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A COMPARISON OF THE STRENGTHS OF THE PRINCIPAL COMPRESSION MEMBERS IN THREE NOTABLE BRIDGES.

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The members of the Engineering Association are perhaps more concerned with the practical use of iron and steel than those of any other Society in the State. The failure of the great Quebec Bridge is, no doubt, the greatest blow ever dealt to the dependance upon theoretical knowledge alone for assuring engineering success in such a great structure, and therefore any light which can be thrown upon the "why and wherefore" of the failure should be acceptable alike to both our old practitioners and students.

It is possible that some of our critics may say: The designing of a bridge is purely a matter of civil engineering and mathematics: that all the mechanical engineer has to do is to put the material where the theoretical designer directs, and be responsible for the workmanship alone.

Now, without in the slightest way depreciating the value of theory, and admitting also that the great engineering structures of the present day would be impossible without the magnificent aid which the mathematician makes available, there seems to be very good grounds for the assumption that such a gigantic disaster as that which overtook the Quebec Bridge would have been impossible under the old school of engineers. In fact, it is hardly conceivable that a Smeaton or a Telford would have passed the plans for that structure, even if backed by all the mathematicians in the world. And why? From the information available it appears that the various parts of the Quebec Bridge were made as large as possible at the construction works, the structure was largely pin-connected, and everything else was done that would save field rivetting. To save money, the simplest and cheapest "sandwich like" arrangement of plates was adopted in the design of the compression, or lower, booms of the cantilevers; and careful calculation must have satisfied the designers that those long, straight sandwiches were strong enough, theoretically, for the work they had to do: But—

What theory apparently did not take account of was the fact that such construction was extremely liable to distortion or bending when being lifted, or when being conveyed long distances by railway on bolster trucks; and it does not seem to have been realised that once these plates were even one inch out of the straight line, all the theory embodied in their assemblage was scattered to the winds. From the accounts given in American journals, it appears they were found to be as much as $2\frac{1}{2}$ inches out of straight before the collapse.

As it is universally admitted that the American system of eyebars and pin connections for tension members is an admirable one, nothing need be said on that aspect of the fated bridge. In fact, no better tribute could be paid to the efficiency of the system, because after the accident the upper chord laid in a practically unbroken chain upon the top of the wreckage below.

Up to the present time the Forth Bridge continues to stand out as the greatest accomplished engineering work of the kind, with its 1,700 feet clear span. In the first competition for the North Sydney Bridge there was a monumental design submitted for a gigantic arch of 2,200 feet span, or $2\frac{3}{4}$ times the span of the present greatest arch in the world, at Niagara. There was also a cantilever design for 1,980 feet, and another arch of 1,800 feet, besides the premiated design for a suspension bridge of 1,800 feet by the author's great colleagues. All these were not only greater spans than the Forth Bridge, but much more important in other ways, because they had to carry tramways, carriage ways, and footways, in addition to the railway, which is alone the object of the Forth Bridge.

In this competition there were also two American bridges competing, which appeared to be very influentially pushed to the front, if one may judge from official reports. One was a cantilever of 1,280 feet span, and the other a suspension bridge of 1,330 feet main span.

These bridges were so much the cheapest of those competing that it was at first proposed to give their authors the sole privilege of amending their tenders. When their prominent features were looked into, however, it was found that, instead of having steel plate decks with concrete and wood blocks (weighing approximately one hundredweight to the square foot), they were simply planked with soft wood—Douglas Pine or Oregon—thus effecting a saving, perhaps, of ten thousand tons in the total weight of the bridge.

An examination of these plans, when on public exhibition, created such an unfavourable impression on the author's mind (especially as coming after what he had personally seen during a ten thousand mile tour through the United States), that, when writing to Sir William Lyne, the then Premier, with regard to his second premiated design, "In Suspense," on the 28th November, 1900, he said (inter alia): "There is no attempt in this design ("In Suspense") to introduce the principle supported by some of my American correspondents of cutting down the material to the finest point, so long as you can get over."

In the latter end of August last, the world was startled by the astounding news that the great Quebec Bridge of 1,800 feet, the greatest span yet put in hand, had collapsed; and that the material had been "cut down to so fine a point" that it had never even got the bridge itself over. By this collapse 20,000 tons of steel, that had cost over half a million pounds, had tumbled into the deep bed of the St. Lawrence River, with a sacrifice of three score human lives that were working on the great structure at the time.

Of course, nothing but sympathy and sorrow can be felt for all the sufferers, professional and otherwise, by that catastrophe; and as more is often learned from failures than from successes, which latter often make us proud, it is our business as engineers to see what is the lesson we can learn from this failure, and also try to ascertain if we have any cause for apprehension about the work of the Advisory Board which dealt with the North Shore Bridge designs.

