Forth bridge in Scotland. But progress was not confined to the introduction of a radically new building material. A parallel advancement took place in the methodology of engineering design. The adoption of a scientific approach gave rise to new technical subjects such as Strength and Elasticity of Materials and Theory of Structures. A quantitative notion of 'factor of safety' emerged. One might think that, with this new reliance on mathematical analysis, the element of 'trial and error' would lose prominence in engineering design.

That such has not been the case is all too evident as recent events in the space and nuclear industries have shown. Indeed there have been so many 'cases' that to attempt an in-depth examination of how engineers learn from their mistakes would be a daunting task, not least because the value of the lesson learnt is not necessarily proportional to the magnitude of the error or the publicity it receives. But the study of one or two isolated

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1 7206 Cambridge Street, Niagara Falls, Ont. L2J 1G6

2 Benjamin Baker, speaking in Montreal on the Forth Bridge, quoted in W. Westhofen, *The Forth Bridge* (London, 1890).

incidents might be expected to indicate areas for further investigation.

Perhaps the most notorious failure in Canadian engineering history was the collapse during construction of the bridge over the St Lawrence near Quebec City (see Figure 1). In the calamity, which occurred on 29 August 1907, 74 of the 85 men working on the bridge at the time lost their lives. The *Engineering News* commented 'The fall of this bridge ranks with the greatest engineering disasters in history.'[3]

Within two days of the accident the Government of Canada had appointed a Commission of Inquiry. After six months of intensive investigation the Commission presented its report.[4] In the most forthright and uncompromising terms the Commission laid the blame firmly on the principal engineers involved, naming names, and effectively ruling out any question that an 'act of God' might have contributed to the accident. Nevertheless the story of the Quebec bridge is reminiscent of a Greek tragedy. Let us discover its moral.

THE CANTILEVER PRINCIPLE

The original Quebec bridge and the one which replaced it are both, like the Forth bridge in Scotland, cantilever bridges. Their outlines are shown on Figure 2.

The fundamental elements of the cantilever structure are shown on Figure 3, and comprise essentially a bracket, jutting out from a tower which is prevented from overturning by a similar bracket firmly anchored to a solid foundation. A pair of these structures support between them the suspended span which completes the crossing of the river. We will later have to consider some of the basic engineering involved in the design of the structure, but in the meantime we should note that the upper members of the cantilever are in tension, while the lower members act as struts and are in compression.

Cantilever bridges, by their very nature, lend themselves to being constructed outwards from the sides, without the necessity of temporary falsework to support the central sections.

HISTORY OF THE QUEBEC BRIDGE

The idea of a crossing of the St Lawrence River in the neighbourhood of Quebec goes back to 1852 when General E.W.

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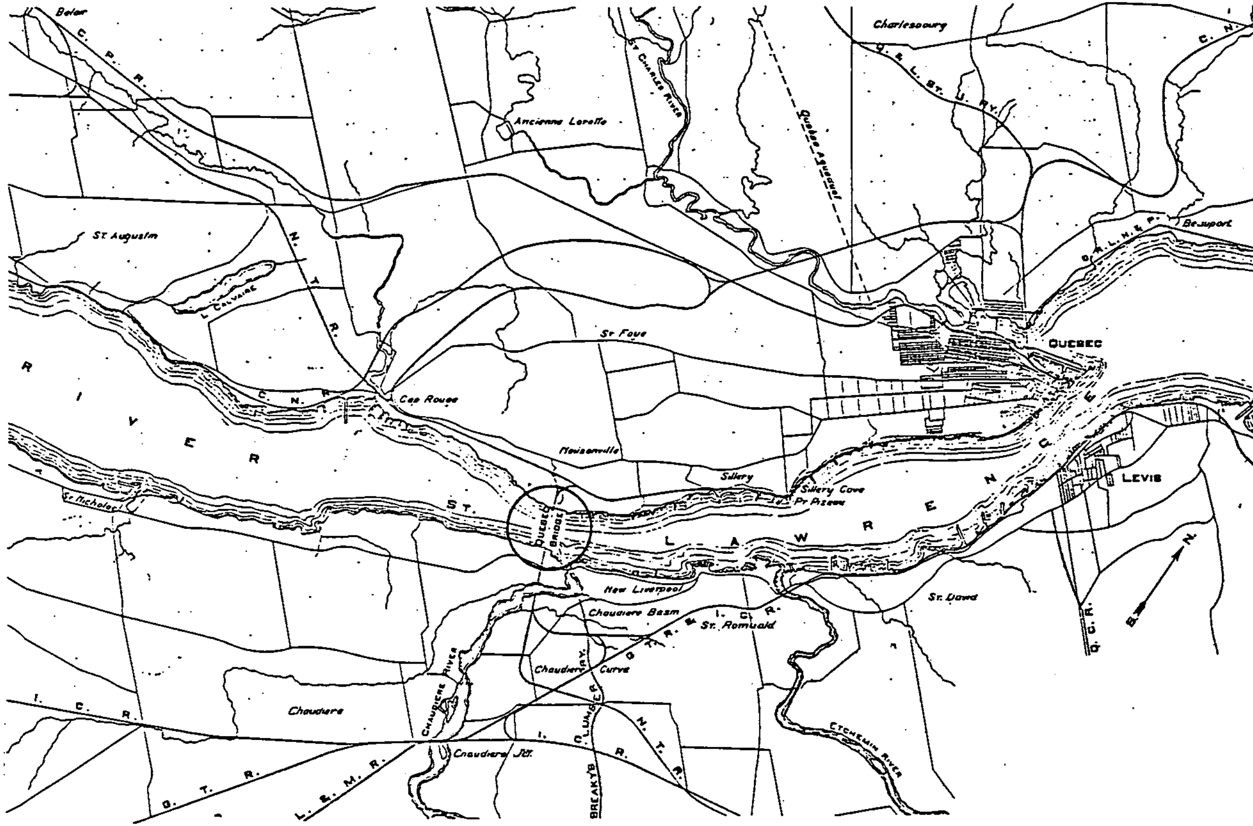
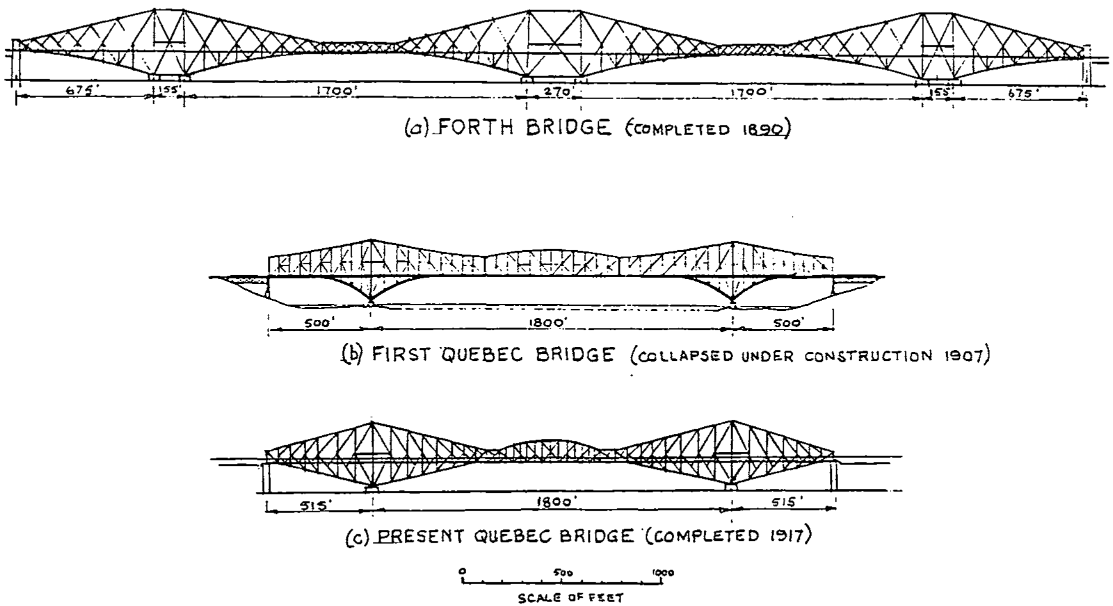
3 *Engineering News*, 5 September 1907.

