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THE DESIGN AND CONSTRUCTION OF LONG SPAN BRIDGES.

(By R. H. FRY.)

The successful design and construction of a long span bridge was perhaps the biggest task, fraught with the greatest difficulties, that the Civil Engineer was called on to perform. The subject was so vast that volumes could easily be written without exhausting all the details. It was intended only to deal briefly in this paper on the subject, and practical details would be dealt with at greater length than purely theoretical considerations. An arbitrary limit of 1,000 ft. minimum span had been set for a long span bridge for purposes of discussion and illustration.

LOCAL CONDITIONS.

The first condition taken into account in designing such a bridge was that of locality. More often than not, the waterway to be bridged was a fairway used frequently by shipping, and these interests had to be looked after. If coastal and smaller vessels were only considered, a much less headway could be allowed than if deep-sea boats were required to pass under. In the former case, a headway of between 100 and 120 ft. would, perhaps, be decided on; but greater judgment had to be exercised in the case of larger boats. The majority of ocean steamers had mast heights below 170 ft.; a few sailing vessels and steamships, however, exceeded this limit. The "Imperator" and "Aquitania" measured about 210 ft. from waterline to mast truck, but if required these masts could be made telescopic, or topmasts struck at sea. The greatest headway of any existing bridge was 150 ft., but it was proposed that the Hudson River and the Sydney Harbour bridges would both have a clear height of 170

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ft. at high water. This latter seemed a much safer limit to employ. However, the amount of headway had a decided effect on the grade of the bridge and approaches, and consequently influenced the cost. The bridge could be divided into two main parts—the substructure dealing with piers and foundation work, and the superstructure or main structural work. For short span bridges, the economic rule followed was that the cost of former and latter should be approximately equal. However, in long spans the steelwork cost considerably more than the piers, the cost of which could not be calculated as accurately as the superstructure.

PROCESS OF DESIGN.

An extensive study of the districts and traffic to be served was necessary, as upon this greatly depended, not only the ultimate cost of the bridge, but also its earning capacity, as all engineering works, besides being constructed successfully, should be a sound commercial investment. In practically every case railways were the main traffic to be served. This being so, the bridge, besides being placed to attract the greatest volume of traffic, should also have approaches which did not call for too steep a grade, thus tending to economy in train haulage. In general, a track grade of 1 in 30 should never be exceeded. Vehicular traffic would be also served, but pedestrians would be few and far between on account of the great distance to be traversed.

The position of piers which decided the span of bridge depended on depth of water and geological formation of river bottom. If possible, foundations should not be driven much deeper than 100 ft., as excavation was very costly at that depth. Trial borings were generally put down to get an idea of the materials through which the caissons for bridge piers would have to be driven; also to locate depth of rock suitable for foundation. This data in hand, the span could be decided upon, the type of bridge fixed, the loading adopted, and then calculations made for the superstructure. There was, however, a limit to the maximum span which could be economically employed, beyond which it was inadvisable to go. This matter would be discussed later on.

SUBSTRUCTURE.

The calculations for the piers were not by any means complex; they were decided on chiefly by previous engineering experience, the kind and bearing power of rock that the foundations would eventually rest on, and the compressive or bearing strength of the material which formed the pier, generally a hearting or filling composed of concrete, faced with granite, standstone, or other masonry. The engineer usually met with greater difficulties in the construction work of this part than perhaps in any other of the bridge, and all his ingenuity, resource and care were required to bring it to a successful termination, and also to minimise accidents to both workmen and materials.