In considering this question it is not intended to strike any hard blows, such as were delivered by the "Scientific American," in the course of several articles, some of which may, however, be referred to later. America is a country of great rivers and great mountains, great enterprise and great engineering works, but it is also the land of great railway accidents, great boiler and fly-wheel burstings, et hoc genus omne. The problem with us, however, is to find out how, with such a wonderfully alert, clever, and progressive people, the failure of a bridge that was to cost over five millions of dollars became possible.

The "Scientific American" of 12th October, 1907, quotes the words of an engineer connected with the Quebec Bridge design, who had stated 16 years ago "that he could have built the Forth Bridge with the money first subscribed, and turned back 50 per cent. of it to the owners, instead of them having to collect 40 per cent., more before the work was completed."

The Editor then caustically remarks: "We have the result of this saving in the fact of 17,000 tons of steel junk now lying in the bed of the St. Lawrence River."

To go from large things to small, an incident may be mentioned which, perhaps, gave the author some of that "unconscious bias" of which Herbert Spencer speaks in one of his works. Some years ago he was in the backwoods of Northern California, and, when standing on a private company's railway bridge over Mad River, a tributary of Humboldt Bay, he had been so much astonished at the slenderness of the tension chords that he measured them, and then, sizing up the general dimensions, commenced a mental calculation as to the load the bridge would safely carry, and the weight of the small locomotives and log trains. Looking up then, he saw a train of redwood logs approaching before he had quite completed his investigations, but he had gone quite far enough to satisfy himself that there was no provision for the extra weight of any foot passengers on that span; so he quickly made his way to a pier, or "bent," as they are called there, until the train was over. The funny thing then was that he found a lot of the foundation of that pier had been washed away by a fresh in the river, and that it was being held up by sand-bags. This incident is absolutely true, and is simply mentioned now as an instance of how closely things are sometimes shaved in that great country.

In discussing the Quebec Bridge the "Scientific American" gives the section of the chord that failed as 735 square inches, and has an illustration of it supporting the Princeton U.S. battleship, stating that the load it was intended to carry was 11,320 tons.

Now, $\frac{11320 \times 2240}{735}$ gives 34,500lbs. to the square inch as the crushing stress, and as the limit of elasticity of the metal only ranges between 28,500 and 31,300lbs. (which not even Americans are allowed to exceed), this paper's information at the time was evidently wrong.

The figures 1, 2, and 3 (Plate X.) on the accompanying plan of sections have been drawn from information received only within the past week, and may be relied upon as being correct in showing the relative proportions of the bottom chords or main compression members in the cantilevers of the Forth, Qusbec, and (approved design for) the Sydney Bridge. With the particulars appended to the sections very instructive information is available for those who will compare the relative proportions.

The theories connected with the strength of long struts have engaged the attention of many able men, including Rankine, Euler, Wohler, and others. There is no intention to discuss them here, but the failure at Quebec is a proof that the last word has not yet been said on such account.

In looking at the question in a more general way, for the purpose of this paper it will suffice, perhaps, if only the following salient points are considered:—

1. The strength of steel in compression does not exceed that of wrought iron in the same way as it does in tension.
2. The limit of elasticity in a plate or bar of steel is not uniform throughout, and may be very different in different parts of a built-up strut or column, which may, therefore, yield on one side before the other and thus produce distortion under stress.
3. A strut or column may be so long that its ultimate strength is altogether dependant upon its resistance to bending, and may be due more to the disposition of the metal with regard to the neutral axis than to the sectional area.
4. The strength of such a strut is reduced by an increase of length, and increased as the material is further away

from the neutral axis, up to the time when the metal itself becomes so thin as to be liable to buckle or corrugate.

5. A tube is the strongest form of strut for a given section of metal.

For these reasons the engineers of the Forth Bridge made nearly all their main members as tubes, and by the magnitude and novelty of their work they established an epoch in bridge building; but it is almost safe to say that that bridge will never be repeated, because of, among other drawbacks of the design, the difficult and costly work at the intersections of the tubes.

If the North Shore Bridge had been contracted for on the lines of some of the designs first submitted, or the Quebec Bridge had been completed, the Forth Bridge by now would have been outclassed. At present, it is still holding the pride of place as the greatest bridge in the world.

The first competition for the North Shore Bridge was very largely a "go-as-you-please," specifications having to be supplied by the competitors, and nothing whatever was said in the conditions as to "unit stresses." Consequently, the Government obtained without payment the matured ideas of many great bridge-building experts of Europe and America on the subject, two competitors only receiving a nominal premium for their trouble.