4 Royal Commission, *Quebec Bridge Inquiry Report* (Ottawa, 1908), 3 vols. This is the prime source for this article.



LOCATION OF QUEBEC BRIDGE FIGURE 1

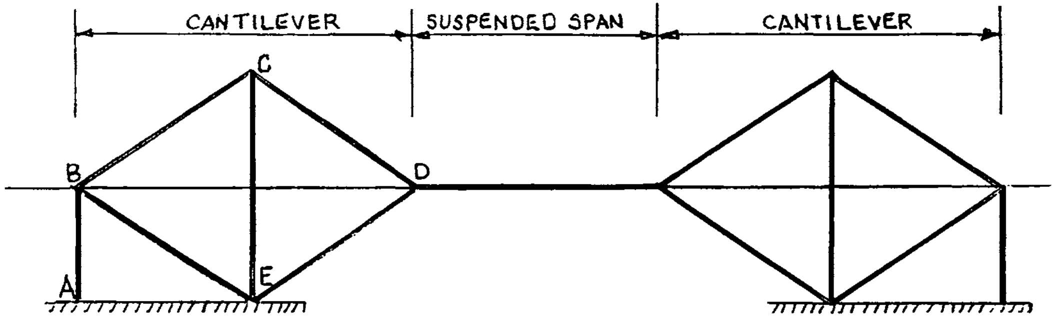


(a) FORTH BRIDGE (COMPLETED 1890)

(b) FIRST QUEBEC BRIDGE (COLLAPSED UNDER CONSTRUCTION 1907)

(c) PRESENT QUEBEC BRIDGE (COMPLETED 1917)

FIGURE 2



Anchor Post AB................*in tension*

Upper Chord BC, CD............*in tension*

Central Tower CE..............*in compression*

Lower Chord BE, ED............*in compression*

THE CANTILEVER PRINCIPLE Figure 3

Serell, the engineer of the Lewiston and Queenston suspension bridge, acting for the City of Quebec, identified the present site. However, it was not until 1887 that the Quebec Bridge Company was formed to build and operate a combined rail and highway bridge. Further legislation followed in 1891, 1897 and 1900 and in 1903 the name was changed to the Quebec Bridge and Railway Company (referred to hereafter as 'the Company').
In the meantime the Company had appointed as Chief Engineer Edward A. Hoare, who had some 35 years of experience in railway work in Canada, not, however, involving bridges with spans greater than about 300 feet. Hoare conducted surveys of the site during the 1890s, and recommended three possible locations from which was selected an alignment very close to the present one.
In mid-1897 Hoare made contact at an engineering conference in Quebec with John S. Deans, Chief Engineer of the Phoenix Bridge Company of Phoenixville, Pennsylvania, and subsequently sent him a profile of the crossing. The Phoenix Bridge Company took an enthusiastic interest in the project and by the end of 1897 had sent a preliminary cantilever design to Hoare. In the meantime Deans had recommended to Hoare a well-reputed New York consultant, Theodore Cooper, who would be prepared to give the Company the benefit of his experience.

During 1898 the Department of Railways and Canals approved the Company's preliminary plans--which were identical with the Phoenix drafts--as a basis for calling tenders. The accompanying specifications, mainly copied from the those of the Department of Railways and Canals, were approved for tender purposes provided that more detailed specifications were drawn up for the actual construction of the bridge.

Tenders were called and in March, 1899, bids were received for the following types of superstructure:[5]

Bidder	Type and Span of Bridge	
	Cantilever	Stiffened Suspension
Dominion Bridge Co.	1600 ft	2000 ft
Keystone Bridge Co.	1600 ft	
Phoenix Bridge Co.	1600 ft	1800 ft
Union Bridge Co.		1800 ft

Tenders were also received for the construction of the substructures.

The Company engaged Theodore Cooper to examine and report on the tenders. In his report, dated 23 June 1899, he recommended

5 See Cooper's 'Report on Tenders,' ibid., III, 439-40.

acceptance of the Phoenix bid for the cantilever bridge as being 'the "best and cheapest" plan and proposal submitted...'. Phoenix's tender price, adjusted by Cooper for purposes of fair comparison, was $2,439,000, to which must be added $1,144,000 for the substructures.[6]
At the same time Cooper made two important recommendations:

(a) that a program of subsurface exploration be undertaken to determine foundation conditions

(b) that provision be made for modifying the specifications and design of the bridge, within reasonable limits, with a view to improvement or economy

The results of the site investigations were sent to Cooper in January, 1900, and in the following May he recommended to the company that the span of the bridge be increased from 1600 feet to 1800 feet. The relocation of the main piers away from the river's edge would, he claimed, result in a reduced risk of potentially costly problems during construction. Cooper also estimated that the cost of this change would amount to $200,000, provided that 'desirable and justifiable' modifications were made to the specifications.[7]

The Company accepted Cooper's report in May 1900, and at the same time appointed him consulting engineer--initially for the examination of plans, but subsequently the scope of the engagement was enlarged to cover the whole period of the design and construction of the bridge.

