SUSPENSION BRIDGES—A STUDY.*

By GEORGE S. MORISON, Past President American Society Civil Engineers.

THE method of demonstration and illustration which has been adopted is the explanation of the design of a suspension bridge of unusual dimensions and capacity. The size selected for this design would give a clear opening of about 3,000 ft., this corresponding to the dimensions proposed for the North River at New York. The plan discussed is simply a general plan, but as such a discussion to be valuable must be accompanied by estimates, the depth to rock at the sites of the towers has been assumed to be 140 ft. below mean high water. It has been assumed also that the anchorages would be built on rock, and elevations have been assumed for these anchorages.

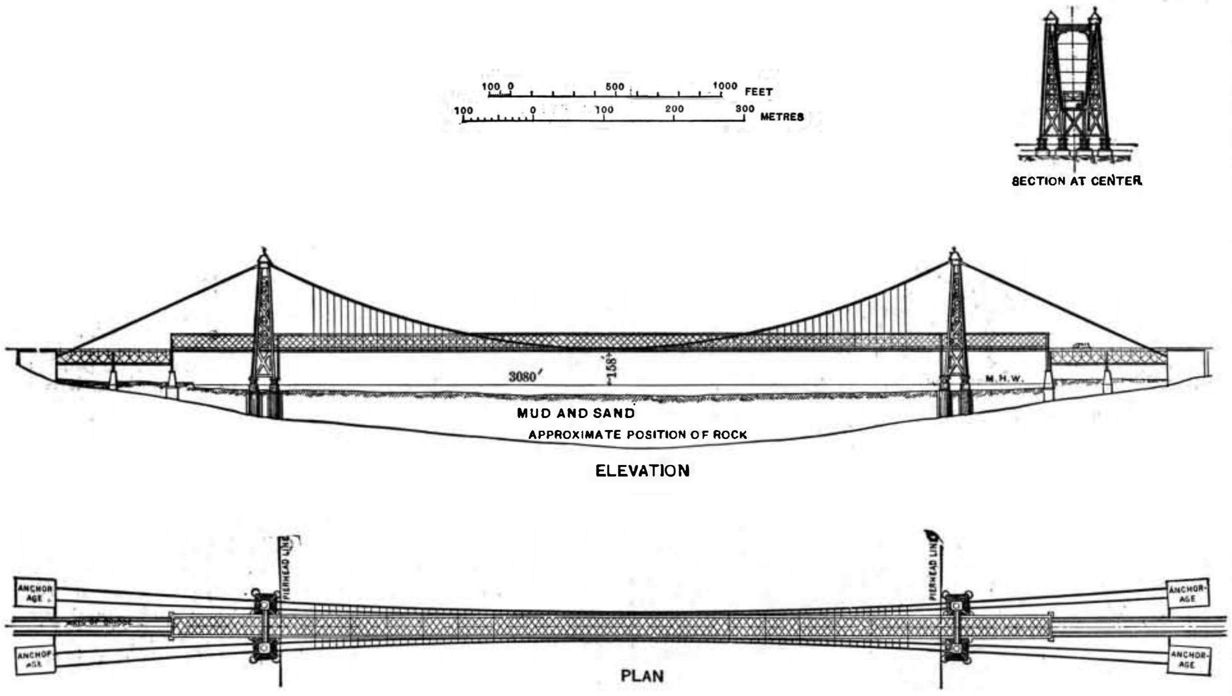

PLATE I.—ELEVATION, PLAN, AND CROSS SECTION OF 3,000 FOOT SUSPENSION BRIDGE.

In one respect the design departs radically from suspension bridges hitherto built. The cables, instead of being made of straight wires, are made of ropes, and these ropes, instead of being passed over the towers and around pins in the anchorages, are socketed, both at the top of the towers and in the anchorages, all connections being made through the sockets. This modification is really the essential feature of the whole design. The objections which will be raised to it are, first, that a straight wire is both stronger and less extensible than a twisted rope made of the same wire; and second, that no socket can be made which will develop the full strength of the rope. Both of these objections are true, but a rope can be laid in such a way that the modulus of elasticity is only about 1,000,000 lb. less than that of a straight wire, and a rope can be socketed in a way which can be absolutely depended upon to a fixed amount of strain, and the strength of the structure will then be determined, not by the strength of the wire, but the strength of the connection at the end of each rope. Furthermore, experiments have shown that ropes constructed in the manner proposed have an extremely uniform modulus of elasticity, which is the most important thing. The advantages of this system of construction are principally two; the ropes can be made in the shop, adjusted to length there, carried to the bridge site and put up in the least possible time; the wires are practically straight from one end to the other, the decided turns required over saddles and the short turns required around pins being entirely avoided. With this arrangement the objections to a strong stiff wire are removed.