In the second competition of 1901 the case was entirely different. The Advisory Board appointed by the Government included the chief engineers of the Public Works Department, the Government Architect, and Professor Warren, of the University. These gentlemen prepared a set of conditions and specifications in detail, which was more than 20 times as long as the original conditions, and they showed that they duly recognised the great responsibility resting upon them by wisely insisting upon an irreproachable standard of strength—one, in fact, that would make such a dreadful denouement as that which attended the Quebec Bridge absolutely impossible. It is in the interest not only of engineers, but for the satisfaction of the general public, that these facts should be made known.

The conditions for the second competition will be found between pages 23 and 39 of the Advisory Board's report, from which the following extract is taken (it is under the head of "Unit Stresses"):—

"All portions of the structure shall be so proportioned that the maximum loads shall not cause the stresses to exceed the following, for medium steel (where not otherwise specified):—

10. COMPRESSION.

"(a) Dead load and live load on all the members, including train momentum, centrifugal force, and impact, where specified:

$p = 17000 - 80\frac{l}{r}$ lbs. per square inch of gross section.

"(b) Temperature and wind pressure on all members:

$p = 22500 - 100\frac{l}{r}$ lbs. per square inch of gross section.

"Where p = Working stress per square inch;
l = Length of members in inches, centre to centre;
r = Least radius of gyration of the section, in inches.

"No compression member shall have a length exceeding 100 times its least radius of gyration ,except for the wind bracing, where the length may be 125 times the least radius of gyration."

The accompanying plan (Plate X.) shows very clearly by contrast the great strength that has been secured by the interpretation which the Advisory Board's wise and safe stipulations received at the hands of the author's colleagues at Nuremburg and Gustavsburg.

It will be noted that in Figure 1 the lower boom of the Quebec Bridge had a section of 785 square inches, and was intended to be loaded by 7,350 tons (not 11,000, as assumed by the "Scientific American" diagram, showing the U.S. warship Princeton supported upon it). This would have given a crushing load of 9.36 tons per square inch of section, at which there would have been a large negative factor of safety under the conditions which prevailed, because the member failed under 5,650 tons, and let the whole structure down.

It will be noticed that the four sandwich-plate sections of the member are kept in place by diagonals of 4 x 3 x $\frac{3}{8}$ inches angle bars, and that at the intersections the web of the lower bar is cut away, while the upper bar is joggled to get over the lower flange. This bracing proved to be totally inadequate, and the member seems to have been crippled and repaired again before it was erected in its place.

In Figure 2 there is a sectional area of 1,100 square inches, to carry a maximum load, including wind pressure, of 9,000 tons, or only 8.18 tons maximum crushing weight per square inch of section, instead of 9.36. But, besides this, the length is only about two-thirds of that of the Quebec Bridge, or 40 feet instead of 57 feet, and the outside dimensions are 85 x 78 inches, instead of only 67 x 54 inches. Apart from this, and the plate connections at the top, there are $\frac{1}{2}$-inch plate diaphragms, stiffened with diagonal angle bars, at every 13 feet.

It thus shows that there is on every point such an important excess of strength in this bridge over the Quebec Bridge as to be extremely satisfactory to those who might be inclined to question the matter, after what has happened elsewhere.

In comparing No. 3, it must be noted that the length of the unsupported member in the Forth Bridge is 100 feet, or two and a half times that of the Sydney Bridge; hence its diameter of 12 feet.

It has recently been stated in the Press that a new Royal Commission is to be appointed by the Government to deal with the North Shore Bridge question, but no information, so far, has appeared as to the particular phase of the enquiry which is to be taken up by it, or whether the completed work of the Public Works Department, with regard to the approaches, and the arduous labours of the Advisory Board, are to be inquired into. One thing, however, is quite certain: by representing that it fully intended to build the bridge, the Government has obtained about sixty thousand pounds' worth of information from competitors, and after three years or more of work the Advisory Board adjudicated upon these designs. The author, in conjunction with the Maschinenbau Gesellschaft of Nuremburg and the Zweiganstalt of Gustavsburg, supplied ten sets, including the successful design, and it will be acknowledged that what has been said in this paper so far, justifies the wisdom of the Government in the selection of the members of the Advisory Board.

Without in any way touching upon the equities attaching to his claims upon the Government in having fulfilled their conditions, or discussing the treatment so far accorded to him, as the reward of his professional success—because they are dealt with in other printed documents—the author felt that it would be a source of gratification, not only to the members of this Association, but also to the public of New South Wales, to know that the Government's advisers in these bridge competitions did their work so faithfully and well, and secured a thoroughly reliable structure from thoroughly reliable bridge-builders, who already had over a thousand great bridges to their credit. It must also be satisfactory to know that, although the result of his success, so far, has been practical ruin to the author, owing to the later Governments not recognising their predecessor's contracts, still the country will be safe in carrying out the bridge which the Advisory Board finally selected.