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Influence of erection methods on design of steel bridges

L'influence des méthodes d'érection sur la conception des ponts métalliques

Der Einfluss der Montage-Methode auf den Entwurf von Stahlbrücken

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INTRODUCTION AND HISTORY

To get the best results and the greatest economy, it is essential that the method of erection of any bridge should be considered when the design is prepared and that the design should be modified as may be necessary in order to conform to it.

Difficulties in erection have largely controlled the development of bridges. From the time of the construction of the Menai Suspension Bridge in 1818–26 until the Forth Bridge was completed in 1890 the longest single span was always of the suspension type, on account of the comparative ease of erecting the cables or chains compared with the difficulty of erecting girder or arch bridges.

In the middle of the nineteenth century suspension bridges fell into disrepute because of the failure of engineers to stiffen them adequately against the aerodynamic effect of wind forces, with their consequent failure in storms and under oscillating or rhythmic loads. The onset of the railway age brought further problems in the form of heavier and more concentrated loading and impact effects. John Roebling, however, by means of diagonal ties above and below deck and the incorporation of stiffening trusses, produced a design in the Grand Trunk Railway Bridge at Niagara which carried railway traffic, although not without difficulties, for some forty years and continued to keep suspension bridges in the lead. The collapse of the Tay Bridge in 1879, however, set up a clamour for bridges of sturdy design that would stand four-square to the wind and so ushered in the era of the great cantilever bridges.

In his well-known treatise *Long Span Railway Bridges*, in 1867, Benjamin Baker states: "Of the numerous practical considerations and contingencies to be duly weighed and carefully estimated before the fitness of a design for a long-span railway bridge could be satisfactorily determined, none are more important than those effecting the facility of erection." This was written only a few years before he and Sir John Fowler began work on the design of the Forth Bridge. Thereafter cantilever bridges held the lead in span until the growth of road traffic led to the construction of the long-span suspension bridges of today.

METHODS OF ERECTION

The following methods of erection may be adopted:

(1) Falsework or temporary staging
(2) Floating out
(3) Service girder
(4) Cantilever
(5) Rolling out
(6) Suspension

Let us see in what ways these methods may affect the design of a bridge.

(1) *Falsework*

Falsework is most suitable for erection of trusses over a dry river-bed or in shallow water where staging can easily be provided. It may also be used for the erection of the anchor arm of a cantilever bridge as in the Quebec and New Howrah Bridges

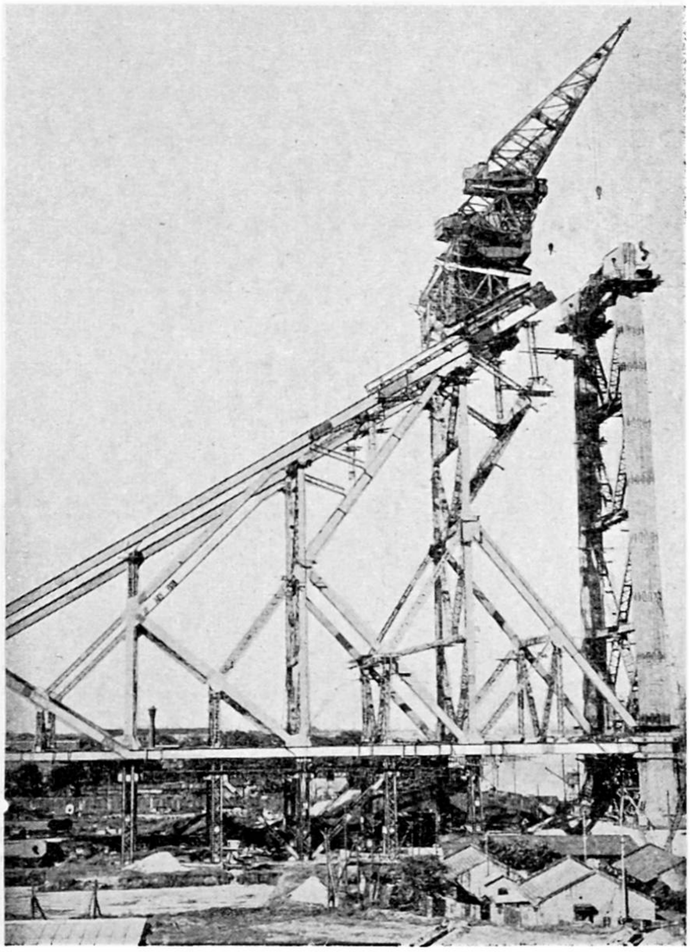

Fig. 1. New Howrah Bridge, Calcutta. Erection of anchor arm on falsework. Note fleeting tracks for creeper crane and temporary members supporting top chord

(fig. 1). It provides easy conditions for carrying out any desired prestressing,* but otherwise does not affect the design of the bridge, except possibly in the location of the connections. It was probably the provision of temporary supports immediately below panel points that originally led to the practice of locating splices in the lower chord some feet to one side of the intersection to facilitate riveting. It is more economical to locate splices at panel points, if possible, because the main gusset plates can then be included in the cover material. If there is any change of angle or depth of member at the panel point, fabrication is simplified by locating the splice there.