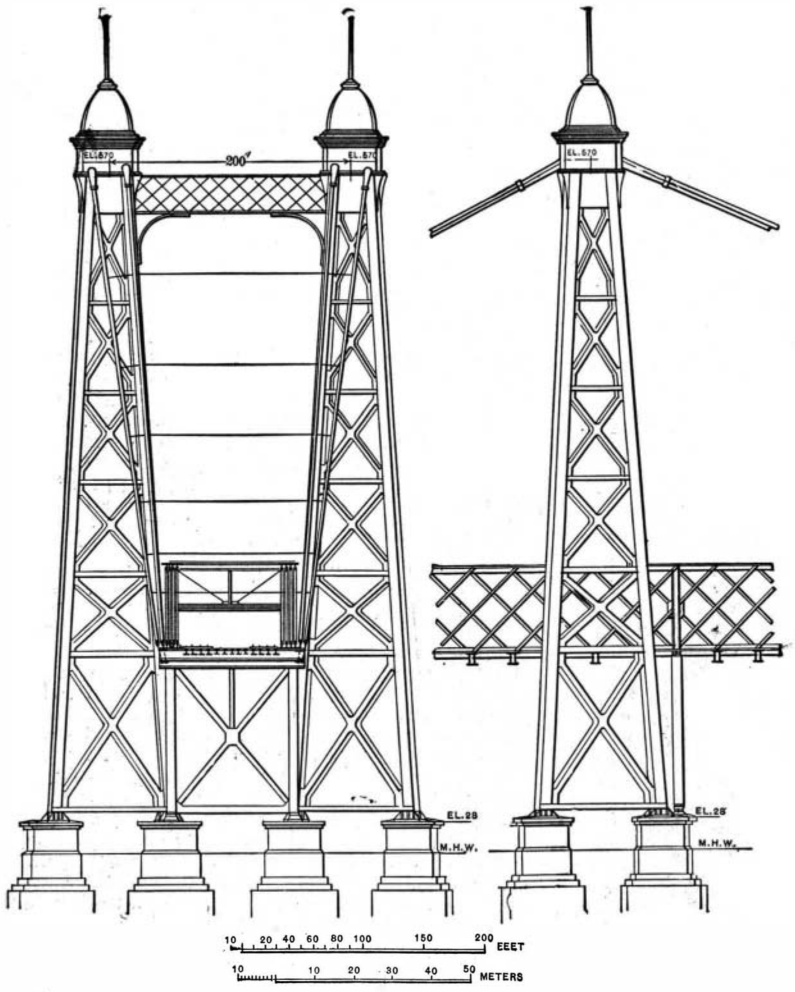

PLATE II.—FRONT AND SIDE ELEVATIONS OF TOWERS FOR 3,000 FOOT SUSPENSION BRIDGE.

