

ECONOMICS IN ERECTION OF LONG SPAN CONTINUOUS BRIDGES

By

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Any profound discussion of economics on an engineering subject would necessitate a searching comparison of innumerable variables which individually or collectively may be considered with respect to the various solutions to be considered. The topic of this discussion, Economics of the Erection of Long Span Continuous Bridges, can only be handled in a superficial manner in this comparatively short paper, as it must be apparent to all that many aspects of the problem must be omitted from consideration unless this paper was to be expanded considerably. I will therefore limit my remarks to generalities in the hope that I can focus attention on a few basic principles which are fundamental. These principles applied to specific problems should help in determining if a continuous structure is the proper solution for the crossing in question. Consideration of erection processes for continuous structures can lead to no conclusions unless comparison is made with the normal erection processes applicable to other types of structures acceptable as solutions for the crossing under consideration.

Based upon types of construction, I have considered that three different ranges of span lengths might be appropriately considered within the scope of the topic. For instance, a deck-beam span composed of 36" wide flange beams continuous over piers spaced 50', 100' and 50' would come within the topic because continuity has enabled the designer to greatly extend the useful span range for this simple structural type.

Similarly, deck plate girder spans continuous over piers spaced 150', 300' and 150' come within the field of long span continuous structures because continuity has practically doubled the possible span length for girders, with the result that continuous girder spans of 300' can often be economically justified.

There is no defined limit on the length of continuous truss spans that engineers by the proper use of initiative and vision might devise, however, it is doubtful if continuous truss spans involving center spans of less than 300' could be economically superior to other solutions.

The previous remarks have been confined to structures continuous over four piers spaced respectively $\frac{1}{4}$, $\frac{1}{2}$ and $\frac{1}{4}$ of the total span length. For 2 or 4 span structures the upper limits of length for beam and girder spans would be modified in accordance with the established principles of economical span ratios.

For each type of structure described a different and overlapping series of types may be competitive from various considerations; thus, the continuous deck beam span might be considered in relation to a single truss span, simple girder spans, or single pony truss spans. The continuous plate girder spans may be considered in relation to simple truss spans, cantilever girder or truss spans, arch or suspension bridges. Continuous truss spans particularly in the upper ranges of span lengths would have to be compared with cantilever, arch and suspension bridges. The shorter spans might be compared with simple spans as well as cantilevers, arches and suspension bridges.

It is probably pertinent to ask what relation exists between the previous remarks and the economics of erection as related to long span continuous structures. The total cost of any bridge is so closely associated with the erection scheme, which in turn is subject to the available equipment and personnel at the contractor's disposal, that it is imperative that any economical design must consider every aspect, particularly since contracts are generally awarded on a competitive bidding basis.

An economical design must consider the possible methods of erection, but it must not dictate the erection scheme as such a restriction severely hampers the bidding fabricators in their efforts to best their competitors, and this, of course, is reflected in the ultimate cost. The erecting facilities of the various contracting companies are varied, and free use of the ingenuities of their personnel in devising erection programs based upon the equipment available and the conditions under which the work must be executed will invariably bring out some economy that the owner will benefit by, either in the form of a lower price or earlier completion of the structure with resultant convenience to the public.

It would be in order to here enumerate some of the most vital principles affecting the erection cost of any bridge structure, and we will then study each class of structure previously mentioned to see how these principles may be applied.

Principle I

Primarily the structure must be designed to permit orderly delivery of the material to the site by truck, rail or barge with the ultimate ob-

ject of placing each member in the structure with a minimum amount of handling and delay in transit from the shop to its final erected position.

The method of transportation is generally a clear problem in economics; however, the choice of the erection scheme is closely dependent upon the type of transportation. For large structures where water shipment by barge is available the erection scheme usually is based upon starting at a river pier and erecting all possible material by lifting direct from a barge anchored immediately below as the work progresses. Portions of the structure that are not over navigable water must be lifted to the erected bridge deck and transported by material trucks running on the floor stringers to the point of erection, and the traveler must be capable of reaching to the rear or side if the bridge is wide enough to lift the members from the trucks. There are innumerable factors that may restrict or prevent the use of water shipment for all parts of the structure. For illustration, truss spans over navigable waters with plate girder span approaches may involve girders of greater length than it is possible to swing through the trusses from barges on the river. In this case rail shipment might be necessary for these parts; however, this would imply setting up equipment to handle these parts from the rail cars at the yard or siding to trailer trucks for transfer to the site and either an additional rig to erect the approaches or dismantling and re-erection of the equipment used on the truss structure. Should the work involve a combination of girder approaches as previously described with an anchor arm or end span of a continuous structure adjacent but over unnavigable shallow water or marshes it may be advisable to ship the span or spans also by rail and to ship by barge only that portion accessible from the structure as the work progresses. If the structure is not too distant from the fabricating plant the parts that cannot be shipped by water may be shipped by truck to avoid the re-handling.