(2) *Floating out*

Floating out may be adopted for the erection of spans of 150 ft. or more, over a river that is too deep or otherwise unsuitable for staging, and where there are facilities for assembling the spans on pontoons, moored close to the shore, e.g. the Willingdon Bridge in Calcutta and the bridges over the Hawkesbury River, N.S.W. (fig. 2). It

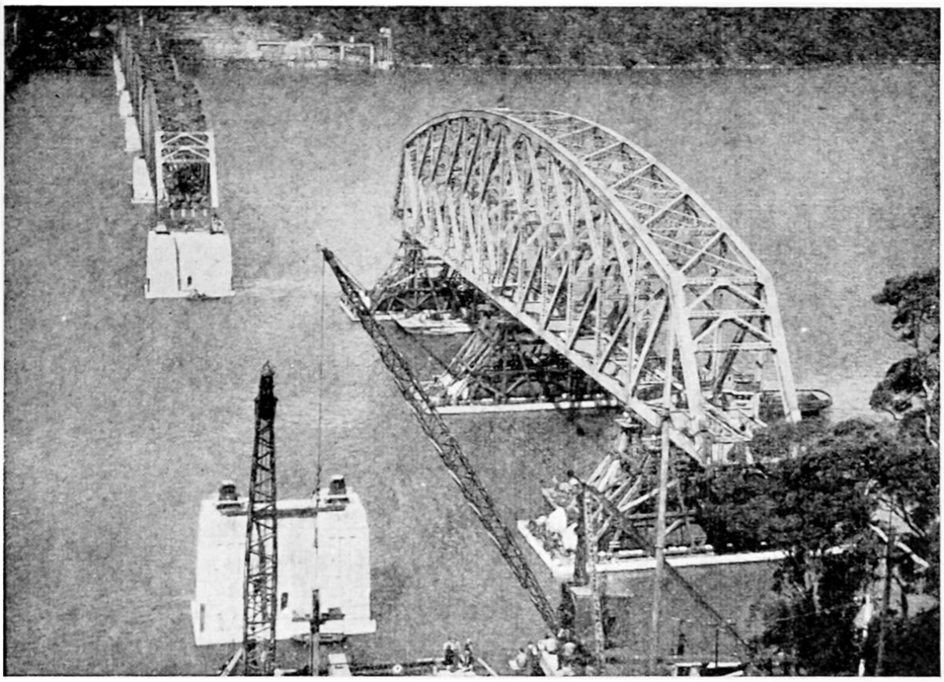

Fig. 2. New Hawkesbury River Railway Bridge. Floating in 445-ft. span

does not affect the design of the spans, except in so far as special details may be required at the ends for subsequently hoisting or lowering them into place. It is noteworthy that the first two substantial girder bridges, Britannia and Saltash, built a hundred years ago, were both floated into position and thereafter raised by hydraulic rams to their final level. This method may also be used for the erection of the suspended span of a cantilever bridge, as at Quebec.

It is usually cheaper, however, to cantilever out the suspended span, even though extra material may have to be used in the end chords and diagonals, rather than to

* *Prestressing.* The members of the trusses are fabricated to such lengths and their intersections to such angles, that under dead and (if desired) live load, the trusses would assume their correct geometric shape and all members would be straight. During erection, therefore, individual members have to be "prestressed," that is, temporarily strained or bent into position. By this means the secondary bending stresses that would otherwise occur under the predetermined load are largely eliminated.

float it out. This remains true even though prestressing is facilitated by the floating-out method.

(3) *Service girder*

Erection on service girders (fig. 3), e.g. Vila Franca Bridge, is similar in its effects to erection on staging and facilitates prestressing.

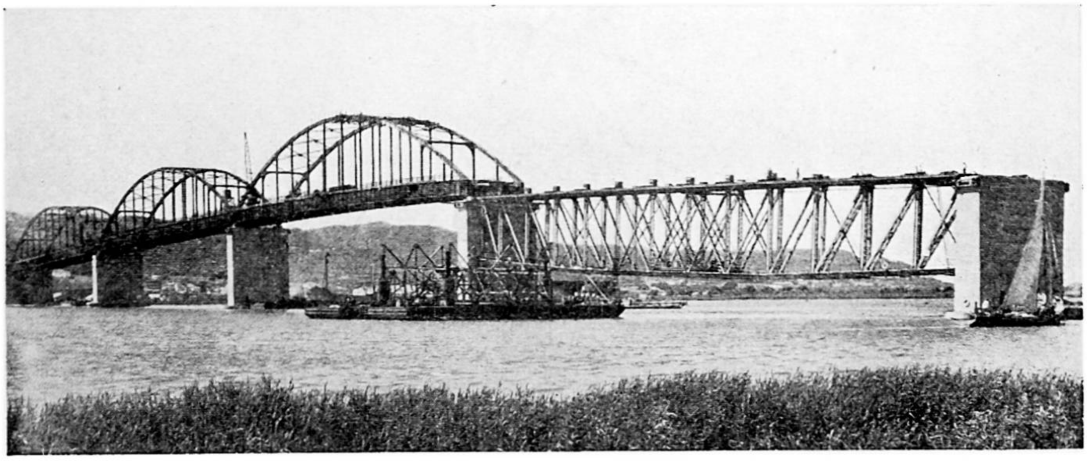

Fig. 3. Vila Franca Bridge over the Tagus near Lisbon. Service girders floated into position ready for erection of fourth span

(4) *Cantilever*

The first notable example of cantilever erection was that of the St. Louis Bridge over the Mississippi by James B. Eads in 1874. It is remarkable that this method was first used for an arch and not for a cantilever bridge. Since this date all big steel arches have been erected by this method with one notable exception, the Bayonne Bridge, which was temporarily supported on trestles. Spandrel-braced arches such as the Victoria Falls Bridge or Sydney Harbour Bridge are more suited to cantilever erection than crescent-shaped arches or ribs of uniform depth, as the anchorage cables can be attached to the ends of the upper chords and, on account of the depth of the truss, need not be moved further out as erection proceeds. Nevertheless extra material will generally be required to reinforce the upper chord and a number of the web members to enable them to resist erection stresses. N-type bracing also lends itself very well to cantilever erection and has been used in practically every long-span arch bridge. The effect of wind stresses during erection must be carefully investigated, particularly if the bridge is slender. In the Birchenough Bridge it was considered advisable to anchor the bearings of the arch against possible uplift arising from wind forces during erection.