The usual method of construction was by sinking a caisson, either a steel or timber structure, excavating the river bed inside, weighing the caisson to sink it to its final resting place on rock bottom, and then filling up with concrete. The caisson could be constructed on shore near the site of pier, and made of either timber or steel plating. The latter was given preference if it had to be sunk to any great depth. This casing was constructed of such a height, that when resting on the mud or sand of river bottom the top was above the level of high water, and was provided with a cutting edge on its under side to facilitate the process of sinking. When completed on shore with all necessary stiffening inside, it was loaded with concrete on top of working chamber, launched, and then floated out to the site. Here it was held in position by means of staging on a series of piles driven round the final position of pier. A further amount of concrete was poured in to weight it, until it sank down and rested on the river bed. Then excavation commenced inside, either by means of grabbing, i.e., dredging with grabs and dredging buckets, or excavation under compressed air. Another interesting method was available, and which seemed quite feasible, viz., the freezing process. Although this system had not been used to any extent for bridge pier foundations, it had been successfully applied to the sinking of mine shafts in wet ground principally on the Continent of Europe, and also in England and America. A number of pipes would be driven from surface to solid rock, through which a cold brine solution would be circulated by powerful machinery. When Messrs. J. Stewart and Co. tendered for the erection of the bridge to span Sydney Harbour, recommended by the Advisory Board in 1901, one of their proposals to form the northern pier on rock bottom, which was located at 172 ft. from high water mark, was to form an island by filling to a short distance above high water mark, and then to freeze the material overlying the rock so as to form a watertight cylinder from the surface downwards. It was estimated that, after several months' work, a ring of earth 8 to 12 ft. thick would be frozen solid from the surface down to bedrock, and that there would be no difficulty in excavating and maintaining a shaft through the frozen material until the pier was completed. The compressed air system, though slow, was that most generally used, as work could be carried out more evenly and accurately, and was, perhaps, the only successful method where the caisson had to be sunk to any great depth. As the casing sank, the structure was added to at the top to prevent the water flowing in. A description of a caisson (Fig. I.) for work under compressed air would not be out of place. A working chamber was provided about 8 or 10 ft. high on the under side, where the workmen, or "sand hogs," as they were called, excavated the clay and sand to enable the caisson to sink down.