To convincingly illustrate the vital influence of transportation on design and erection, I would like to discuss two structures which I personally designed and a third which I designed jointly with a colleague. The first case was a continuous deck plate girder highway structure of 103', 168' and 108' designed to meet the requirements of a state highway department which specified the type of structure desired and fixed the span lengths, and in response to questions concerning the possible methods of shipment stated that the structure could be shipped by barge to the site, and that there were no limiting dimensions as far as shipment was concerned. After the design was completed it was

found that the locks on the stream in question could not handle barges large enough to carry the relatively modest size girders, and it was necessary to introduce several additional field splices in each girder to permit truck shipment over mountainous highways. If the shipping information had been accurate at the start of this job the highway department probably would have specified three simple through truss spans as the shipping would have been no problem and a more economical structure would have resulted.

The second case involved a continuous deck girder bridge over four piers spaced 125', 250' and 125', respectively. This was designed in 1937 and at the time it was about as long as any girder spans projected up to that time. It was contemporary with the Kentucky River Bridge at Frankfort, which I believe has the same span lengths. The choice of girder depths at the piers and the location of splices in the two 500' girders was promised upon the maximum size girder that could be brought through the shop doors of either of two fabricating plants located on navigable rivers permitting barge shipment direct to the site without dimensional restrictions.

It appeared virtually certain that only these two fabricators could bid on the structure; however, a third company which was over one hundred miles from a navigable stream was successful in obtaining the contract at a price substantially below their competitors. To illustrate the ingenuity of contractors in overcoming odds, they fabricated the deep portions of the girders, fitted them in the shop, and then disassembled the parts and shipped them to the site for assembly and riveting. The center span was erected on falsework mounted on barges, and it was then floated into position on the piers.

The third case involved a two span continuous skewed half through E60 girder span 393' in length, that is, two spans of 191'-6 each. This bridge was on the West coast where the freight rate was a vital factor, and clearances for rail shipment were of great importance. The main girders were designed of silicon steel to reduce the shipping weight and the net results of competitive pricing showed that the silicon steel continuous girder design saved the fabricator approximately \$10,000 over two skewed truss spans of 191'-6, and that the railroad saved a corresponding sum on the erection of the structure since the railroad erecting crew was enabled to erect the entire structure with a locomotive wrecking crane and one temporary wood bent.

These examples should clearly demonstrate that design must be clearly related to the methods of transportation and erection that are available and that an apparently clear economic advantage from the

designer's viewpoint can be easily lost or additional advantages may be gained when the fabricators have weighed the problem in the light of their own experience, equipment, and shop conditions at the time of bidding. Needless to say, these conditions may not be applicable to a similar problem at some other time since the variables are too numerous to be exactly evaluated in terms of any other solution.

Principle II

The erection program for any structure should if possible contemplate starting at that end where the material can be best received and continuing without delay to the other end of the structure erecting all structural material as the erection rig advances across the structure.

This factor is so important from an economy standpoint that fabricators often sacrifice the advantages of symmetry in symmetrical spans to achieve continuity of erection. This entails the preparation of approximately double the number of truss details since the complete articulation or erection order must first be established and details must then be made to show all erection clearances and gusset plates on the proper members. Changes in design of individual members in the vicinity of erection bents may affect certain members, but their mates by symmetry would not be affected unless the erection program is symmetrical. Successive passes of travelers over the structure to place floor decks or other material omitted to have dead load are time consuming and except in extreme cases are not to be considered if economy of construction is to be attained.

Principle III

The erection program must be consummated within a minimum over-all construction period with a minimum of equipment used a maximum amount of the time. Equipment which is used for a short time and then must be held in readiness for many months for a short time at the completion of the job runs up the expense charged against the job, and shipping and re-handling the equipment twice would likewise add expense. If an erection program involves several successive operations of starting at a pier with an auxiliary bent and erecting two travelers for balanced cantilever erection the expense of duplicating effort in dismantling and transferring equipment for re-erection, coupled with the increased length of time for completion, would indicate that either a different erection scheme should have been devised or that duplicate sets of equipment should have been furnished if the tonnage to be erected justifies this approach to the problem.