The most economical way of erecting a cantilever bridge, if the site is suitable, is by means of balanced cantilever erection, as on the Forth Bridge. In this method the anchor and cantilever arms are built out equally from the main pier and no falsework or temporary foundations are required. After the ends of the anchor arms have been tied down, the erection of the cantilever arms and suspended span proceeds to the centre (fig. 4). No extra material is required on account of erection stresses, except in the ends of the suspended span if it is erected as two cantilevers. Provision, of course, must be made for closing the bridge at the centre and subsequently "swinging" the suspended span, so as to convert it to a freely supported structure. This method has also been used on cantilever bridges which have single end-posts, by employing one or more temporary trestles close to the main pier and so providing a base from which to cantilever.

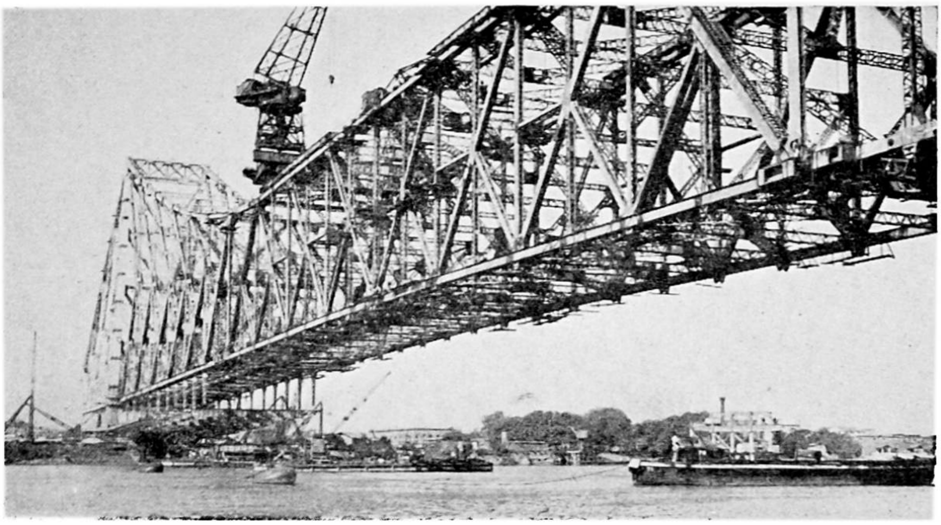

Fig. 4. New Howrah Bridge, Calcutta. Junction of suspended span after erection as two cantilevers

The prestressing of a cantilever arm is not very difficult but certain items of special plant may be needed. On the New Howrah Bridge two adjustable jacking members (fig. 5) had to be designed for this purpose. These members were telescopic and had 200-ton jacks incorporated in them, to enable the lower chord panel points to be forced upwards, so that connections in the diagonals above them could be made.

The cantilever method of erection may be used for simple spans, as, for example, on the Beit Bridge over the Limpopo River. In this bridge of 14 spans, the first was erected on falsework and all the other spans were built as cantilevers; this enabled erection to proceed independently of floods. Extra material will, of course, be needed at the ends of the spans to resist erection stresses, and temporary ties between the spans are required. Great difficulty may be experienced if a simple span of high-tensile steel is erected as a cantilever, and has also to be prestressed. The reason for this is that the erector has a dual task in that he has first to eliminate the distortions of the truss as a cantilever and then to impose the distortions necessitated for prestressing.

(5) *Rolling out*

The method of rolling out is more applicable to short than to long spans. Its most extensive civilian use is in the reconstruction of railway bridges, where in a week-end occupation the old bridge may be rolled out sideways on temporary trestles and a new one, which has been assembled beside it, may be rolled into position.

The method of balanced launching "end-on" was considerably developed in the erection of Bailey bridges during World War II. In one method the bridge was built on rollers on the river bank with a temporary extension piece or nose on the end of the bridge. It was then launched out on two or three sets of fixed rollers, and before the centre of gravity of the span had moved beyond the last set of rollers on the near side, the nose end reached the far bank. If this could not be contrived, the "derrick