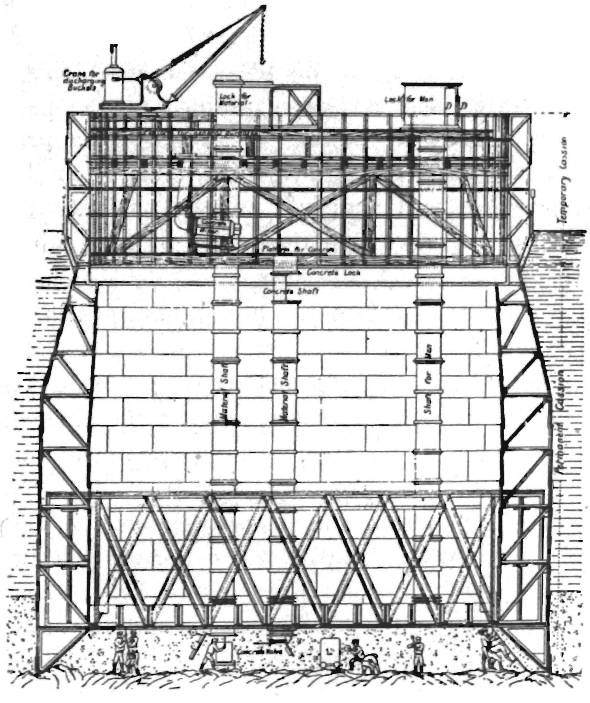

Fig. 1

From this chamber lead upward several large circular tubes or pipes about 2 or 3 ft. in diameter into air locks or chambers containing several air-tight doors. Some of these shafts were used by the men in entering and leaving the working chamber, and others were used for hoisting up the spoil, consisting of mud, stones, rock. etc., in buckets, and these were called the material shafts. Compressed air was led to the working chamber, and was so regulated, in accordance with rise and fall of tides, that the pressure under which the men worked was about equal to the hydrostatic head. By this means water was prevented from flowing in under the cutting edge. The idea of the air-lock system was, that a workman coming out of a high-pressure atmosphere into the ordinary air would suffer acutely from what was known as "Caisson sickness" or "The Bends," if this transition were too sudden. This disease or sickness was explained by the fact that under air greatly in excess of atmospheric pressure, nitrogen was dissolved in the blood, and, when that external pressure was suddenly relieved, minute bubbles of this gas congregated in the region of the limb joints, causing intense agony, the only relief for which seemed to have been a return to the high-pressure atmosphere, and for that pressure to be very slowly relieved. So this air-lock formed an intermediate stage. To get at the working chamber the workman entered the air-lock and closed the atmospheric door. The air pressure was then raised gradually (the process taking from 10 to 20 minutes, according to range in pressures), until it equalled that of the working chamber, when the connecting door could be opened. Special precautions were taken that both the doors could not be opened simultaneously, and also that the application and withdrawal of pressure was very gradual. The operation on leaving the caisson was exactly the reverse, and still greater care was taken in exhausting the pressure in air-lock. For fairly low pressures the men were usually worked in eight-hour shifts; medium pressures called for six to four hour shifts; and for high pressures shifts were reduced from four hours down to even one hour's duration in some cases. These "sand hogs" were specially-selected men, all medically examined and physically fit, abstainers from intoxicants, and, besides receiving high pay, were generally well looked after. On leaving work at end of shift, hot drinks, such as tea or coffee, were provided as stimulants, to keep them in condition and good health. Theirs was a very strenuous occupation, especially working under the greater pressures, and the death rate was rather high, although with careful management and modern scientific treatment the death percentage was considerably less than formerly, when "Caisson sickness" was only imperfectly understood.

While sinking one of the caissons for the Quebec Bridge foundations, the timber caisson tilted over; the framework was strained, water flowed in through the cracks which opened up, and the pumps were unable to keep it dry. It was taken up later and moved to the site of one of the anchor piers. Afterwards, while sinking it on the new site, it was deemed advisable not to let the full weight of caisson rest on the cutting edge, for fear it should be strained again; so an ingenious method was devised by which it could be let down evenly and gradually without opening out any of the timber joints. A number of sand jacks were constructed by rivetting up ¼-in. plating to form hollow cylinders 30 in. in diameter by 3 ft. long, having a 2-in. hole drilled near the bottom. These were nearly filled with sand, then timber plungers, 30 in. in diameter by 4 ft. long, inserted. Small excavations were made in the bottom of river bed to take these plungers; then the jacks were placed against the ceiling of working chamber. By means of hydraulic jets the sand was washed out, the plungers entered the casing further, and so the caisson was allowed to descend evenly to the amount required, and the cutting edge thereby relieved of a great deal of pressure. The south pier of this bridge was sunk to a penetration of 110 ft., at a maximum rate of 8 ft. per week. Difficulty was often experienced in keeping the caisson in position during sinking operations. The best method was to check the centre line and position every day, with the theoretical exact position, and in excavating to allow for the error by cutting beyond the lower edge of caisson, and inserting struts at an angle with the ceiling. This tended to throw it over in the required direction. When some of the Forth Bridge caissons were sunk, they tilted over on account of the sloping surface of the river bed. Sand-bags were placed under their lower edges while the higher ground was excavated. Then, when it was levelled sufficiently, these bags were taken away and the usual work proceeded with.

On this work hard boulder clay was met with, and ordinary excavation became rather slow, so an hydraulic spade was designed similar to an attachment of a spade to the ram of an hydraulic jack. The base of this was placed against the roof of the working chamber, and the spade forced into the ground, cutting out blocks of this clay, which were afterwards hoisted out through the material shaft. For some of the softer strata an hydraulic jet was played on it; this loosed it, and another workman, by directing an ejector pipe on to the loose material, allowed some of the compressed air to escape with the mud, which was then sucked up and discharged by means of this pipe through the wall of caisson. It seemed incredible that compressed air could eject material against a water pressure almost equal to it, but this was explained by the fact that the momentum of the air and material in the ejector pipe overcame the static pressure, and was analogous to the action of an injector on a steam boiler.