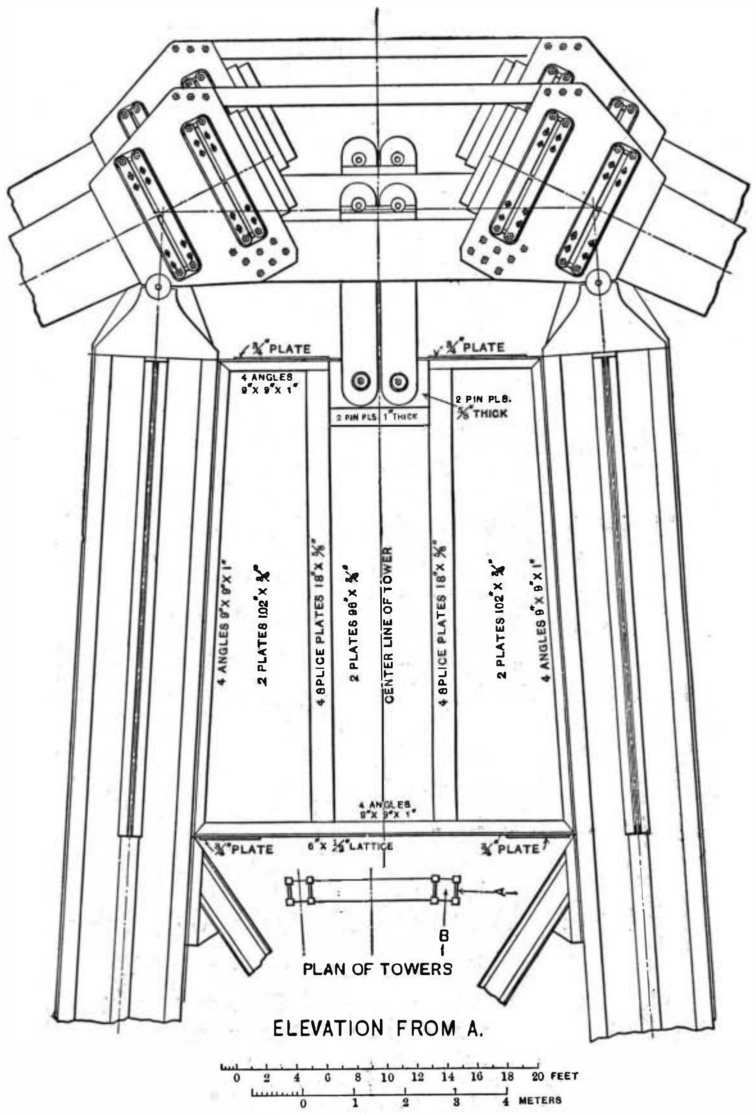

PLATE III.—METHOD OF FASTENING CABLES AND BACKSTAYS AT THE TOP OF TOWERS—3,000 FOOT SUSPENSION BRIDGE.

Another feature which is believed to be novel is the method of holding down the ends of the stiffening truss. When one-half the span is loaded, the upward reaction at the unloaded end is equal to the downward reaction at the loaded end, so that the stiffening truss must not only be supported but anchored down. The stiffening truss of this design is made 1,000 feet longer than the span, thus extending 500 ft. back toward the shore from each tower, while the suspenders in the 150 ft. next to each tower are omitted. The result is that the duties of the stiffening truss proper are confined to a length of 2,800 ft.; back of each tower is a span of 500 ft., from which a cantilever 150 ft. long projects to each end of the stiffening truss proper. The reactions of the stiffening truss are taken by the ends of the cantilevers, and the cantilevers are themselves anchored by the weight of the shore spans. This arrangement has the further advantage of leaving 150 ft. between the towers and end suspenders, within which the cables will adapt themselves to any changes of length and height due to temperature, loads or otherwise.

GENERAL DESIGN.

The general design is that of a stiffened suspension bridge, the cables to be of wire, the towers of steel on masonry foundations, the structure being stiffened by steel trusses suspended from the cables.

The cables are four in number, two on each side, the length of span between the theoretical intersection points on the top of the towers being 3,200 ft. and the versed sine 400 ft. To secure lateral stability, the two stiffening trusses are placed 100 ft. between centers horizontally, this affording an opening 92 ft. wide in the clear. At the middle of the span the two cables on each side are brought as close together as possible, or 4 ft. between centers, the width at the center of the span between points midway between the two cable centers being 115 ft. At the top of the towers the cables are spread apart to a distance of 28 ft., the width between the centers of the towers being 200 ft. Each inside cable has, therefore, a cradling of 30·5 ft. and each outer cable a cradling of 54·5 ft., the average cradling between 42·5 ft. The backstays are carried from the towers to the anchorages in planes which are tangent to the horizontal projection of the cradled cables, thus splaying the backstays apart between towers and anchorage. By this arrangement the towers are relieved of all transverse strain, and become, as it were, simply gin poles to sustain the cables. The lateral stability produced by this arrangement is evident from the plan, Fig. 1.

The towers are of steel, each really consisting of two independent towers formed of four posts, 94 ft. square at the base and battered together so as to be 28 ft. square on the top, the two square towers being connected by a cross truss at the top and resting on masonry cylinders at the bottom. The exact shape and location of the half towers are determined by the direction of the cables, the sides of the two half towers not being parallel and the squares being only approximate.

It has been considered important to reduce the number of cables to four, two on each side. If the cables of the main span and the backstays are counted as separate cables, which the detail hereafter described shows them to be, there are four cables, two leading in each direction, terminating at the top of each tower, the number of cables corresponding to the number of posts, so that the weight from each cable is transferred directly to one of the four posts. This requires cables of much larger dimensions than have ever been used, but there is nothing impracticable in making cables of the required size.

The stiffening truss is 4,100 ft. long over all, divided into panels of 33 ft. 4 in. each, supported for the central 2,800 ft. by suspenders leading from the cables, while the ends are supported on piers 4,100 ft. apart and intermediate supports are taken on rocking bents 3,100 ft. apart. The truss is continuous for its whole length of 4,100 ft., fastened to the cables at the center

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* Digest of a paper read before the American Society of Civil Engineers, October 21, 1896.

and free to move longitudinally at each end. It is considered of great importance to use a continuous truss, thus avoiding the difficulties and lost motion of a central hinge. The difficulties of fastening down a stiffening truss are overcome by the end supports, the end of each truss being a 500 ft. span resting on two supports, from which a 150 ft. cantilever projects toward the point where the suspenders begin. The suspended stiffening truss is only 2,800 ft. long and exerts an upward or downward reaction at the end of the 150 ft. cantilever, according to the position of the moving load; the cantilevers are anchored by the weights of the end spans. The stiffening truss is 66 ft. 8 in. deep between the centers of gravity of the chords, this depth being adopted for reasons given hereafter; it at once secures the necessary rigidity and permits sufficient flexibility to allow a considerable portion of the irregular moving load to be taken care of by the change of shape in the cables.