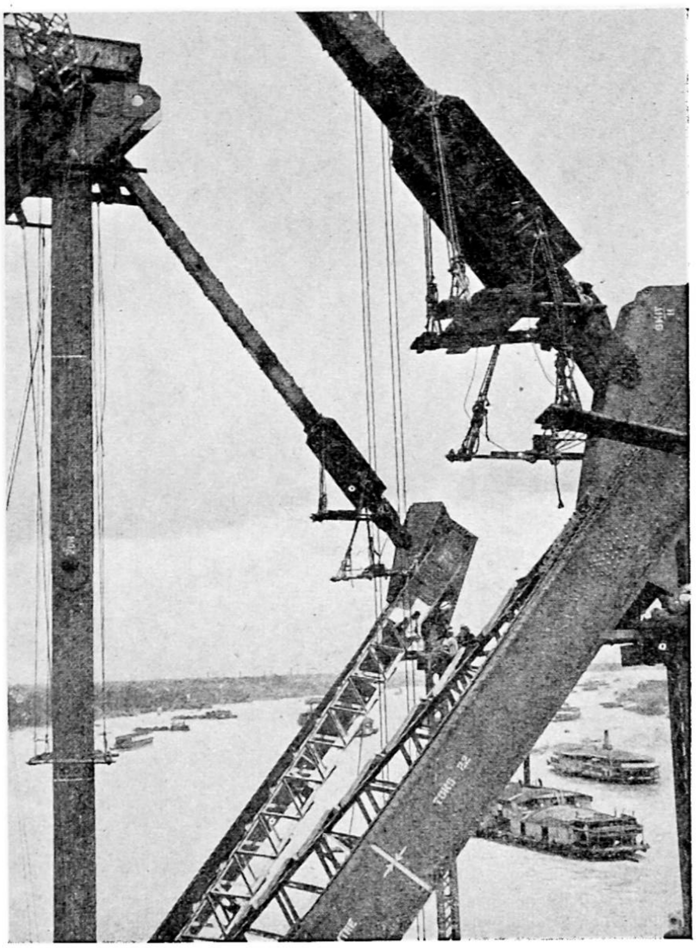

Fig. 5. New Howrah Bridge, Calcutta. Temporary adjustable members with 200-ton jacks being used for prestressing of cantilever arm

and preventer" method was used. In this system the span was prevented from overbalancing by supporting the nose end by means of tackle suspended from a pole on the far shore. The forward pull was resisted by means of preventer tackle attached to the near end of the span to hold it back. Alternatively, counterweights might be used, if available, on the near end to prevent overturning. In all these methods the truss has not only to be designed to resist the effects of cantilevering to the extent required, but the lower chord has to be capable of resisting in bending the reaction from the rollers.

(6) *Suspension*

The design of a suspension bridge as a whole is not much affected by the method of erection of the cables. These may consist of parallel wires spun in place, squeezed together and bound, as in standard United States practice; or they may be composed of a number of prestressed stranded ropes or locked-coil cables that permanently maintain their individual character. Alternatively, links may be used, as in the reconstruction of the Menai Suspension Bridge.

The most significant difference in design occurs in the method of connection of the cable to the anchorage. The loops of wire forming parallel wire cables are connected by passing them round the curved ends of the strand shoes so that the wire remains continuous and is in a state of tension, bending and compression. Cold-drawn high-tensile wire, unlike heat-treated wire, appears to suffer no harm in this condition, The ends of individual strands in the stranded-rope cable, however, are usually connected by means of white-metal into a cast-steel socket which is bolted to the anchor bars. Each wire remains virtually straight and is in a state of tension only.

An interesting innovation in the Otto Beit Bridge was to use parallel wire cables but to pull each strand across in the form of a flat ribbon made up of a number of wires side by side. Strands were socketed at the ends for connection to the anchorages and retained their individuality to some extent at the tower saddles, which were specially shaped to accommodate the layers of wires; but throughout the remainder of their length they were squeezed together and bound (fig. 6).

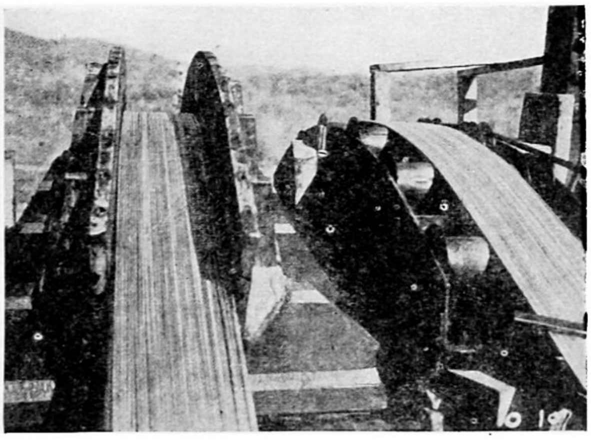

Fig. 6. Otto Beit Bridge, Rhodesia. Erection of cable strands in the form of ribbons of parallel wires. Note tower saddle on left with new strand about to be placed

Suspenders may be either socketed at the ends, so that the wires remain straight or they may be looped over the top of the cable bands as in United States practice.

Towers may be either fixed or hinged at the base. The usual practice today, particularly on long spans where the towers are massive, is to fix the base. After erection the cables are also fixed to the top of the tower, which is thereby subjected to slight bending, but not enough to be of any significance. To facilitate the erection of straight backstays on a fixed tower the saddle is usually moved back to enable the backstays to be connected, and subsequently jacked forward and bolted in its permanent position centrally on the tower. A recent example of hinged towers is the new Chelsea Bridge in London.

Very wide variety is found in the arrangement of deck and stiffening trusses. Greatest economy is gained by bringing the sag of the cable as low down as possible relative to the deck and thus achieving the maximum sag with the shortest tower. In a number of early suspension bridges, such as Brooklyn Bridge and Clark's famous bridge at Budapest, this was done by bringing the cable down below the upper chord of the stiffening truss. This arrangement was also successfully adopted on the Otto Beit Bridge. There the ends of the cross girders were suspended from the cables and the stiffening trusses were subsequently erected on the cross girders. The deck could thus be erected before the truss and the truss material could be laid out on the deck stringers right along the span before erection, thereby avoiding severe distortion of the cables (fig. 7).