SUPERSTRUCTURE.

The superstructure was the steel structural work which rested on the piers or foundations. It could be divided distinctly into four different types of structures: (1) Simple truss; (2) arch; (3) suspension; and (4) cantilever.

(1) The truss or girder span bridge was the simplest of all, both to calculate, design, and construct. However, the longest span of this type was that over the Mississippi River at St. Louis, U.S., which had a clear span of 668 ft., and this was about the economic limit for that type.

(2) The arch type bridge was rather more difficult to design and construct, but was often chosen for light traffic from an aesthetic standpoint. The longest span bridge of this type was that over the Niagara River near the Falls, and had a span of 840 ft. This type, as well as the simple girder, would not be economical for greater spans than 1,000 ft., and for that reason would not be discussed further.

(3) The suspension bridge (Fig. 2) consisted essentially of a system of cables supported by towers over piers and from these cables was hung the decking by means of hangers. The great advantage of this bridge was that, with the exception of the towers, all the main members were in tension; the cables were continuous, and, being in tension, took the main load, had a much higher efficiency than built-up plate members, and also a much higher working stress. So, in comparison with other types, for the same light loading, this bridge would be much lighter and cheaper to construct. A point that often received consideration was that, from an aesthetic point of view, the suspension bridge appeared very graceful and more in harmony with its natural surroundings than perhaps any other. Stresses were rather indeterminate, however, and this greatly added to the difficulty of successful design. The structure was not rigid, and with a moving load the deflection of the cable travelled in a wave motion. The main members or cables generally consisted of steel wire cables, but occasionally eye-bar cables were employed. Deflections were big, chiefly owing to—