CAPACITY.

The bridge has been proportioned to carry a total load of 50,000 lb. per lineal foot, which is equivalent to a stress of 40,000,000 lb. on each of the four cables at the center of the span. The actual dead weight of the cables and suspended superstructure is about 39,000 lb. per lineal foot, thus leaving 11,000 lb. for moving load.

The width in the clear between trusses is 92 ft., which will provide for two double track railroads, each occupying 26 ft., with a space 40 ft. wide between. This 40 ft. can be occupied in various ways; its width is the same as the width between the curbs of Broadway at Twenty-sixth Street; it could be used for four rapid transit tracks either for street cars or for rolling stock of the same dimensions as that used on the elevated railroads; it could be used as a street with two sidewalks and a roadway between wide enough for four carriages to pass; it could be used for two standard gage railroad tracks, with a broad promenade for foot passengers between, or it could be used as a driveway with a street railroad track on each side. Another possible arrangement is the construction of eight parallel railroad tracks 11 ft. between centers, which is admissible on perfectly straight lines, but it is not important to decide how this bridge would be used. Enough has been said to show the capacity which would be afforded, and the weights for which it should be designed.

CABLES.

The cables are the fundamental feature of the design, and will therefore be described first. The design of the cables departs radically from the features hitherto followed in suspension bridges, and provides a method of constructing suspension bridge cables, under which it is possible to do nearly all the work in the shops, and to diminish field work to minimum.

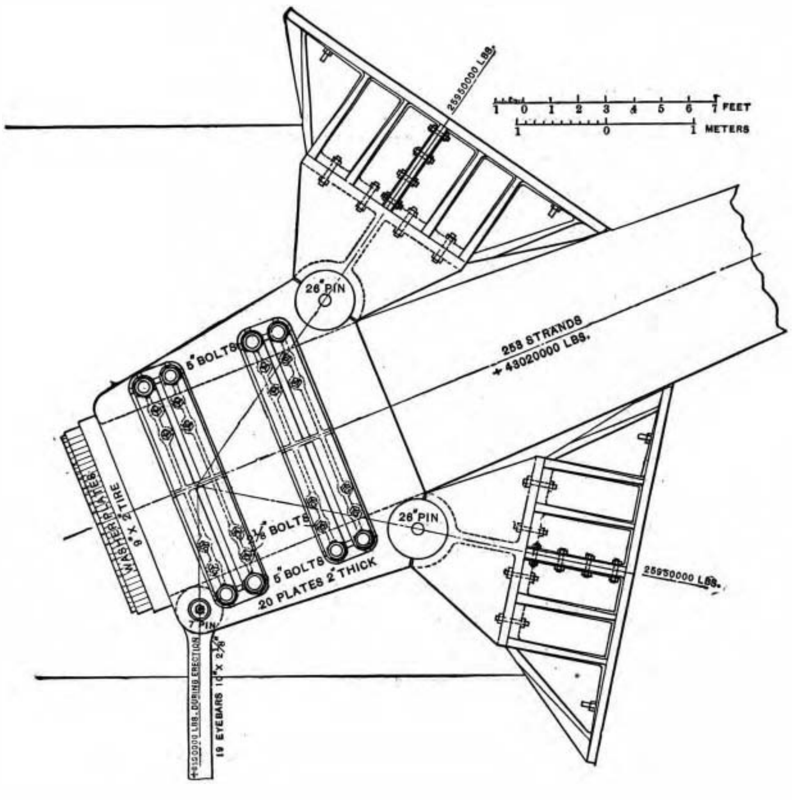

Plate IV.—METHOD OF FASTENING BACKSTAYS AT ANCHORAGES.

Each cable is composed of 253 ropes of equal size arranged in the form of a hexagon with three ropes omitted from each corner; the maximum stress on each rope will therefore be 76,764 lb. In the design, the ropes are made 2⅛ in. diameter, each rope being assumed to have a section equivalent to 3 sq. in. of solid metal and to weigh 10 lb. per lineal foot. The stress per square inch on these ropes will, therefore, be 58,921 lb., of which $\frac{39}{50}$, or 45,958 lb., will be caused by dead load, and $\frac{11}{50}$, or 12,963 lb., by moving load.

Each rope will be a specially laid rope formed of a single straight wire at the center, around which are grouped successive layers of helicoidal wires, so inclined that all will be of the same length, the alternate layers being inclined in opposite directions. When put under strain all wires are equally strained, except the single central wire, which acts as a core. This rope bears no resemblance to the ordinary twisted rope. If not larger than No. 8, the wires of each rope can be made continuous from end to end without splicing.