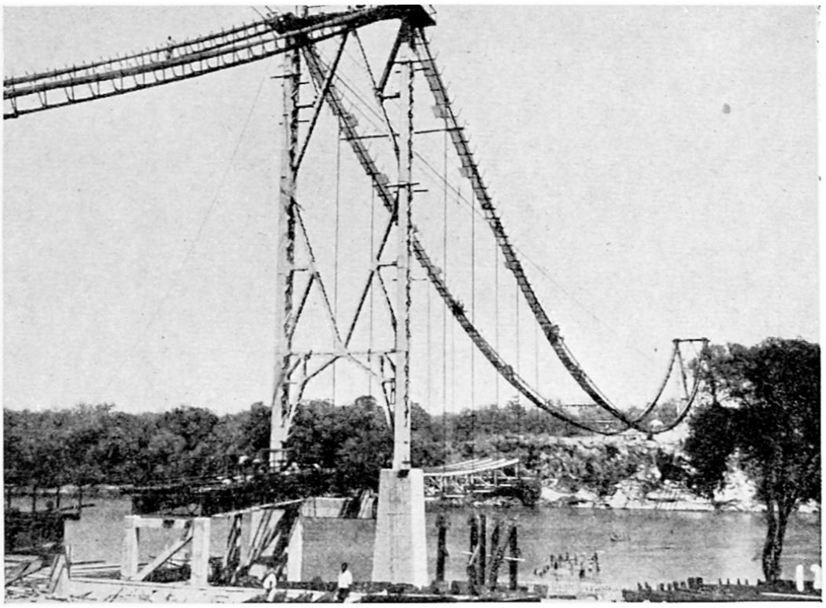

Fig. 7. Otto Beit Bridge, Rhodesia. Erection of deck cross girders. Note opening in tower bracing for Blondin on Bridge centre line

The usual modern practice in the United States is to put the cables and stiffening trusses in the same plane, so that the suspenders directly connect the top of the truss to the cable. In this arrangement taller towers are required; moreover the erection of the stiffening truss, which has to be built before the deck, or together with it, is complicated by distortion of the cables. This distortion is particularly severe if the stiffening truss is built out continuously from the towers, as on the Golden Gate Bridge. In the Bay Bridge the deck steel was erected by means of tackle suspended from the main cables and in units weighing from 75 to 203 tons. Erection was begun at the centre of the main spans and at the ends of the side spans (fig. 8).

Effect of erection crane on design

Cranes may be situated:

(1) On the bridge, i.e. Scotch derrick, or creeper crane.
(2) Independent of the bridge, i.e. on the ground on staging, on service girders, or floating cranes.
(3) Blondins.

(1) *Cranes on the bridge*

(*a*) Creeper cranes

Early bridges, such as the St. Louis Bridge and the Forth Bridge, were erected piecemeal with very light cranes that travelled on the bridge. At the beginning of this century the tendency to use heavy creeper cranes for assembling large units developed. On the Hell Gate Bridge pieces were erected weighing up to 180 tons each; the heavy traveller on Quebec Bridge weighed 920 tons and was equipped with four

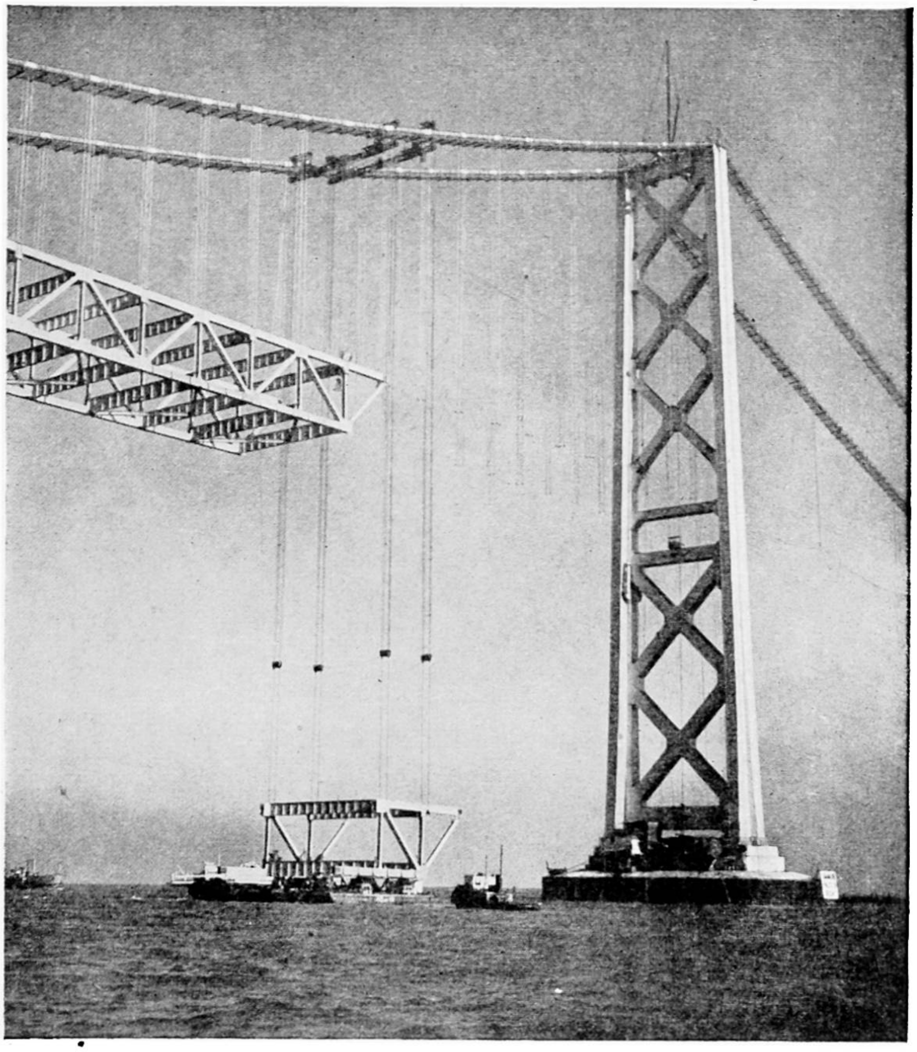

Fig. 8. San-Francisco–Oakland Bay Bridge. Erection of heavy units of deck steelwork

55-ton and four 20-ton hoists, in addition to numerous light derricks of 5- and 10-ton capacity.