By the end of 1900 the Company had entered into contracts with W. Davis & Sons for the substructure works and with the Phoenix Bridge Company for the approach spans. Construction commenced at the site in October, 1900. Then there was a hiatus. And this gives us the opportunity to summarise events so far:

(a) A company was founded to build and operate a major rail and highway bridge, which would be an important link in Canada's trans-continental communications system

(b) The Company engaged as its Chief Engineer a person (Hoare) well experienced in general railway work but in no way a specialist in large bridges

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6 *Inquiry Report*, III, 444-5.

7 Ibid., 446-7.

(c) All the preliminary designs of the bridge were prepared by a contractor (Phoenix Bridge Company) at its own expense, clearly in the hope that by so doing it would stand a good chance of being awarded the job in due course

(d) Tenders were called on the basis of a preliminary design essentially the same as that of the Phoenix Bridge Company, and the standard specification of the Department of Railways and Canals

(e) The Company retained as its Consulting Engineer a specialist in bridge design (Cooper), well-reputed in North America

(f) In his report on the bids Cooper favoured the Phoenix Bridge Company

(g) Following subsurface exploration Cooper recommended that the span of the bridge be increased from 1600 to 1800 feet. This was accepted.

(h) Contracts for the substructures and approach spans were awarded and work commenced at the site.

The involvement of a contractor to assist with preliminary designs in the very early stages of a project is noteworthy. In a comparison of six major bridges (including the Forth bridge) the Royal Commission observed that 'all the bridges ...were designed by independent engineers except the Quebec bridge.'[8] The implications of not obtaining an independent design will be discussed later.

It had been public knowledge from the start that the Company was seriously under-funded.[9] Attempts by Deans to interest US bankers failed, and, not surprisingly, the Phoenix Bridge Company was reluctant to incur the high cost of the detailed design, let alone the fabrication, of the superstructure steelwork without some assurance it would be paid. Work on the main bridge was thus delayed and it was not until June, 1903, that an agreement was signed with the Phoenix Bridge Company, which incorporated the changed span of the bridge and a set of specifications amended by Cooper. Even then work was not started until October, 1903, when the government's Guarantee Act put the Company on a firm financial footing.

The agreement of June, 1903, was a unit-price contract, as opposed to the 1899 lump-sum tender. The specified date for

8 Ibid., I, 146.

9 Ibid., 35.

completion was 31 December 1906, but in an attached letter D. Reeves, President of the Phoenix Bridge Company, refused to accept responsibility for damages due to delayed completion prior to 31 December 1908.[10] Clearly it was felt that three years, including three summer construction seasons, was a very short time for the design, fabrication of component members, shipping to site and erection of what would be a record-breaking cantilever bridge.

The organization which evolved to carry out the design and construction of the bridge is illustrated in the diagram on Figure 4.[11]. The Company's Chief Engineer, E.A. Hoare, was in principle the senior man on the whole project, responsible to the Company for final decision-making, at least in technical matters. But his lack of experience in major bridges led him to defer greatly to the Consulting Engineer, Cooper, who effectively assumed the reins of Chief Engineer.

For the important function of detailed checking of the work in progress, the Company engaged three inspectors: N.R. McLure, E.L. Edwards (both selected by Cooper) and E.R. Kinloch. Edwards was inspector of shop work, assisted initially by McLure. After erection started McLure moved to the site, where he and Kinloch were the only full-time representatives of the Company, Hoare being located in Quebec City, across the river some 10 miles away. It should be noted that McLure was a recent graduate (1904) while Kinloch was not a graduate engineer but had considerable experience in bridge construction from the practical standpoint.

In the Phoenix Bridge Company, the detailed design of the bridge was the responsibility of P.L. Szlapka, Design Engineer, who reported to J.S. Deans, the Chief Engineer. A.B. Milliken was Superintendant of Erection and had the responsibility of appointing and generally supervising the field staff on all the firm's projects. He spent much time visiting the Quebec bridge site but while there acted in an advisory capacity so as not to undermine the authority of his senior site man, B.A. Yenser. Working under Yenser, who was classified as General Foreman, were two qualified engineers, A.H. Birks and F.A. Cudworth.

The Organization Chart shows the formal procedure for approval of plans: Szlapka -> Cooper -> Szlapka -> Hoare -> Deputy Minister. In practice, as indicated in a table of dates at which various operations were performed,[12] when approved drawings were

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10 Ibid., 31.