The method of fastening the cables is shown in Plate III. Fifty feet from each end the several ropes, which are compressed compactly together in the body of the cable, begin to separate so that they are 4·9 in. between centers at the ends, and the successive vertical sets of ropes are 4¼ in. between centers. On the top of each tower post is placed a steel casting through which all vertical strains are transmitted, and on this casting rests a 20 in. steel pin. On this pin are set up 20 steel plates 2 in. thick, each plate measuring 10 ft. in the direction of the axis of the cable and weighing 9,255 lb. The several ropes of which the main cable is composed, when spread, pass between these several plates, being held in exact position by cheap cast iron fillers between the ropes. These plates are machined to a true plane surface on the upper edges, and on these are placed a series of washer plates on which the sockets at the ends of the cables bear. These washer plates are 2¼ in. thick by 16 in. deep, and the divisions come in line with the centers of the ropes. Each washer plate is bored out for its whole depth on each side with half holes slightly larger than the diameter of the ropes, and for a depth of 10 in. with half holes of the diameter of the sockets. Each rope therefore passes through a round hole, one-half of which is bored in each adjacent washer plate and the socket fits into an enlargement of this round hole, bearing on the annular surfaces between the large and small cylinders. The series of washer plates are bound together by a steel tire shrunk around them. The large plates are bolted together with eight 5 in. bolts and sixteen smaller bolts inclined so as to pass between the ropes, all of these bolts screwing up against heavy cast steel washers on the outside, the plates being kept at proper distances by cast iron fillers.

The entire strain in the cables is transmitted to the large steel plates through the washer plates which bear against them. In the large plates this strain is decomposed into a nearly vertical strain which passes through the 20 in. pin and the steel casting into the post, and a horizontal strain which is taken across the top of the tower to the corresponding backstay connection. For convenience of construction and erection this horizontal strain is divided between two tension members, the lower one consisting of nineteen bars each 48 × 2¼ in. and the upper of the same number of bars each 15 × 2¼ in., the strain being transmitted to the former by nine 5 in. pins and to the latter by three 5 in. pins. The full details of this arrangement appear in Fig. 2.

The backstays are of the same dimensions as the main cables and connected at the top of the towers in precisely the same way, the plates to which the backstays are attached being tied to those to which the main cables are attached. In order to keep the cradled cables of precisely the same length, the outer bearings on top of the tower are lower than the inner bearings.

Though the backstays are of the same dimensions as the main cables, they carry no weight but themselves and run in approximately straight lines (being deflected from absolutely straight lines by their own weight) to and through the anchorages, each anchorage having two tunnels in it through which the backstays run.

At the lower end the ropes of the backstays are spread between plates in the same manner as at the top of tower, though the details are different because of the direction in which the strains must be transferred. These details are shown in Plate IV. The strain in the cable is divided into two equal strains, on lines making equal angles with the axis of the cable, and transferred through 26 in. pins to steel castings which bear on closely cut granite masonry, which is built into the coarser material of the anchorage.

When the cables are completed, the clamps which carry the suspenders will be put on. The form of clamp proposed is shown in Plate V, and is quite unlike that commonly used in suspension bridges. The clamp is formed of two steel plates pressed into shape and bound together by eight steel bolts; the lower half is a perfectly plain steel plate, but the upper half has two auxiliary plates riveted on, to hold the saddles which carry the suspenders. By means of cast iron fillers the irregularities in the cables are filled out, and the whole is then surrounded by a sheet of thin metal about 6 in. longer than the clamp plates, this thin metal being simply for protection against weather. The clamp plates are then put on and screwed up tight so that the full friction which can be produced by the bolts is obtained. Two bent saddles of soft metal are then placed on top of the clamp and everything is in readiness to attach the suspenders.

It is thought best not to wrap cables of this size, made of independent ropes, with soft wire as is usually done, but to cover them with a thin layer of some non-conducting substance, which will allow the heat from the sun's rays to reach the metal of the cables no faster than it will be dissipated through the whole volume of the cable.

The arrangement of the suspenders is shown in Plate V. They are wire ropes of the same character and dimensions that are used in the main cables. The detail selected provides for four suspending ropes at each clamp. Each rope would therefore have to carry 81,458 lb., equivalent to 27,153 lb. per square inch, or less than half the stress allowed in the main cables.

There are really but two ropes used at each point, each rope being twice the length of the suspender and fitted at each end into a long socket on which a screw is cut. Each rope passes over the saddle and so forms two suspending ropes; the long sockets pass through washer plates under the floor beams and are adjusted by nuts under these washers, a detail which might be modified in construction. The suspenders are clamped together about 36 ft. below the cables, so as to prevent unnecessary vibration, and where it can conveniently be done the cables will be connected with the stiffening trusses.

TOWERS.

The towers naturally follow the cables in studying the design. The support of the cables at each end of the main span consists of two towers, which form a double tower. Each tower is of approximately square section, with four corner posts, each battering one in sixteen in both directions.