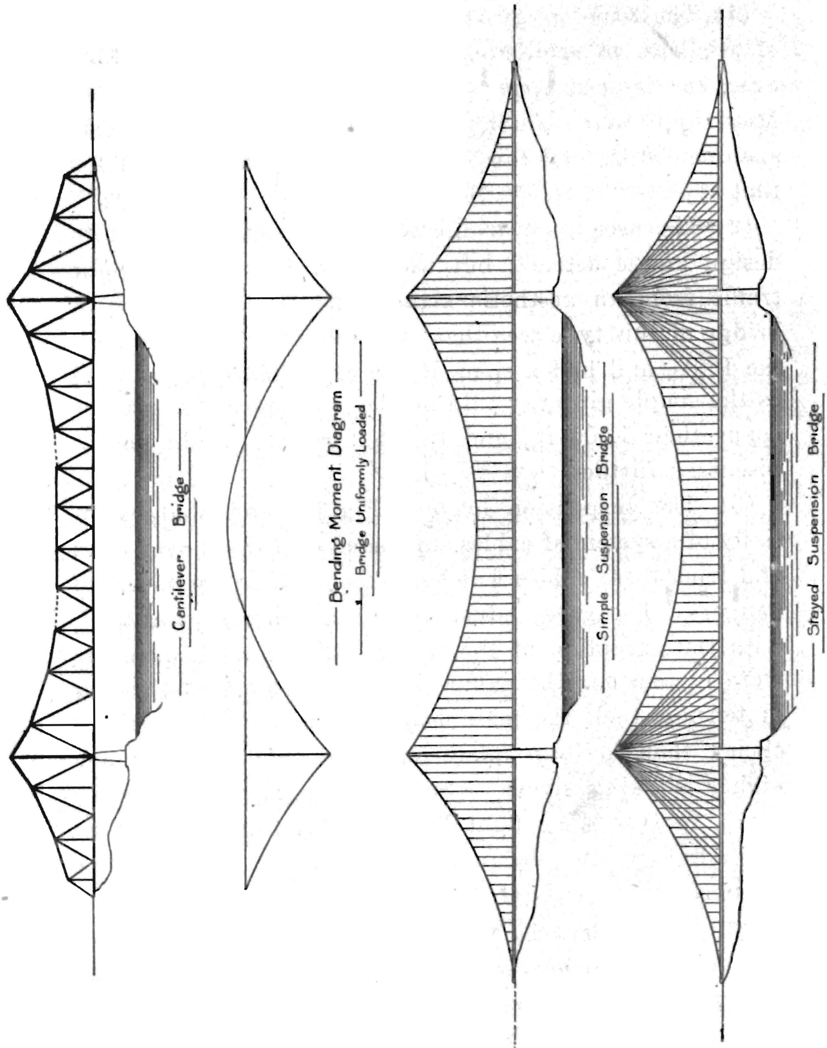

Fig. 2

1. Elongation through increase of temperature.
2. Increase in length owing to high working stresses allowable.

A cable suspension bridge designed for 1,800-ft. span, with 120 degrees variation in temperature and full live load, as used in the calculations for the Quebec Bridge, would have a maximum deflection of about of 7 ft., with live load only a deflection of 2 ft., and a similar cantilever structure would show only 11¾ in. under maximum load. The working stresses in cables varied from 55,000 lbs. to 60,000 per square inch, which was about three times the working stress for rolled carbon steel plates and shapes.

A cable free to hang would describe a catenary curve, but when uniformly loaded it was constrained to form a parabola. A concentrated load on either side of the axis tended to displace that axis, and its new position would be nearer the load. Usually two systems of cables were employed, separated from each other by about the width of bridge at the towers. However, to take the wind pressure it was sometimes the practice to bring the cables closer together at centre of span than at the towers. This construction tended greatly to minimise the sway induced by wind loads. To lessen deflections due to loads, and at the same time to make the structure more rigid, two systems of stiffening the span could be used—

1. Stiffening the deck by means of continuous or one or more hinged trusses, or
2. By means of braced and stiffened cables.

1. The stiffening trusses did not carry any loads to the tower; their function was to distribute the concentrated loading created by traffic on them into uniform loads on the cables, at the same time lessening deflection, and preventing oscillation due to wind pressure and unsymmetrical loads. Stiffening trusses could be made continuous from anchorage to anchorage, or the chords could be cut similar to a cantilever bridge; or, again, the truss could extend only from tower to tower, and contain one, two, three, or four hinges. This truss was not under any dead load stress, as it was supported at panel points by

means of hangers from the cables. The advantage a three-hinged truss possessed for stiffening was that secondary stresses were eliminated owing to deflection due to large expansion and contraction of cable.

2. There were several methods of stiffening the cables to prevent oscillations due to wind, live load, and temperature. A system of trussing connecting cables with roadway had been used only to a limited extent, and for this type of bracing it was found generally convenient to make the cables of eye-bars or links to take the stiffening members, and thus the structure was no longer a true suspension bridge, or the cable could be stiffened to form two or three hinged trusses or inverted arches. (Fig 3.)

The ratio of cable sag to span played an important part in the design, and if the sag was excessive, the temperature and load deflections would also be excessive. A ratio of from one-seventh to one-fifteenth of span length was a fairly good one to adopt; however, a ratio of one-eighth gave the most economical span possible.

Owing to tension in cable under load, and the construction at top of towers where the cables pass over, a large bending movement was induced at the base of tower. This, however, could be very greatly reduced if the cables rested on a carriage carried by roller bearings, free to move and equalise the tensions. The longest suspension span built was the Williamsburg Bridge, which had a span of 1,600 ft.

Principal data for design of suspension bridges (D. B. Steinman) :—

l = length of span in feet.

l_1 = side span = $\dfrac{l}{2}$.

f = versed sine = $\cdot 12l$.

f_1 = versed sine in side span = $\dfrac{f}{4}$.

d = depth of stiffening truss = $\cdot 024\,l$

Type: Stiffening truss hinged at towers; suspension rods in side span.