11 Adapted from ibid., 55.

12 Ibid., 61.

FIRST QUEBEC BRIDGE - ORGANIZATION CHART

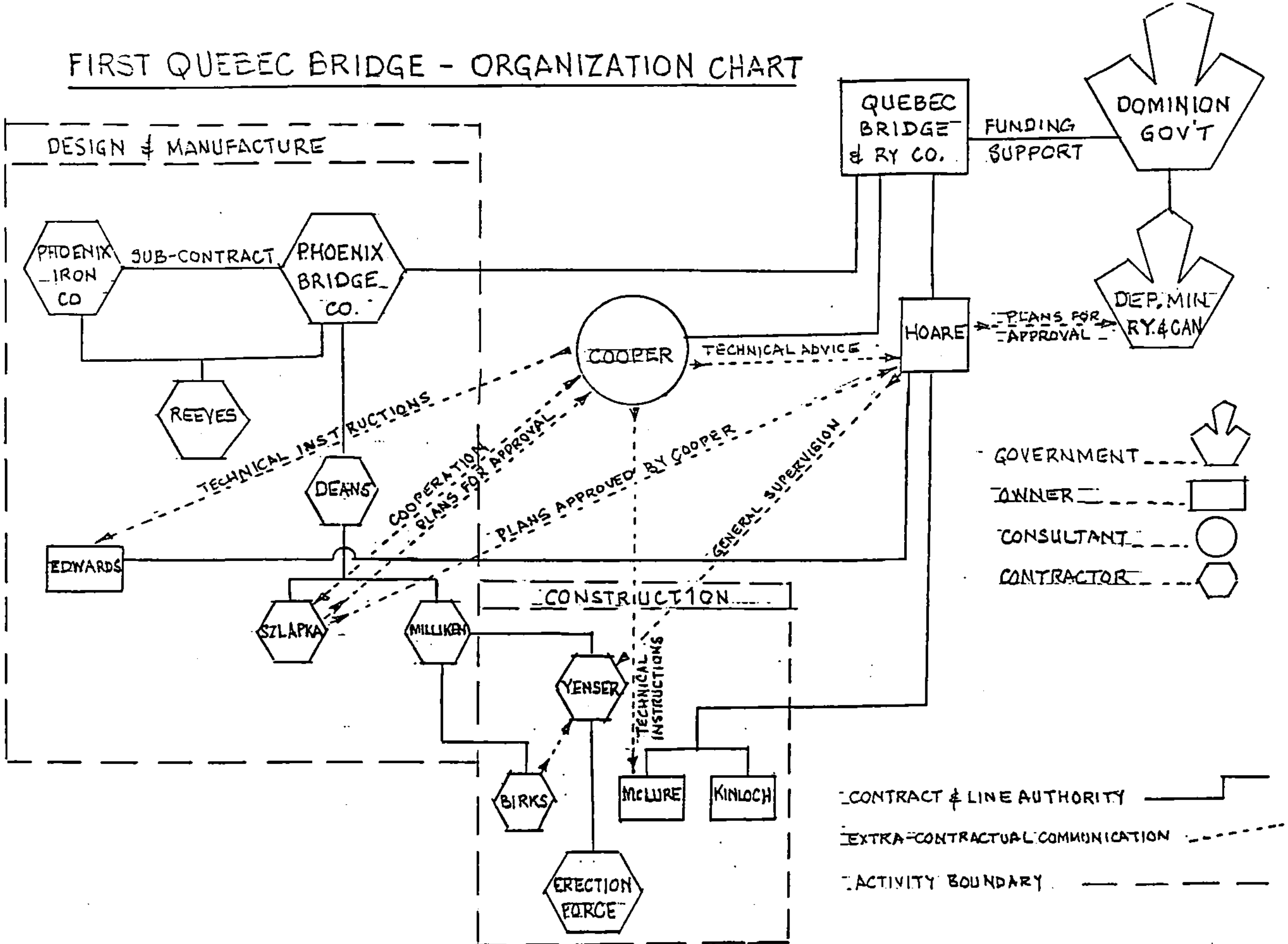

FIGURE 4

received in Phoenixville from Cooper, they were passed on to the shops for fabrication.

We turn now to those design aspects which featured most prominently in the ultimate failure of the bridge. The three main categories of loading for which a bridge has to be designed are (1) the 'live load,' which includes the traffic the bridge is required to carry, as well as the wind load, (2) the 'dead load,' which is the self-weight of the bridge, and (3) special loading conditions which can occur during construction.

The structure itself must have adequate strength to carry the combined effect of these loads safely. Tension members may be and often are made up of flat bars connected by steel 'pins.' Such an arrangement would not work in the case of compression members ('columns' and 'struts') since the bars would have insufficient stiffness by themselves to resist buckling. Subsidiary bracing members ('latticing') must be provided to increase the stiffness or the struts must be made in such a form (e.g. cylindrical) as to be inherently resistant to buckling.

Fundamentally, the design process involves the following steps:

(a) The 'live loads': the intended traffic and the wind load are given in the specification

(b) The maximum working stresses are also laid down in the specification

(c) The designer estimates the self-weight of the structure (the 'dead load') from a previously-conceived, approximate configuration

(d) The total load is the combination of (a) and (c)

(e) The 'scantlings' (essentially the cross-sections of the individual members) are determined by recognized methods of structural analysis, taking into account the total load (d) and the specified stress limits (b)

(f) The self-weight is recalculated based on the scantlings arrived at in step (e), and compared with the assumed weight (c)

(g) There follows a series of successive approximations in which the analysis is repeated, using the adjusted values of self-weight, until the values of (c) and (f) are equal

We should note first that the working stresses specified by Cooper were somewhat higher than in normal usage. It is evident from his testimony[13] that this decision was taken after careful consideration and appeared, at the time, reasonable. It was only in combination with other factors that the higher stresses used as a basis for design became critical.

Although the design procedure summarized above was accepted practice at the time, the Phoenix Bridge Company failed to carry out steps (f) and (g), with the following result:[14]

Weight of Half Bridge	Lb
Weight assumed for design	31,364,800
Actual weight	40,539,941
Excess not designed for	29.3%

The error was not drawn to the attention of Cooper until February, 1906, by which time the anchor arm, tower and two panels of the cantilever arm had been fabricated, and six panels of the anchor arm had been erected at the site. In the Quebec bridge the shore side of the cantilever was referred to as the 'anchor arm,' the river side as the 'cantilever arm,' and the

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13 Ibid., II, 409-10.

14 The derivation of these crucial figures is as follows

(from the *Inquiry Report*, I, 57):

Weights assumed for design	lb
half suspended span	4,842,000
cantilever arm	13,205,200
anchor arm	13,307,600
Total assumed for design	31,354,800
corresponding total weigh recalculated from drawings 25 June 1907	38,816,000
of this, steelwork weight	25,316,000
[Thus weight of non-steel members	3,500,000]

(from *Report*, I, 64):

Actual weight of steelwork (revised from records, 25 September 1907)	37,039,941
[Thus actual total weight	40,539,941]

central support as the 'tower;' each approximately 50-foot section of the bridge was referred to as a 'panel.' Cooper estimated that the resulting increase in stress would be from 7 to 10 per cent, and, feeling that there was at this stage no remedy, permitted the work to continue.[15]

We have now to consider the design of the compression members and in particular those of the lower chord, that part of the cantilever incorporating the distinct curve shown in Figure 2(b). As noted above, the strength of a compression member or strut depends principally on its resistance to buckling. In the case of the Forth bridge this was neatly accomplished by giving the members a cylindrical form, which during the erection stage involved the building up of the member curved plate by curved plate, a procedure well suited to the skills of Scottish shipwrights. But in North America the accepted practice was to use standard rolled steel sections (angles, flats, I-beams, etc.) in the fabrication of structural members. In the Quebec bridge the struts were built up from an array of parallel flat plates. Figure 5 shows a comparison of the compression members of the Forth and Quebec bridges. The bracing introduced for stiffening the latter may be clearly seen. The active cross-sectional area was about 800 square inches in Forth bridge and 842 square inches in the Quebec bridge.

The design of such members was at the time a mixture of theory and practice with empirical formulae playing an important part. In particular there was no rigorous way of determining the amount of latticing. These subjects were addressed at length in Appendix 16 of the QBI Report, which concluded:

> The foregoing discussion shows that even at the present time theories of lattice design are in serious conflict and the strength of any lattice system will vary materially according to the formula adopted. Mr. Szlapka used, with his own modifications, the only system of lattice computation generally known to American engineers.... [He] selected the column formula adopted by his own company, and used the constants for it that, in his judgment, were most in keeping with the conditions of the case and in the best accord with the spirit of the specification. He made what he considered a liberal increase in his adopted sections over what his computations called for. The result has shown that his judgment was faulty, but we are not prepared at this date to define the minimum safe sections for the latticing of these chords.[16]

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15 *Inquiry Report*, I, 58. See also Cooper's testimony, ibid., II, 411.