In designing these towers the special functions which they have to perform must be considered. The arrangement by which the cables are attached to the top of the towers holds the towers absolutely, there being no movable saddles. Any change of length in the backstays must be taken up by a change in the position of the top of the tower. These movements at the top of the tower, combined with changes in length in the main cables, regulate the position of the suspended superstructure. It is important that the towers should be comparatively slender, so that they can bend without overstraining the metal. As the top of the tower is anchored by the backstays, a broad base is not necessary for stability.

The actual motion in the top of the tower after the completion of work, due to changes in the length of the backstay caused by a maximum moving load, on the basis of a modulus of elasticity of 26,000,000, will be 6⅞ in., which corresponds to a stress of 2,176 lb. per square inch in the posts of the tower.

The section of each post varies from 1,051 sq. in. at the top to 1,145 sq. in. at the bottom. Each post is 8 ft. square. At intervals of 24 ft. diaphragms would be built in each post, thus coming opposite one of the joints, the function of these diaphragms being the same

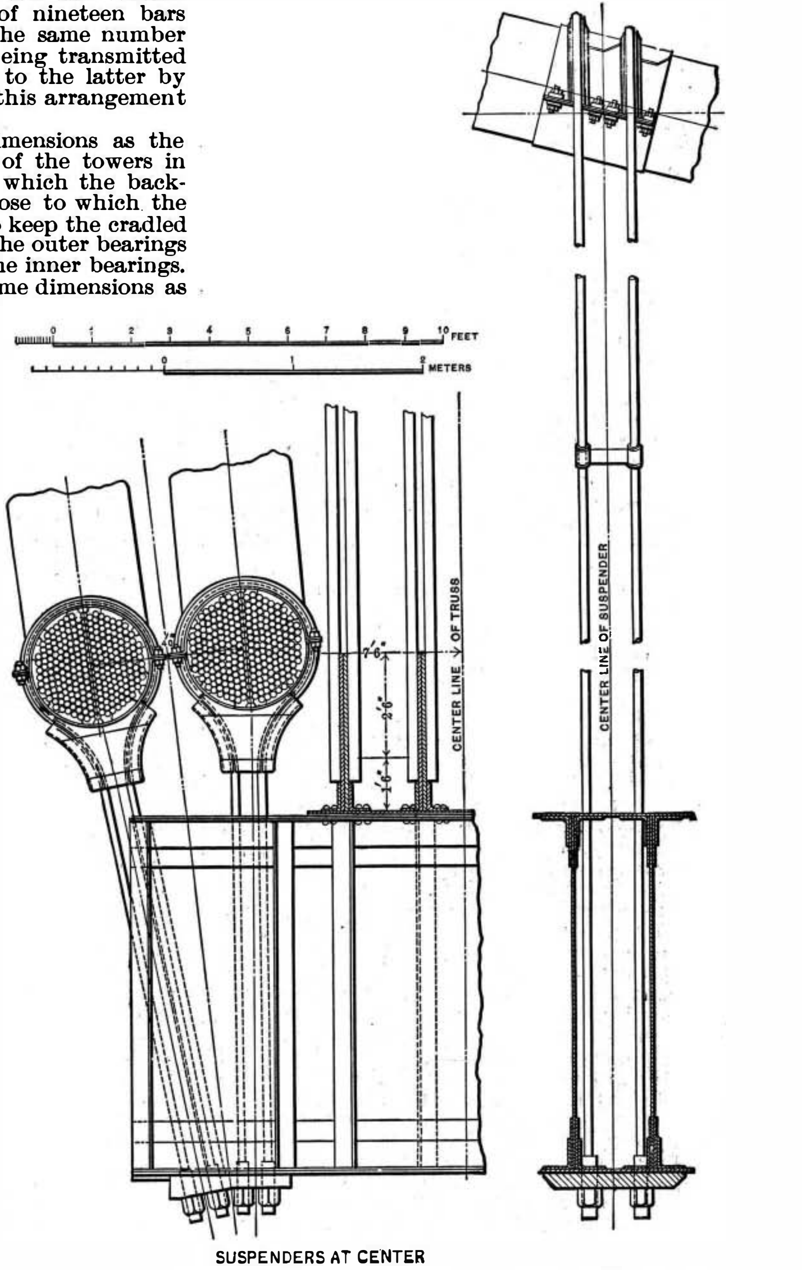

Plate V.—METHOD OF ATTACHING SUSPENDERS TO CABLES AND FLOOR BEAMS.

as that of the diaphragms in a bamboo rod. At the top two extra cross webs would be built into the post to support the steel casting.

At the bottom the post would rest on a large casting. For convenience of inspection, a hole is made through the middle of each diaphragm, and a series of ladders would reach from diaphragm to diaphragm, by which inspectors could pass through the whole interior of the post, a manhole being placed near the base, through which they could enter. At the bottom each post would be held down by an anchor bolt at each corner, though this is hardly a necessary provision.