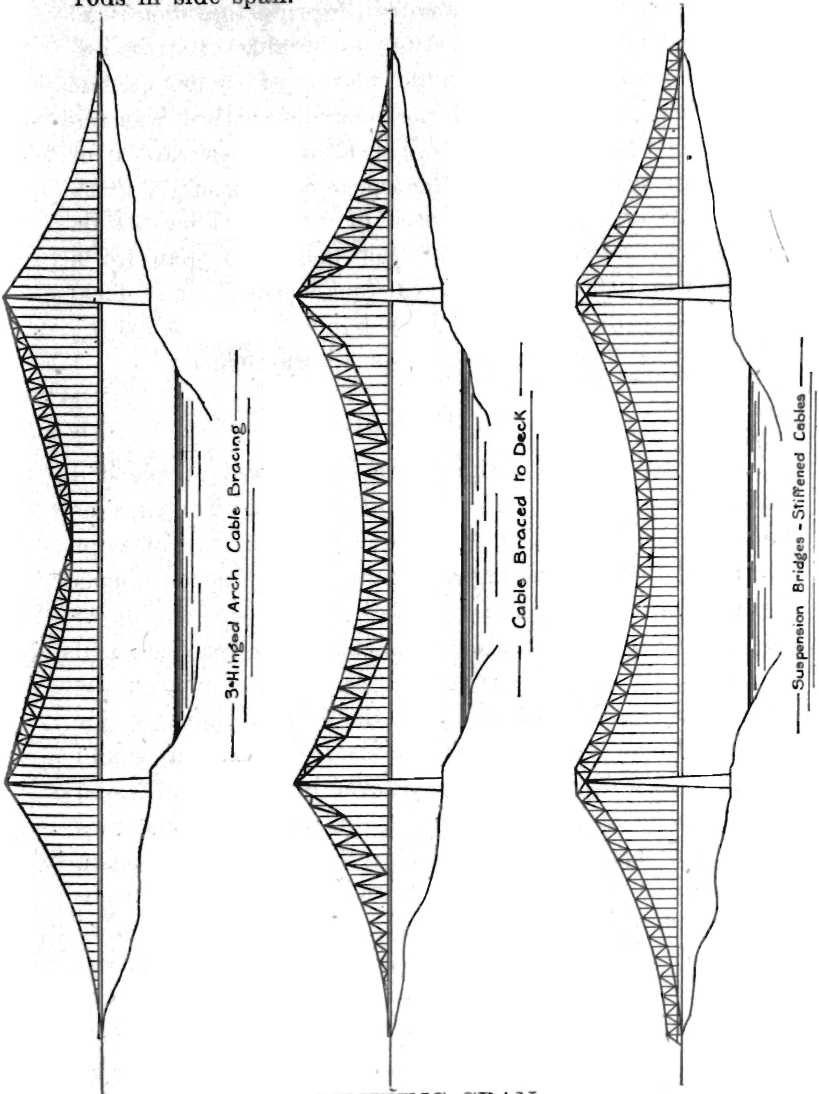

Fig. 3

LIMITING SPAN.

The cables on Brooklyn Bridge were 15⅝ in. diam.
Those on Williamsburg Bridge were 18¾ in. diam.
And those on Manhattan Bridge were 21¼ in. diam.

It is doubtful whether larger cables than 24 in. diam. could be manufactured, practically owing to difficulty of manipulation and uncertainty of uniformity of stress distribution among the strands. No existing bridge had more than six cables of large diameter, and it was improbable that a greater number than sixteen cables, or eight per system, could be incorporated in a single structure. Assuming sectional area of sixteen cables 24 in. diam., Steinman stated that the maximum span for a loading of 10,000 lbs. per lineal foot worked out at 4,900 ft.; for a loading of 15,000 lbs. per lineal foot, at 4,000 ft.; while for a 20,000-lb. load the span was 3,500 ft.