16 Ibid., I, 137.

It is often remarked that engineering disasters are rarely due to a single fault but are caused rather by a combination of more than one unfavorable condition. In the case of the Quebec bridge we have the following concatenation of circumstances:

- The load on the structure was significantly greater than that for which it was designed

- This led to the stresses in the members being more than the specified working stresses, which were already higher than normal

- Key members were under-designed

It should be mentioned here that inferiority of materials--often a contributing cause of structural failure--was not a factor in the case of the Quebec bridge. The large quantity of steel required was obtained from four mills: the Phoenix Iron Company (a subsidiary of the main contractor), the Central Iron and Steel Company, the Carnegie Steel Company and the Bethlehem Steel Company. Normal structural steel was specified for the bridge, except in the case of the eyebars for the tension members, for which Cooper specified a slightly higher grade. In its investigations the Commission of Inquiry found that 'the disaster could not be traced to the furnaces or rolling mills.'[17]

By August, 1907, construction had reached the stage where the south cantilever had been completed and erection of the suspended span, jutting out from the end of the cantilever, was in hand. The 'big traveller,' a movable gantry used in the handling of components, was being dismantled in anticipation of transferring it to the north bank, and a 'little traveller' was in use for the work on the suspended span (see Figure 6).

During the month signs of distress were observed in the lower chord members. The web plates (i.e. the main load-carrying elements) of two members of the cantilever arm and one member (A9L) of the anchor arm were bent, and measurements were taken. On Tuesday, 27 August, the misalignment of A9L had increased from 3/4 inch (measured the previous week) to 2 1/4 inches. After discussions with Birks, McLure and Kinloch, Yenser decided he would not increase the load on the bridge, by moving the traveller out, until he received instructions as to what remedial action should be taken. While there was definite concern at this time regarding the problem of straightening the bent chords, it appears that none of the site staff thought the bridge was in any immediate danger. However, the attitude of the engineers on the project is worth noting. Both Kinloch and Yenser considered the matter serious enough to warrant a special visit by McLure and

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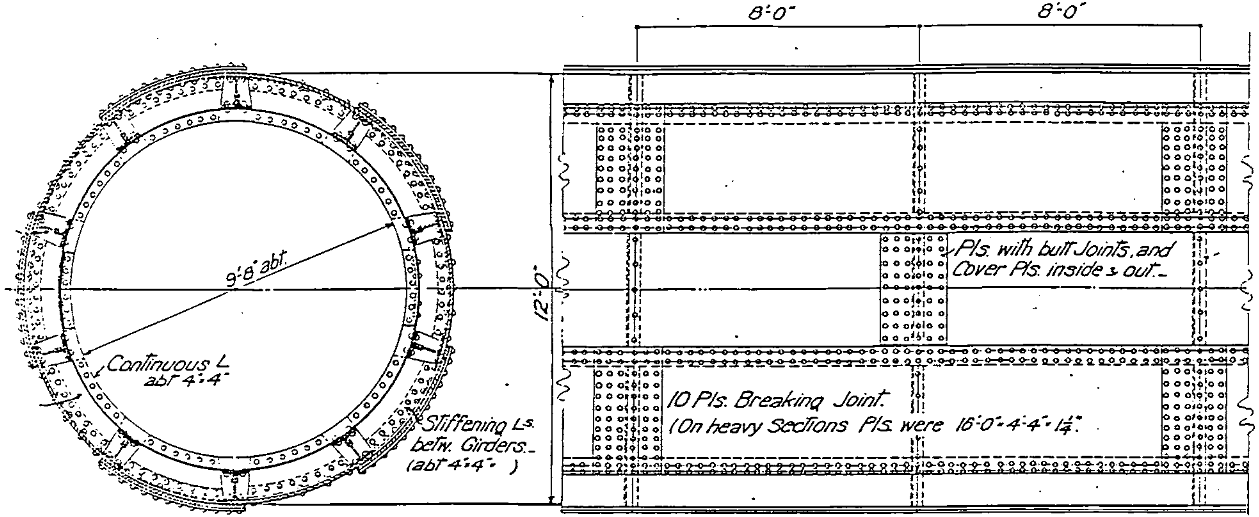
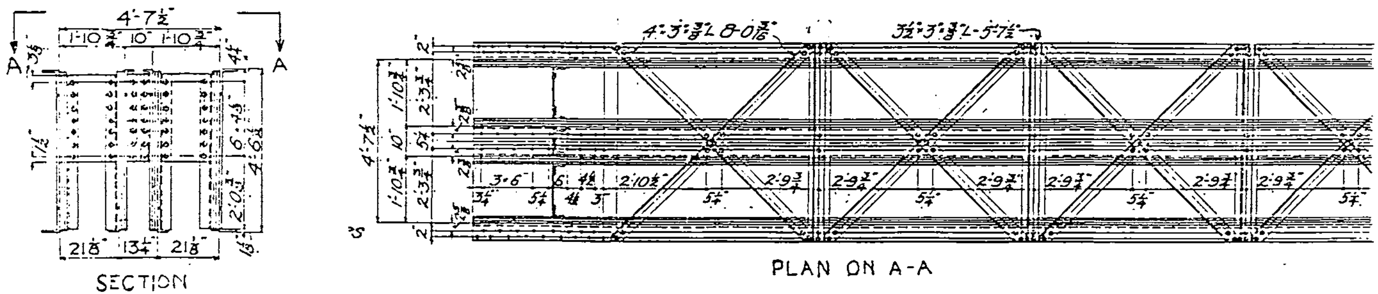
17 Ibid., 55-6.

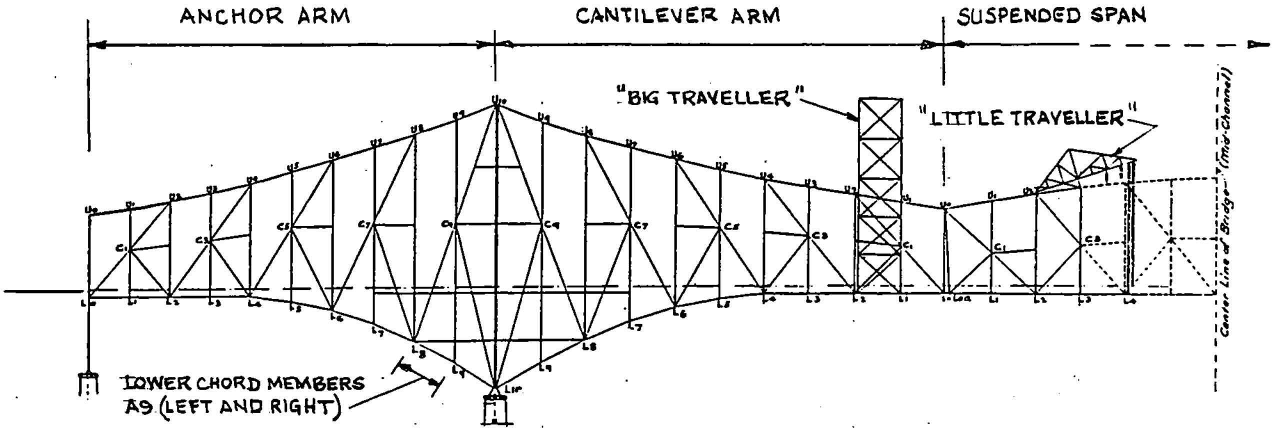


(a) FORTH BRIDGE COMPRESSION MEMBER - SECTION AND ELEVATION



(b) QUEBEC BRIDGE COMPRESSION MEMBER

FIGURE 5



CONDITIONS ON AUGUST 29, 1907

FIGURE 6

Birks to Cooper and Phoenixville for advice. This suggestion was not welcomed by the two engineers who felt they would be ridiculed. In particular Birks felt that the bend must have occurred prior to construction and was not due to the gradually increasing erection load.