Principle IV

The erection scheme should, insofar as possible, be based upon a program that is applicable to the entire structure. Thus, schemes that involve entirely dis-similar methods for erecting similar portions of a structure cannot be economical. For the structure as designed there may be no other choice; however, this would be a clear indication that the structure was not economically sound regardless of how many pages of facts and figures could be assembled to prove that it was an academically economical solution. Unfortunately, the actual cost of the completed structure is the only measure of the economy achieved and since even comparative designs in the abstract do not duplicate bidding conditions, the only solution for determining comparative economy would be to simultaneously erect parallel structures with duplicate personnel and identical conditions. Even this would not be conclusive since numerous factors might aid progress on one type of structure and work at a disadvantage on the other. Therefore, we will have to rely on the experience and ability of engineers to properly evaluate the relative merits of the various factors involved, and realize that the contractor's bid price is his own shrewd appraisal of what he can do with the structure to successfully and profitably erect it at a price that is lower than his competitors' evaluations.

Principle V

The erection program should permit the orderly riveting of the parts of the structure already erected at an early stage, preferably while the individual members have stresses of the same character as they will carry in the completed structure, and without intermediate erection supports unless the entire structure is carried on falsework at every panel with camber blocking set at no load camber, in which case riveting may follow erection very closely.

Principle VI

An economical erection scheme cannot be evolved without considering the volume of design work required to develop it and the amount of delay that will result if the calculations are so extensive that the erection must be postponed until another season. From personal experience in both fields I can state without hesitation that development of an erection scheme for a major river crossing is a greater engineering task than the preparation of the original design.

Stresses must be determined for every member for dead loads, erection loads, wind loads, stability under ordinary and hurricane winds, water, ice, wind and debris loads on falsework bents and pile

cages, seam protection, study of every truss joint for erection stresses with pins and bolts at a lower value than the final rivet values, and in the case of balanced cantilever erection a rigid control of the sequence of operations and a careful check of stability under all conditions, such as loss of a traveler. Deflections vertically and horizontally must be computed for every point where support is furnished, and the range of movement required to land on successive piers and to release the jacks must be carefully computed to stay within the range of the equipment used. All increases in members to provide for erection stresses must be determined, and if the metal allowed to remain in the structure is excessive the final dead load stresses must be computed to see that no members are overstressed in the completed structure. The cambered length of every member must be calculated and the "no load" shape of the truss as cambered must be determined. A Mississippi or Ohio River crossing will often involve thirty or more structures that must be analyzed as described for the structure to be considered during erection, changes every time a new erection stage occurs.

Unless this work can be prosecuted while the detail drawings are being made and substantially completed in time to permit changes before fabrication, extensive delays will result.

Principle VII

All material added to the structure for erection purposes is added at the contractor's own expense as part of the erection scheme and whether it is allowed to remain in the bridge or removed, excessive amounts of such material can materially affect the resultant economy of the structure.

Sometimes certain members of the structure can be used temporarily as erection members, in which case they must be modified to suit the erection requirements, and then altered in the field to fit in the final structure.

For work in foreign countries and other places remote from the fabricator's plant this is a worthwhile means of saving shipping costs on material that would otherwise be scrapped.

Principle VIII

Erection schemes should contemplate a minimum of special jacking for adjusting shoes, closing truss spans, or weighing reactions. However, all necessary provisions must be predetermined and provided as an essential part of the scheme. Rolling operations and jacking of initial stress in bridge members, either axial or bending in character,

is expensive. Geometrical camber for dead load should be used to reduce secondary stresses in the completed structure.

Principle IX

The erection scheme selected for any structure must be safe, and no expense can be spared to see that it is safe under every possible contingency. To attain a proper degree of safety every operation must be considered from the standpoint of conservatism, and any spectacular or freakish schemes of questionable validity must be completely rejected. This does not mean that ingenuity and inventive enterprise are to be discouraged; however, it cautions against over-enthusiastic acceptance of schemes likely to prove dangerous or ill advised.

Principle X

Every erection scheme used must be clean cut and precise, in order that the bidder can properly evaluate his work to determine a bid price for doing the work, and that will enable him to complete the work within his estimate and to earn a fair estimated profit if he is successful in securing the contract. The securing of economically justified bid prices on succeeding work is directly dependent upon the continued success of the available contractors if the bids are to reflect true pictures of the technical progress that we are making.

We are now ready to see how these principles may be applied to the erection of continuous bridge structures of the three categories previously outlined.