On Sydney Harbour Bridge the heaviest chord member weighed more than 500 tons. In order to keep the weights of individual lifts to a reasonable figure all the chords were subdivided longitudinally and most of them were given one or more field splices in their length. By this means a fairly uniform range of lifts was obtained, all within the capacity of the 120-ton creeper cranes. It is generally more economical to reduce the heaviest lifts by means of splices in this way than to provide a crane capable of lifting the heaviest member in one piece. If by this means the capacity of the crane can be halved, as it well may be, its weight and cost will be very substantially reduced and it will be quicker in use. Moreover, the cost of temporary trestles, foundations and fleeting tracks will all be substantially less.

On arch bridges, creeper cranes generally run on the upper chord, which is usually sturdy enough to carry the weight. No reinforcement was required in the Sydney Harbour Bridge or Birchenough Bridge. On through cantilever bridges creeper cranes may be run over the top chord as on the New Howrah Bridge or a tower traveller may be used running on the deck. The disadvantage of running a creeper crane over the top chord is that upper chord members of a cantilever bridge are seldom heavy enough to support its weight in bending. On the Howrah Bridge special fleeting tracks had to be bolted on to stools on the top chord and temporary members had to be inserted in the bracing to support the chord under the weight of the crane (fig. 9). Moreover, if the cantilever bridge is of conventional outline, special means have to be provided to haul the crane over the peak at the end post. The tendency in America today is to use comparatively light guyed-derricks, as on the San-Francisco–Oakland Bay Cantilever Bridge, in preference to heavy creeper cranes.

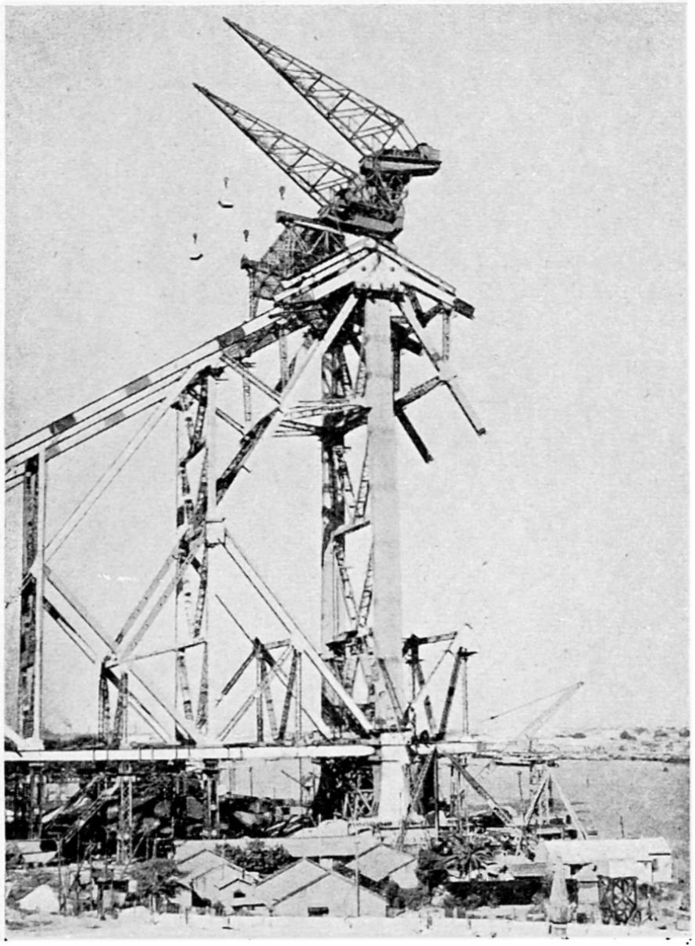

Fig. 9. New Howrah Bridge, Calcutta. Creeper crane moving off temporary cradle on which it had been hoisted up anchor arm on to fleeting tracks on cantilever arm

Cantilever bridges rarely require any strengthening of members to resist direct stresses, including those from the weight of the crane during erection, because the members adjacent to the piers are the most heavily stressed in the final condition. But on arch bridges the circumstances are entirely different. The ends of the upper chords of a spandrel-braced arch carry little stress in the final condition and substantial reinforcement is required in them during erection. On the Sydney Harbour Bridge part of the extra section needed was added in permanent material and part in the form of temporary side webs which were removed after the arch was closed.

(*b*) Scotch derricks

Instead of employing creeper cranes, Scotch derricks may be used in a kind of leap-frog, as on the new Tyne Bridge at Newcastle. In this method a derrick on the steelwork erects the members of the bridge as far ahead as it can reach and then erects a second derrick on the end panel. This derrick then proceeds with the erection and dismantles the first derrick and re-erects it ahead, and so on. The effect of this method on design is less than that of creeper cranes, in that the derricks themselves are lighter; no fleeting tracks are required, nor does the upper chord have to support the weight of the crane in bending.

(2) *Independent cranes*

(*a*) On the ground, on staging or on service girders

None of these has any direct effect on the design of the bridge, but it may be well to consider the circumstances under which the use of cranes on service girders becomes economical. In multiple-span bridges it will probably pay to use special plant, such as a Goliath crane travelling on a service girder, as in the Lower Zambesi Bridge, rather than to adopt cantilever erection which necessitates strengthening the bridge by using extra material in the end chords and web members of every span.

(*b*) Floating cranes

Erection by means of floating cranes generally has no effect on the design of the superstructure. In the Storstrom Bridge complete plate-girder side-spans weighing up to 500 tons each were hoisted up bodily by means of a huge floating crane and placed on their bearings on the piers at a height of 90 ft. above water level (fig. 10).