> [Birks] knew better than anyone else on the work the care with which the calculations and designs had been made, he was familiar with the experience and abilities of the designers, and could calculate that the stresses were then far below the expected maximum. To engineers the force of such reasoning is very great, and we do not consider that the confidence Mr. Birks placed in his superiors was in any way unusual or unreasonable. There was no misunderstanding, however, on his part; he realized that if the bends had not been in the chord before it was erected the bridge was doomed, and although Mr. McLure had evidence that the bends had increased more than one inch in the course of a week, although Mr. Kinloch was positive that the bends had very recently greatly increased, and although Mr. Clark [storage yard foreman] stubbornly maintained that the chord was absolutely straight when it left [the] yard, Mr. Birks still strove to convince himself that they must have been mistaken.[18]

Hoare visited the site on Wednesday, 28 August, and 'appeared very anxious that [Kinloch] should abandon [his] position that the bend had occurred since the erection of the cantilever arm.' Nevertheless he authorised McLure to visit Cooper and wire back if the latter took a serious view of the situation.

On the same day, 26 August, Yenser, rather than have an idle workforce on his hands, changed his mind and decided to continue with erection. McLure objected that he thought this was 'poor policy,' but Hoare confirmed the decision 'as the moral effect of holding up the work would be very bad on all concerned...'[19]

McLure proceeded to New York, arriving there on the morning of 29 August. Cooper, who had just received by mail McLure's sketches showing the bends in chord A9L, decided that no further weight should be added to the bridge. But he was concerned as to whether the contractor's general foreman (Yenser) would take his direct order to stop work and wired the Phoenix Bridge Company 'to add no more load to the bridge until after due consideration of the facts.' This was felt to be the surest way of communicating with the site, since the Bridge company had a direct telephone line.

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18 Ibid., 87.

19 Hoare to Cooper, 28 August, ibid., I, 88.

Cooper instructed McLure to discuss the problem with Deans. McLure's arrival in Phoenixville, at about 5.00 pm on Thursday, 29 August, coincided with the collapse into a tangled heap of the whole superstructure, taking the lives of 74 men, including Yenser and Birks. (Figures 7)

THE ROYAL COMMISSION

The Canadian Government lost no time in reacting to the disaster. By Order of Council dated 31 August 1907, a Commission of Inquiry was appointed comprising the following members:

- Henry Holgate (Chairman), a partner in the firm of Ross and Holgate, with considerable experience in railway and electrical engineering, and as an arbitrator

- John Galbraith, President of the Canadian Society of Civil Engineers, and for 30 years Professor of Engineering at the University of Toronto

- John G.G. Kerry, a partner in the firm of Smith, Kerry and Chase, and (part-time) Associate Professor at McGill College

It was generally felt that these three eminent engineers constituted a broad and well-balanced commission, well qualified to carry out the detailed investigation so obviously required. To provide an independent opinion of the design of the bridge the Department of Railways and Canals appointed C.C. Schneider, Consulting Engineer of Philadelphia, whose report is attached to that of the Commission.[20]

The investigation lasted for six months, and included the intensive questioning of some 44 witnesses. As might be expected the examination was particularly relentless of the key figures in the drama: Hoare, Cooper, Deans, Szlapka, McLure and Kinloch. But there is no indication of reluctance on the part of the witnesses. On the contrary, considering how many of them must have been feeling, their apparent willingness to cooperate to the full is noteworthy.
It is not the intention here to rehearse in any detail the progress of the Commission's comprehensive investigations. However, an examination of the behaviour of compression members was carried out, the results of which, having to do with the mode of failure of the bridge, are particularly relevant.

The Phoenix Bridge Company possessed the largest compression testing machine in existence. After the collapse of the bridge the Bridge Company, at its own cost and on its own initiative,

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20 Ibid., 152-206.

built and tested a model of the A9 chords, scaled down to 1/3 full size to bring it within the capacity of the machine. Subsequently other models were made and tested at the request of the Commission. The tests clearly demonstrated how, for the load-bearing webs to buckle, the latticing mustfail first. (Figure 8)

Appendix 16 of the Commission's Report, which is devoted to a discussion of the theory of built-up compression members, takes into account the results of these tests. Its comments included the remarks quoted above.

The somewhat indecisive conclusion reached by the Commission in the matter of compression member design did not deter them from pointing an unwavering finger at Szlapka and Cooper as being primarily responsible for the shortcomings in the design of the bridge as a whole. At the same time the Company was criticized for its selection of Hoare as its Chief Engineer and for the very weak field organization, which lacked anyone having the experience to identify a critical situation when it arose combined with the authority to call a halt to construction when lives were in danger.

The Commission's report, with 19 Appendices, comprises three volumes including a folio of 37 drawings. The report itself consists of 5-page letter in volume 1 and is a masterpiece of economy.