Continuous beam span designs have offered desirable and highly practical solutions for crossings over medium-sized streams. Piers can be often founded on solid rock or suitable foundations can be furnished without difficulty. The fabricated material can be delivered direct to the site by truck either direct from the fabricating plant or the closest railroad siding. Erection is simple and can ordinarily be conducted from one end of the span. The beams can be handled from above by a crawler crane or any other suitable erection rig. Some sites will permit use of a crawler crane working from the stream bed. Some of these spans can be erected with practically no equipment other than false-work bents and stringers to permit rolling the beams across the opening for placement by manual labor using jacks to accomplish the lowering operation. The number of parts required to complete a crossing are reduced to a minimum because only one shoe is required under each girder at each of the intermediate piers, and the number of roadway expansion joints is reduced proportionately. This type of design in most cases would probably satisfy the entire group of ten listed requirements for economical erection.

Continuous girder spans have many of the advantages listed for beam spans; however, the increase in size for girders approaching the upper limits of feasible span lengths may easily conflict with the principles of erection economy. Contrasted with the shorter continuous beam span we find that this type of structure could be designed to completely satisfy all ten erection requirements or it could fail to completely satisfy any of them, although competitive types of structures for the same crossing and conditions might easily meet these requirements. It is apparent, therefore, that the designer must question the propriety of proposing a continuous girder span when the conditions for economy are not met.

The erection processes are, of course, more complicated because of the larger parts to be handled, and cantilevering may involve the necessity for hold-down devices at the end piers. The field of operations, however, is wide open for choice of delivery, erection equipment, and methods of erection. The greater latitude of choice, of course, makes it more difficult to choose the most economical solution for the erection of the structure, whereas simple truss spans might present a more obvious decision as to the best erection procedure that would satisfy all economy requirements.

Finally, designing for economical erection of long span continuous trusses requires consideration of all possible variables. It should be remembered, of course, that all other solutions for the crossing in question would probably be subject to the same or other difficulties of comparable magnitude.

For such crossings continuous structures as compared with cantilevers or simple spans may offer some apparent advantages. However, closure of center spans erected by cantilevering towards the center with adjacent spans as anchor arms would involve moving half of the structure longitudinally and tipping both halves by erecting the ends low. Closure of a cantilever structure under similar conditions may be effected by jacks at the hinge points and in the dummy members. In the case of cantilever erection of a simple truss span with adjacent spans as anchor arms the adjustment for rotation and longitudinal movement can be made at the temporary connections between the two spans. The economy of arches and suspension bridges would generally be based upon the foundation conditions, although good foundation conditions would also be favorable to a continuous structure.

The design of continuous structures that are virtually tied arches continuous with adjacent spans cannot be justified on an economy

basis because the requirement that special travelers operating from the top chords must ordinarily be used and because such a program ordinarily involves erecting the deck later.

For long span highway bridges the dead load stresses may have a four to one or greater ratio of dead to live loads and the resultant movement of the points of contra-flexure would be small since only partial live loads would affect the location of these points. Therefore, for highway spans a cantilever structure with the suspended span hinge points falling between the dead load points of contra-flexure will give practically identical stresses that would be obtained in the similar continuous structure, but erection problems may be more easily solved.

A specialized patented type of continuous structure known as the Wichert automatically adjustable continuous bridge provides for pier settlement and also facilitates erection adjustments. This type of continuous structure has considerable merit; however, it has repeatedly been my personal experience that much of the merit is offset by the expensive and complicated articulated rhomboid joints which are an essential, indispensable part of the design.

If a continuous structure is designed without a preconceived commitment regarding the erection scheme to be used, then it is quite possible that additional area in some members to provide for erection stresses may be required. If such is the case then the contractor should be required to reanalyze the structure on the basis of the revised sections to determine the true dead load stresses in the final structure, and to correct the design if the re-distribution of reactions affects still other members than those originally changed for erection. This would delay completion of the erection scheme and detail drawings and, of course, would be an added expense.

A summary of these remarks concerning continuous bridge structures would indicate that for beam and girder structures continuity can secure valuable results often at a considerable saving, while achieving the desirable appearance qualities so often obtained in continuous structures.

For intermediate length truss structures, continuity may secure economy of metal and appearance, but it is quite likely that the economy of fabrication will be lost in the field because the erection would be more expensive.

For long span continuous truss structures of monumental character the special provisions required may be quite justified, particularly if a pleasing outline is desired and it is felt that a cantilever structure would not meet this test. Certainly, however, in this case suspension

bridges and arches would have to be considered in relation to their respective merits before a decision could be reached.

The final emphasis must be made on the fact that any structure to be truly economical must be designed to permit adoption of an erection scheme of the contractor's choice, and that it must conform with as many of the principles of erection economy as the site conditions will permit. Under those conditions the completed structure will remain as a monument to the skill and ability of the men responsible for its design, and if beauty of line is also achieved the structure will be a true credit to the profession.