CANTILEVER BRIDGE.

A cantilever really signified a beam fixed at one end and free or without support at the other. The idea of a cantilever bridge was first developed in the attempt to avoid the disadvantages of continuity in a continuous girder. In this latter, a slight difference in elevation of one of the supports caused great changes in reactions and stresses. If, however, the chords were cut at or near the points of inflection for full load, the point of inflection for a partial load would occur there also, and reactions would be statically determinate. Cantilever bridges usually had three spans as shown. The main span contained two cantilever arms, and generally a suspended truss span. The anchor or side cantilever arms usually had a negative dead load reaction at ends, and accordingly were anchored down to piers, to balance the weight of suspended truss span, and difference in weight between cantileter and anchor arms. Each arm consisted essentially of top and bottom chords, rigidly braced with one of various systems—Warren, Pratt, K. bracing, etc. For simplicity of design, calculation of stresses and erection, in the author's opinion K. bracing was the best under suitable conditions. These trusses were connected at either top or bottom chords, or at both, with a system of diagonal wind-bracing to transmit wind-stresses to the towers. Where bottom wind laterals were used, diagonal members were put in. and the cross-girders which supported the decking bore the shear. These cross-girders were attached to the trusses at panel points or points of connection of truss-bracing with bottom boom. Sway-bracing was inserted in a transverse vertical plane, and was attached to each vertical strut at panel points. This, as well as the lateral wind-bracing, kept the bridge rigid against wind and unsymmetrical loads. The bottom booms of cantilever and anchor arms, also top chords of suspended span, were compression members, and in every case were built up of plates and shapes. Very little was known about bridge compression members as compared with tension eye-bars, owing to the large number of full-size and model tests made with the latter. Only on large bridges, where preliminary and experimental work bore a very small ratio to total cost, could model tests be made. In the construction of the Forth Bridge these compression members were made tubular, as metal for metal this construction is the strongest and most efficient; but difficulty was experienced in making connections at panel points and at piers. The top chord of anchor and cantilever arms, also bottom chords of suspended span, were tension members, and could either be built up of plates and angles or forged eye-bars. In efficiency there was no comparison between the two, as with eye-bars there was no loss of efficiency through rivetted joints, and being much lighter for the same strength, were therefore much cheaper. However, when the suspended span was erected by the cantilever method—i.e., building out from the end of cantilever arms—it was objectionable to make the tension chord of eye-bars, owing to the reversal of stress during erection, and eye-bars were of no use whatever where they are called on to carry large compressive stresses.

TOWERS.

The height of towers was greatly dependent on the shape of the cantilevers. If the bottom chord was curved and reached close to the water at the pier, the height of tower from water level would be much less than if the bottom chord were straight and the top chord curved. With this latter construction there was a greater overturning movement at the piers due to wind, on account of greater wind velocity at higher elevation, and this called for attention, but the higher towers and curved top chord resembled a suspension bridge, and looked more graceful and artistic than perhaps the stronger and plainer type. A good design of tower might include a rocker bearing, resting on the piers, to minimise secondary stresses induced in tower through bending moments. This bearing usually consisted of a steel casting, of which the convex part formed an arc of a circle separated from a concave base plate, of similar radius, by rollers; an end rack was interposed to limit the movement. This construction allowed the tower to move, and thus equalise any secondary stresses.

SUSPENDED SPAN.

The suspended span was generally calculated first. The traffic loading being known, the loads reacted to each panel point through the deck system could be found, and the truss designed. The truss was suspended from the end of cantilever arm, and to allow for expansion of bridge through temperature, loading, and wind pressure, an expansion joint was placed between one end of centre truss and cantilever, and which possibly took the form of a crosshead working in slides for wind pressure, and usually an arm hung from truss for the temperture and load expansions.

Principal data for design of cantilever bridges (Steinman):—