THE REACTION OF THE TECHNICAL PRESS

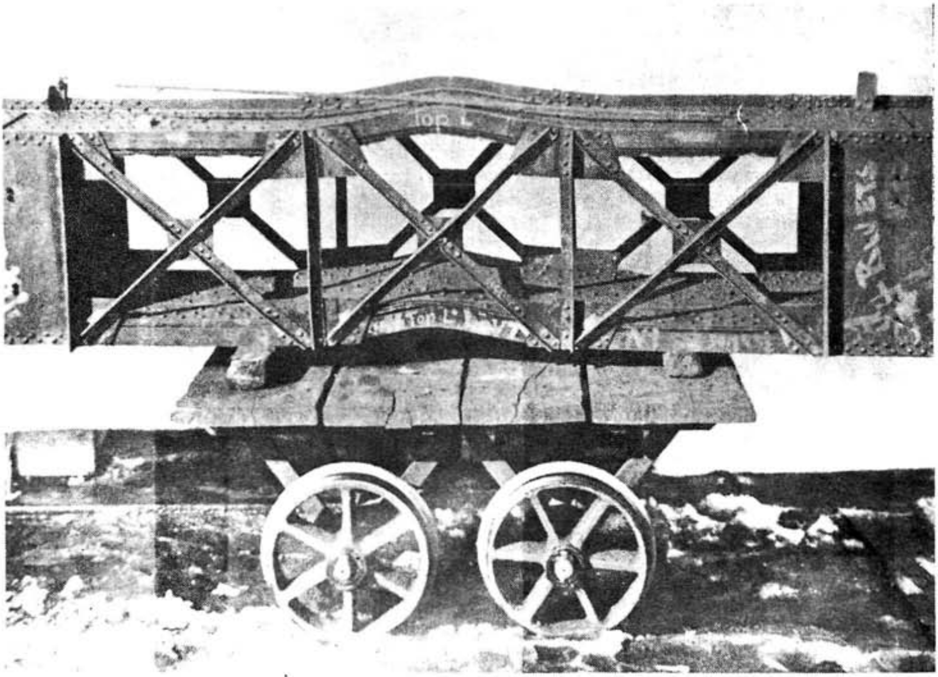
News of the collapse of the Quebec bridge was received by the technical press with the sympathy one would expect, not only for the victims, but also for the engineers who were involved. There was a clear recognition that a detailed investigation was needed to identify the cause of the disaster and particularly to determine what lessons might be learned from it.

The reporting by the *Engineering News* (the predecessor of the current *Engineering News-Record* was outstanding. Within days they had a team at the site and were publishing detailed accounts, illustrated with several photographs, of the events before and after the collapse. The progress of the Commission's investigation was regularly reported on. But the important contribution of the technical press came after the issue of the Commission's Report in February, 1908. The British journal *Engineering* contained some critical editorial comment:

> The moral of the disaster is that very important changes are necessary in American methods of bridge-building when applied to structures of exceptional size. The evidence shows that there has unquestionably been in the

Figure 7(a) Wreckage, looking south [top]; 7(b) looking north

Figure 8: Test of model chord



> past too great a gulf between the drawing office and shops of American bridge-works.

and again:

> Another characteristic of the ultra school of American bridge design is the reliance placed on formulae, which appear to be used as a substitute for judgment rather than as an aid to it.[21]

The Canadian Engineer of 13 March 1908 included a summary of the Commission's Report with little comment, but saw fit to print in a later issue a letter from a certain A.G. Midford, which concluded with chauvinistic fervour:

> The Yankee has had his opportunity and failed. Now that the Quebec Bridge is to be nationalized and--including its failure--paid for by Canadians, it is high time that Canadian engineers should design and erect it, for with them the habit of dropping into the river half erected or completed bridges has not become chronic.[22]

But, once again, it was the *The Engineering News* which published in its issue of 19 March, the most comprehensive account of the Commission's report. And its editorial in the same issue, endorsing and at the same time going beyond the Commission's conclusions, should be required reading for all latter-day technocrats. The following brief extracts present the American version of the transatlantic criticism quoted above:

> And the lesson is the contrast between the practical man --the man whose only training was the training of the shop and the field--and the engineer with a thorough technical education.
>
> When the inspectors of the bridge found a bottom-chord member bent--not merely kinked but bent alike in every component part and on its entire length--who was it that perceived the seriousness of the situation? Not the scientifically-trained engineering directors of the work. Birks laughed down all fears. He set his belief that the chord could not be crippling because, forsooth, it was not yet loaded to anything like what it was designed to carry...
>
> Kinloch, the bridge inspector, a 'practical' man, saw more clearly than any other man the fast coming

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21 *Engineering*, 27 March 1908.

22 *The Canadian Engineer*, 24 April 1908.

> disaster, and he made a two-days fight to bring all the others to see the danger.
>
> McLure also, who had the advantage of a college training, saw the danger, but, as the man of least experience among those on the ground, he appears to have been least ready to assert his views strongly.[23]

The editorial went on to assert that it was of course in favour of college training for engineers, but stressed that such graduates had an obligation to be 'even more practical than the workman,' there being lessons to be learned on the shop floor which cannot be taught in the classroom.

> It is of course true that things like this have been said many times before; but the trouble is, we have not taken them to heart. We have supposed that they referred to the men who try to do professional work with nothing but theoretical knowledge. It has not occurred to us that the men in the top ranks of the profession, who have been building great engineering works for nearly a lifetime, needed such admonitions. And yet that is what the event shows. We all of us, juniors and seniors alike, need to know more, -to test our theories constantly in the light of new knowledge when it comes, well attested, from any source. Yes, surely, the great lesson from this greatest disaster is the lesson of humility.[24]

CONSEQUENCE: THE SECOND BRIDGE

Before commenting on the disaster itself and the manner in which it was treated on the technical press, let us look briefly at what was done in the case of the second Quebec bridge shown in outline on Figure 2(c).

The successful completion of this bridge in 1917 must be credited primarily to the fresh administrative approach, which is in sharp contrast to the weak organization which managed the first bridge. The 'owner,' which was effectively the Government of Canada, appointed a powerful Board of Engineers, including, until his death in 1916, the consultant C.C. Schneider, which in turn was supported by a substantial staff of engineers, draftsmen, calculators, as well as shop, field and mill inspectors. Prior to going to tender the Board's engineers carried out extensive preliminary studies, and followed these with the detailed design of a cantilever bridge. The bidders were asked to tender on this

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23 *Engineering News*, 19 March 1908.

24 Ibid.

plus four modifications, and the final design is that of the successful bidder, the St Lawrence Bridge Company Limited.
Details of the bridge are given in a 'completion report' prepared by the Board of Engineers.[25] It will be seen from Figure 2(c) that the cantilever structure still has a span of 1800 feet. The framing also has the same 'K-truss' configuration as the old bridge. But the specifications for the new bridge called for greater live loads and lower working stresses. These factors, combined with a greater degree of conservatism in the detailed design of the structure, resulted in a much heavier bridge, as the following comparison with the old bridge shows:

	Second Bridge	First Bridge
Total weight (tons)	66,480	40,500
Lower chord member		
Height	7'-3 3/8"	4'-6 1/2"
Width	10'-3 1/4"	5'-7 1/2"
Area of steel (sq. in.)	1,941	842

The new bridge differed from its predecessor in one other important feature: the method of erecting the central suspended span. It will be recollected that in the first bridge this was built outwards as a temporary extension of the cantilever, with the intention of freeing the support when the connection was finally made with the northern half of the bridge. In the case of the new bridge both sides were built out only to the ends of the cantilevers. The central span was completed separately and floated out to the site on pontoons, from which it was hoisted into position between the cantilevers. The first attempt, on 11 September 1916, ended in failure when a component of the hoisting tackle fractured and the suspended span fell into the river (pace Midford), unfortunately with some loss of life. But this accident in no way reflected on the design of the bridge or the basic method of construction.