At the top the four posts are connected by girders 31 ft. deep, there being two girders on each longitudinal side and one on each transverse side.

The tower is braced on each side between the four posts, this bracing being divided into six panels, the second panel from the bottom corresponding in height to the depth of the stiffening truss, this arrangement being adopted so that the wind strains can be thrown from the stiffening truss into the tower at the panel points of the bracing.

FOUNDATIONS.

The average depth from mean high water to rock at the site of each tower is assumed to be 140 ft. In order to prevent any possible disturbance from expansion and contraction of transverse members at the feet of the metallic towers, it is thought best to rest each post on an entirely independent foundation. There would, therefore, be four independent foundations under each tower, or eight on each side of the river, making sixteen in all. Of these the two center ones next to the river, on each side, would have to support the reaction of the stiffening truss as well as the weight of the tower post, and they are therefore made larger than the others.

ANCHORAGES.

The anchorages at each end of the bridge would be divided into two parts, each of which anchors two cables, the position of these anchorages being shown in Plate I.

The anchorage has no duty to perform except to provide weight, and may be built of a very cheap class of masonry or of concrete. Any class of work which is entirely free from voids and weighs at least 140 lb. per cubic foot, or 3,780 lb. per cubic yard, will answer this purpose.

There will be two tunnels running through each anchorage, each of which should be lined with brick, and be large enough for convenient inspection of cables, and perhaps, also, for running a carrier during erection. At the lower end of each cable there will be a room in which the detail connection is placed, and it will probably be expedient to have some kind of a staircase placed in a small shaft by which these two rooms can be reached. The bearing of the castings must be taken on granite masonry of very high quality, the pressure on the bottom of the castings being 1,000 lb. per square inch, and enough of this masonry has been provided to reduce the pressure on the cheap masonry to 250 lb. per square inch.

Each anchorage would consist of a single block of masonry. It is 180 ft. long, 130 ft. wide, and the top finishes at elevation 155, this being the elevation of the rails.

SUSPENDED SUPERSTRUCTURE.

The suspended superstructure embraces the floor beams and the stiffening truss, with all the necessary cross bracing, laterals, etc. The stiffening truss is the principal feature of the whole, and its peculiar function is such that the calculation of the exact strains is a work of extreme difficulty.

A stiffening truss with a hinge at the center has the advantage of greater simplicity in the calculations, but the details of the hinge are much more objectionable than any irregularities of strain which might occur, and a continuous stiffening truss without a hinge has been used in this design.

The functions of a stiffening truss may be considered in two ways. It may be regarded simply as a floor stiffener, preventing short local changes; or it may be considered as a complete stiffening truss which distributes the entire moving load with practical uniformity over the whole length of the structure. The former is the usual function performed by the stiffening truss of a long span highway bridge; the latter is the function which a stiffening truss must perform in a short span bridge or in a railroad bridge of moderate length.

In the present case the dead load is so great in proportion to the moving load that the distortion of the cables will be comparatively small, even under the passage of trains; it will, however, be so great that if the stiffening truss performed no other functions than that of a floor stiffener, the deflection might disturb the rapid passage of trains.

The condition of loading which will cause the greatest deflection in the loaded portion of the stiffening truss will occur when the maximum moving load covers one-half of the 2,800 suspended feet of stiffening truss, occupying 1,400 ft. on either side of the center; this is also the case in which all calculations are most simple. A limit of deflection of one four-hundredth of the half span, or 3½ ft. in 1,400 ft., corresponds to a 1 per cent. grade at each extreme end of the deflection, and has been selected as the limit in this case.

The moving load which the cables are capable of carrying is equivalent to 11,000 lb. per lineal foot over the entire structure, and it is assumed that this load is distributed over the equivalent of six railroad tracks, corresponding to 1,833 lb. per foot of track. In estimating the effects of an unequal load a weight of 12,000 lb. per lineal foot is taken in accordance with the provisions stated at the beginning of this paper. While it may be considered that the load per foot on one-half or one-third of a span ought to be more than 10 per cent. greater than the load per foot on the whole span, it must be remembered that the peculiar conditions of this bridge are such that it is only under very rare conditions that any considerable portion of the moving load must be distributed by the stiffening truss. In fact, two passenger trains could cross this bridge side by side without disturbing the position of the cables beyond the limits of deflection which are permissible; it is only when the load exceeds that of two maximum passenger trains that the stiffening truss has any duties to perform beyond that of a floor stiffener.

The excess load required to produce a distortion of 3·5 ft. at the quarter on a 2,800 ft. span with a versed sine of 310 ft. (which corresponds to the design) will be 9·424 per cent. of the load on the unloaded portion. Taking the dead load at 39,000 lb. per lineal foot, 9·424 per cent. of this is 3,675 lb.; deducting this from 12,000 lb., there remains 8,325 lb. as the weight per foot to be distributed by the stiffening trusses, or 4,162 lb. for each truss.