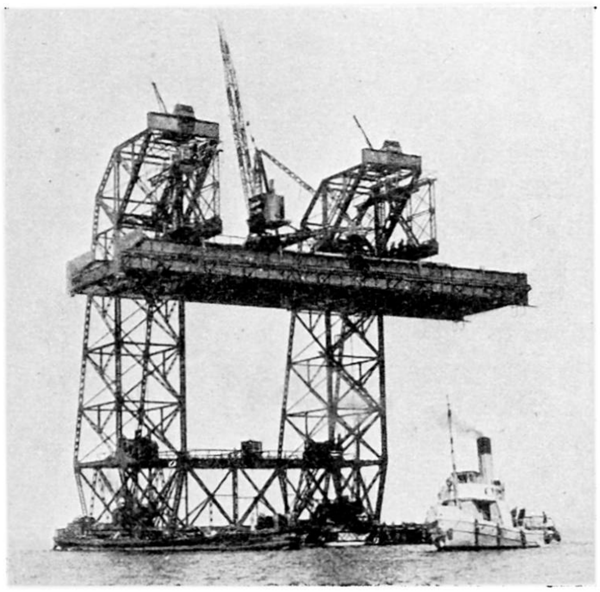

Fig. 10. Storstrom Bridge. Floating crane lifting 500-ton side span complete with erection crane on it

The main spans on this bridge consisted of tied arches with plate girders 12 ft. deep in the deck. The plate girders were erected in halves by the floating crane and joined on a temporary trestle at the centre (fig. 11). The arch rib was then erected overhead

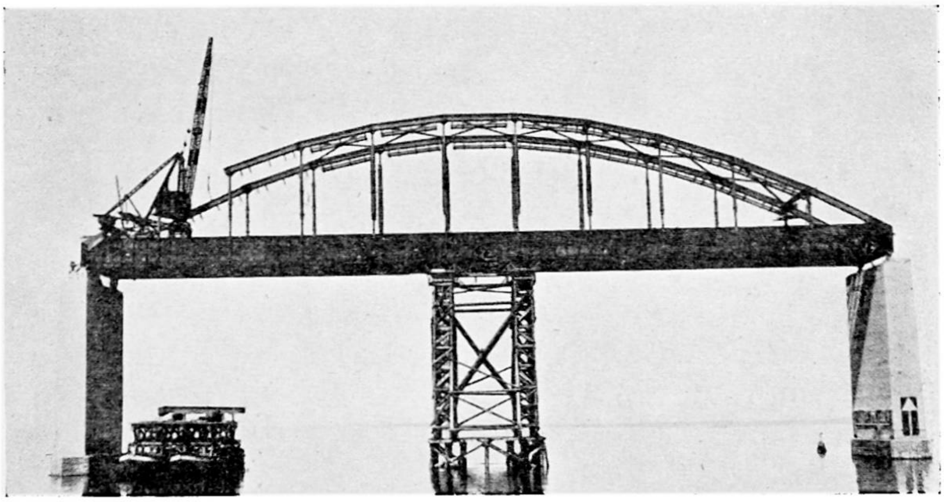

Fig. 11. Storstrom Bridge. Plate girders of navigation span assembled in two halves by floating crane and connected on temporary trestle. Arch rib and hangers erected by travelling crane

by means of a travelling crane running on the deck. This method enabled long-span plate girders to be erected on a bridge spanning deep water, and the arch rib to be built without using a creeper crane.

(3) *Blondins*

On certain sites, such as a gorge or river with good access only at one end, a blondin may be necessary to take the steel across the river or even to erect it. On the Birchenough Bridge a 7-ton electrically operated cableway was used alongside the bridge. Members were taken out on the blondin and transported to the crane in mid-air, a platform being provided for the erector around the cableway hook. The same blondin was subsequently used for the erection of the Otto Beit Suspension Bridge (fig. 7). Here it was assembled on the centre line and a large opening was provided in the tower bracing to leave space for it. The legs of the towers were erected by means of the blondin, two sections being assembled at a time, at the ends of a lifting beam which spanned the width of the bridge. Subsequently the blondin was used to erect the deck steelwork. The cross-girders and inner roadway-stringers were erected in sets of two each with only one bolt at each joint. This method of connection enabled the set to be folded up, as it were, so that it would pass through the opening of the tower. An erector was carried at each end of the cross-girders to make the suspender connections.

A blondin not only saves the necessity for a crane on the deck of a suspension bridge, but it also provides the means of laying out the stiffening truss along the whole length of the deck before erection (if the design permits this to be done) so as to avoid distortions of the cable.

ALL-WELDED BRIDGES

The development of all-welded trusses of substantial size is delayed by the following problems which have yet to be satisfactorily solved:

(1) Holding members securely in place during welding of the site connections.
(2) Making the correct allowance in advance for distortions that will occur during site welding. The distortion has to be correctly estimated and the

initial lengths of members predetermined. The assumptions made cannot be proved by pre-assembly in the shop, as they can in the case of a riveted truss; but unless they are correct the truss will not be true to line and level after welding.

(3) Carrying out prestressing, if desired, during erection.

These difficulties do not apply to plate girders in which splices can be satisfactorily welded at site.

A compromise sometimes adopted is to make all-welded members with the end connections reinforced and drilled for site bolting and riveting. This method has been adopted in New South Wales and found to be economic; it does not, however, overcome the difficulties but avoids them. Moreover some economy of the all-welded design is lost and the shop-work is complicated by both welding and drilling having to be performed.