COMMENTS

After a span of eighty years is there anything more that can be said of the Quebec bridge experience? In view of Benjamin Baker's comment quoted at the head of this article, we should ask if the first Quebec bridge was precedent-setting. At first glance the answer must be 'no,' for the Forth bridge itself, designed by John Fowler and Benjamin Baker, was the first bridge to employ the cantilever principle on such an large scale, and remains to this day, with its three cantilevers having centre-to-centre

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25 Government Board of Engineers, *The Quebec Bridge over the St Lawrence* (Ottawa, 1918).

spans over 100 feet longer than the Quebec bridge, a much more impressive structure.[26] But there are important differences, as remarked by Professor C.E. Inglis in an address to the Institution of Civil Engineers in 1944:

> The [Forth] bridge was a hand-made production, being built up plate by plate even as a ship is constructed. Cheap and abundant labour could be obtained from the neighbouring Clyde shipyards, and consequently it was possible and legitimate to indulge in refinements of design which nowadays would have to be ruled out because of their prohibitive cost...
>
> In [the] first Quebec bridge money was very tight and to keep costs within certain prescribed limits the designer adopted the hazardous expedient of putting his working stresses up to a limit well beyond all previous practice...
>
> The Quebec bridge, like all modern bridges, was machine made. To reduce labour costs the work of erection was cut down to the minimum. The various members were brought to the site as far as possible in a completed form, and the design was dominated by two main considerations: ease of erection and the transportation of ready-made parts.[27]

While the last paragraph of Inglis's comments referred to the second Quebec bridge, it could equally be applied to the first. In the all-important matter of the compression members we have noted (with Inglis) that the tubular struts of the Forth bridge were tailor-made plate by plate. There was at least one precedent for this: the massive elliptical tubes which formed the arch elements in I.K. Brunel's Tamar bridge (opened 1859). It would probably be fair to say that the prefabricated struts of the Quebec bridge involved a far greater departure from previous experience than in the British case. The minimum dimensional tolerances which could be achieved in practice left room for

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26 The eye of the observer is drawn to the centre-to-centre spacing of the cantilevers. In the case of the Quebec bridge, where the central towers comprise *single* trestle frames, this dimension is also the clear span, which the Quebec bridge can rightly claim to be the world's longest for the type of structure. The towers of the Forth bridge comprise *two* trestles, and the eye observes more readily the centre-to-centre spacing of 1912.5 feet than the clear span of 1700 feet (see figures 2).

27 C.E. Inglis, 'The Aesthetic Aspect of Civil Engineering Design,' in The Institution of Civil Engineers, *The Aesthetic Aspect of Civil Engineering Design--A Record of Six Lectures Delivered at the Institution* (London, 1945), 59-61.

misfits in the field assembly that could lead to eccentricity of loading.[28] In the face of the imperfect methods available for designing the latticing, the need for conservatism should have been self-evident.

The most conspicuous error in design was, in my view, the omission of the iterative process which equated the design dead load to the weight of the structure. The result of this neglect meant that the bridge was virtually doomed to failure before a single piece of steel had been erected. As the load on the bridge increased during construction, the growing stresses would inevitably seek out the weakest elements of the bridge's fabric, and it would only have been by the providential absence of any unfavourable circumstances of an secondary nature that a very weak bridge *might* have been completed. And then all traffic would have been at risk. If, conversely, the bridge had been designed for its actual dead weight, it is conceivable that the other shortcomings would not have caused failure, but, again, a less than ideal structure would have resulted.

The explanation for this appalling error would seem to be that, once the Phoenix Bridge Company resumed active work on the superstructure contract following the 1900-1903 hiatus, insufficient time and money were budgetted for Szlapka's department to carry out a critical review of the preliminary studies and complete a thorough working design. When he discovered the omission early in 1906 Szlapka must have realized its implications. Clearly he decided to 'pass the buck' to Cooper. Neither had the courage to 'blow the whistle.'

In the event, the weaknesses manifested themselves in the field during August, 1907, and the failure on the part of the site staff and Hoare to foresee the perilous consequences of the *increasing* distortions in member A9L was responsible for the loss of life when the bridge inevitably collapsed.

The technical press made much of the comparison between the 'practical' man and the college-trained professional. This oft-repeated argument must surely have arisen when, during the nineteenth century, an increasing number of graduates from technical schools entered the profession and started applying analytical methods in engineering design. It is unfortunate that an impression is sometimes given of a mistrust of calculation in favour of 'judgement.' Nevertheless judgement is often called for, never more obviously than in August, 1907. The point is not that the 'practical man' (Kinloch) was right and the college-trained engineers (Birk and McLure) were wrong, but that

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28 Eccentricity of loading could, in turn, lead to distortions such as were observed in chord member A9L.

the latter failed to apply their technical knowledge in response to Kinloch's concerns.

We have already noted one aspect of the first Quebec bridge which was unusual, namely that all stages of the design were carried out by the contractor. No separate charges were made for this service, the cost of which would be absorbed in the billing rates for the manufacture and construction of the bridge itself. Once these rates were fixed, any cost saved by cutting corners in the design would be reflected in an increase of the contractor's profit.

The more normal practice was, and remains, that the early design studies, as well as the basic final design, including the general sizing of the members and preparation of technical specifications, are carried out by a staff of engineers working directly for the client. Whether this staff is directly employed or a firm of consulting engineers is engaged, the important fact is that *the service is paid for*. The contractor may or may not be invited to submit alternative designs at the tendering stage. Certainly it is quite common for the contractor to prepare detail drawings, subject to the approval of the client's engineers, of such elements as the joints between members, and he will always prepare his own shop drawings for the manufacture and fabrication stages. Again, during the construction phase the client will engage a competent supervisory staff to oversee the work of the contractor in the field. A similar procedure was followed and played an important role in the case of the second Quebec bridge.

But we must repeat that this procedure for the execution of a major public works project was already established practice when the Quebec bridge was first promoted. The initial blame for the 1907 disaster must rest with the Quebec Bridge Company for failing to recognize that there is no such thing as free engineering.

Whether this lesson has yet been learned is debatable.

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SOURCE OF FIGURES

Certain of the figures have been copied or adapted from the following sources: Fig. 1 from Board of Engineers, *The Quebec Bridge over the St. Lawrence River* (Ottawa, 1918); Figs. 2-8 from Royal Commission, *Quebec Bridge Inquiry, Report* (Ottawa, 1908).