The two stiffening trusses designed are each 66·67 ft. deep between centers of gravity, or 70 ft. over all. They are placed 100 ft. between centers. There is a stiff riveted lateral bracing between the top chords and a transverse bracing at every panel point. The floor system is entirely below the bottom chord and the bottom laterals are built in as a portion of this floor system. The webs are riveted lattices with four independent lines of bracing.

The suspended portion of the truss is carried by the floor beams, and as its weight exceeds the amount of moving load which has to be distributed, its action really amounts to varying the portion of its own weight which is transferred to the floor beams, there never being any conditions under which any portion of the weight of the floor system has to be transferred to the stiffening truss. Beyond the limits of the suspenders the floor beams are hung from the stiffening truss, to which they transfer the weight of the floor system.

The floor beams are strong enough to carry the whole weight from truss to truss, thus leaving a clear space for the whole distance. The two double track railroads are placed next to the trusses, thus reducing the weight of the floor beams to a minimum, while the possible deflection of one end of the beam below the other is found not to be enough to produce trouble.

There will be eight railroad stringers in each panel and eight lighter stringers which carry the roadway or the rapid transit tracks.

WIND PRESSURE.

The wind surface per lineal foot presented by one-half of one web, the lower chord and the floor system is 11·35 sq. ft., and the wind surface presented by the upper half of the web and the upper chord is 7·77 sq. ft. As the trusses are 100 ft. apart, the area of the trusses should be doubled, but the floor comes so near to being solid that it need not be doubled. The total surface presented to the wind which must be resisted by the top laterals is therefore 15·54 sq. ft. per lineal foot, and the total surface presented to the wind which must be resisted by the bottom laterals 19·12 sq. ft. per lineal foot. To the latter should be added the area of a passing train, which is equivalent to 8 ft. above the bottom chord, thus making the total wind surface to be provided for 27·12 sq. ft. per lineal foot. On a basis of 30 lb. per square foot the total wind pressure to be resisted is:

Top lateral system	466 lb.
Bottom lateral system	814 "
Total	1,280 "

For the calculations, these figures have been slightly varied, and the top laterals are proportioned to resist a wind pressure of 500 lb. per lineal foot and the bottom laterals a wind pressure of 750 lb. per lineal foot.

There is no probability that anything like these wind strains will ever be reached over the whole length of the span, though considerably greater pressures may occur for limited lengths. To reduce these amounts, however, would be a departure from established practice.

The wind pressure would be transferred to the towers where the stiffening truss passes the towers, by horizontal cables, these cables reaching from each chord to the outer posts of the towers, the cables clearing the inner posts and being long enough to provide for the longitudinal motion of the trusses without overstraining. These horizontal cables would be tightened under strain so that they would always stiffen the trusses. A portion of the wind strain would undoubtedly be taken by the transverse bracing of the rocking bent.

There is also another element which materially reduces the effect of wind. To produce the above-mentioned strains in the chords, the whole suspended superstructure must move laterally 8·75 ft. This involves swinging the main cradled cables and raising the center of gravity of the suspended superstructure, a lateral movement of 8·75 ft. corresponding to a lift of 0·075 ft. or 1 vertical to 117 horizontal. As the suspended superstructure weighs 27,000 lb. per lineal foot, this will require a horizontal force of 230 lb., so that before this deflection can occur the actual wind pressure must be about 1,000 lb. per lineal foot on the bottom chord.

ESTIMATE.

The work has been described in the manner in which the design has taken shape, and the cost of each separate portion has been estimated in connection with this description. In execution the work would necessarily be differently divided and may properly be grouped under the respective heads of substructure and superstructure.

Under these heads the cost may be stated as follows:

Tower foundations	$5,456,000	
Anchorages	2,642,800	
Shore piers	753,600	
Substructure		$8,852,400
Metallic steel towers	$1,912,000	
Wire work, etc	4,866,149	
Suspended superstructure, etc	4,492,800	
Superstructure		11,270,949
Total		$20,123,349

For purposes of inspection an elevator ought to be placed in each of the four towers, and two of these elevators ought to be of sufficient size to accommodate passengers; $100,000 should be reserved for these elevators and the various appliances in connection with them.

The ornamental work on top of the towers, with provisions for lighting, etc., would cost another $100,000.

The structure, with a 10 per cent. allowance for contingencies and engineering, would cost about $22,500,000, or somewhat less than $5,500 a foot for the 4,100 ft. of suspended superstructure.

By making some modifications in the plan, among which may be mentioned allowing a greater flexibility under extreme conditions and reducing the depth of the stiffening truss, the cost could probably be reduced to about $20,000,000.

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