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Summary

It is essential in order to get the best results and the greatest economy that the method of erection of any bridge should be considered when the design is prepared and that the design should be modified as may be necessary in order to conform to it. The historical background shows that difficulties in erection have in fact been one of the outstanding factors controlling the development of bridges.

In the paper, the various methods of erection and their effect on the design of bridges are considered. These methods include the use of falsework, floating out, service girders, cantilevering, rolling out and suspension. Numerous examples are quoted and reference made to suitability for prestressing and other requirements. Some alternatives are quoted to the more or less standard types of details used in

American suspension bridges, and reference made to their effect on economy in erection and design.

The various kinds of erection cranes are then dealt with, including creeper cranes on the bridge; cranes travelling on service girders or staging and floating cranes; and blondin cableways. The necessary capacity of the erection crane is considered and the desirability of keeping it as low as possible, by means of the provision of site splices in the heaviest members to reduce the maximum weight of lift. Examples are given of this and of the reinforcement that may be required in a bridge to enable it to carry the weight of the crane. The conditions under which floating cranes or blondins are necessary are considered and examples of the use of both are given.

In conclusion reference is made to the erection problems which have yet to be satisfactorily solved in the development of all-welded truss bridges of substantial size; and the compromise sometimes adopted of shop-welded members with end connections designed for riveting or bolting.

Résumé

Si l'on veut obtenir les meilleurs résultats et réaliser le maximum d'économie dans la construction d'un pont métallique, il est nécessaire de tenir compte de la méthode d'érection lorsque l'on étudie la conception même de l'ouvrage, cette conception devant être adaptée aux conditions d'érection. L'expérience montre que les difficultés de montage ont constitué l'un des plus importants facteurs qui conditionnent le développement des ponts métalliques.

L'auteur passe en revue les différentes méthodes d'érection et étudie leur influence sur la conception des ponts. Ces méthodes comportent l'emploi d'ouvrages provisoires, de supports flottants, de poutres de service, de montages en porte-à-faux, du roulage et de la suspension. De nombreux exemples sont cités et mention est faite de l'opportunité de la précontrainte et autres conditions. Différentes dispositions de détail plus ou moins normalisées sont signalées à propos de la technique américaine de construction des ponts suspendus, avec indication de leur influence du point de vue économique.

L'auteur présente les différents types d'appareils de manutention employés, y compris les grues se déplaçant sur le pont lui-même, ou sur des poutres de service, les grues échafaudées et les grues flottantes, ainsi que les blondins. Il indique la capacité à prévoir pour la grue de montage, ainsi que l'opportunité de la maintenir aussi basse que possible, en prévoyant tous dispositifs d'assemblage permettant de réduire le poids maximum à lever. Il cite des exemples, portant également sur le renforcement qu'il peut être nécessaire de prévoir sur un pont pour lui permettre de porter le pouds de la grue. Il expose les conditions qui nécessitent l'emploi de grues flottantes ou de blondins.

En conclusion, l'auteur signale les problèmes de montage qu'il importe de résoudre d'une manière satisfaisante en vue du développement des grands ponts en treillis entièrement soudés, ainsi que le compromis parfois adopté, consistant à prévoir des éléments soudés en atelier, avec assemblage par rivetage ou boulonnage.

Zusammenfassung

Zur Ermittlung der besten und wirtschaftlichsten Lösung muss die Montage-Methode schon bei den Entwurfsarbeiten für eine Brücke in Betracht gezogen werden und der Entwurf muss dem Montagevorgang nötigenfalls angepasst werden. Ein Blick in die Vergangenheit zeigt uns, dass Montage-Schwierigkeiten in grossem Masse die Entwicklung des Brückenbaus hemmten.

Der Verfasser betrachtet die verschiedenen Montage-Methoden und ihren Einfluss auf den Entwurf einer Brücke. Bei diesen Verfahren handelt es sich um die Verwendung von Lehrgerüsten, das Einschwimmen, den Bau von Hilfsträgern, den Freivorbau, das Einschieben und das Einhängen. Zahlreiche Beispiele werden aufgeführt und die Möglichkeiten der Vorspannung und anderen Massnahmen werden erwähnt. Einige Varianten für die mehr oder weniger vereinheitlichten Lösungen des amerikanischen Hängebrückenbaus werden angegeben und hinsichtlich ihres Einflusses auf die Zweckmässigkeit der Montage und des ganzen Entwurfs untersucht.

Anschliessend werden die verschiedenen Typen von Montagekranen beschrieben unter Einschluss von Laufkranen auf die Brücke selbst, Kranen, die auf Hilfsbrücken montiert sind, Derricks, Schwimmkranen und Blondin-Seilkranen. Das notwendige Tragvermögen eines Montagekrans wird untersucht und auch die Forderung, dieses so niedrig wie möglich zu halten, indem zur Abminderung des grössten zu hebenden Gewichts die schwersten Bauteile mit Montagestössen versehen werden. Dieses Problem und die Frage der Verstärkung einer Brücke zwecks Aufnahme der Belastung durch einen Kran werden an Hand von Beispielen dargelegt. Die Bedingungen, unter welchen Schwimmkrane oder Blondins zweckmässig sind, werden untersucht und durch Anwendungsbeispiele belegt.

Zum Schluss wird auf das Montage-Problem hingewiesen, das sich im Zusammenhang mit der Entwicklung von vollständig geschweissten Fachwerkbrücken beträchtlicher Spannweite stellt. Dieses Problem konnte noch nicht befriedigend gelöst werden. Auch der nicht selten gewählte Kompromiss mit in der Werkstätte geschweissten Stäben und verschraubten oder genieteten Knotenpunkten wird erwähnt.

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