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Space Frame Action and Load Distribution in Skew Bridges

Comportement tridimensionnel et distribution des charges dans les ponts biais

Räumliche Tragwirkung und Lastverteilung in schiefen Brücken

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Introduction

The usual method of calculating the stresses in the different parts of a bridge is to split it up into a group of vertical and horizontal plane frames and trusses acting independently of each other, the vertical loads being taken by the vertical main girders, the horizontal loads by the horizontal wind bracings and then transmitted through the transverse frames to the bearings of the bridge. In reality the whole bridge acts as a space structure; the vertical loads produce stresses not only in the main girders, but also in the wind bracings and transverse frames. In case of a skew bridge, the effect of the space frame action is much greater than in the case of a square bridge on account of the much greater twisting moments produced at the end transverse frames.

The object of this research is to investigate how skew bridges with two or more main girders connected rigidly together by cross frames and wind bracings will behave if they are treated as space structures. The results of the space frame calculation are compared with those obtained by the ordinary method and it has been found that the design of a safe skew bridge should be carried out as a space structure. Furthermore some types of square bridges are treated as space structures in order to compare their behaviour with that of skew bridges.

Space Frame Method of Calculation

The space structure is considered to be composed of several plane frames or trusses connected together at their lines of intersection. Along these lines the plane frames or trusses will act mutually on one another. The corresponding actions and reactions are called edge forces, since their lines of action in the case of plane frames with negligible lateral stiffness coincide with the edge. After the determination of these edge forces, the calculation of the space frame is carried back to the calculation of several plane frames or trusses loaded by external forces and edge forces in their own planes.

The general shape of a bridge with two main girders, an upper and a lower wind bracing, and two end cross frames, is a closed polyhedron. If the main girders are trusses or plate girders with parallel chords, the polyhedron will possess six surfaces and twelve edges. For the equilibrium of each plane surface of the polyhedron, the external loads and edge forces acting upon this surface must satisfy the three conditions of equilibrium in the plane. If the bridge is supported by means of four vertical and three horizontal reactions, the total number of unknown reactions and edge forces is $7+12=19$, the number of equations of equilibrium is $6 \times 3 = 18$, and therefore the space frame is once statically indeterminate.

By eliminating one of the four vertical reactions, or by omitting either of the two end cross frames or one diagonal in the upper or the lower wind bracing, we obtain a statically determinate space structure. On the other hand, each additional cross frame increases the number of unknowns by one (4 edge forces and 3 equations of equil.) so that a bridge with two main girders, two wind bracings, two end cross frames and (n) intermediate cross frames, supported by seven reactions (four vertical and three horizontal) is $(n+1)$ times statically indeterminate. This means that the redundant edge forces can be obtained from $(n+1)$ equations. This is true not only when all the component parts of the bridge are statically determinate plane plate girders or trusses, but also when they are statically indeterminate ones, because the additional indeterminacy of the plane trusses can be calculated separately.

Furthermore, skew bridges are not symmetrical with regard to vertical planes, as are square bridges, but they can in most cases be made symmetrical with regard to a vertical axis through the centre of the bridge. By splitting up the acting vertical or horizontal loads into symmetrical and asymmetrical loadings, the number of redundant forces can be reduced by one half.

Skew Bridges with Two Main Girders

In order to study the effect of the stiffness of the end portals as well as the effect of the intermediate transverse frames on the stress distribution, four different cases of a single track railway bridge, Fig. 1, have been investigated:

a) A through bridge with two wind bracings and two end portals.
b) A through bridge with two wind bracings, two end, and two intermediate portals.
c) A deck bridge with two wind bracings and two end cross frames.
d) A deck bridge with two wind bracings, two end, and two intermediate cross frames.

The general arrangement and cross sections of members of main girders and wind bracings are the same in all four cases, but the stiffness of the end portals in the case of deck bridges is about 25 times greater than that in the case of through bridges.

All these bridges are supported by four vertical and three horizontal reactions and thus bridges a) and c) are once, while bridges b) and d) are three times statically indeterminate space structures.

In order to compare the behaviour of square and skew bridges as space structures, two square through and deck bridges with only two end transverse frames have been calculated. The influence line of the redundant edge force (Y) between the plane surfaces of the upper wind bracing and the end transverse frame, for the square and the skew through bridges, due to vertical loads moving either in the plane of one main girder or along the centre line of the bridge, are shown in Fig. 2.

In the square through bridge, the influence line for a unit load moving in the plane of one main girder has negative ordinates on the left half and equal positive ordinates on the right half. All ordinates of the influence line for an axle load of two tons moving along the centre line of the bridge are

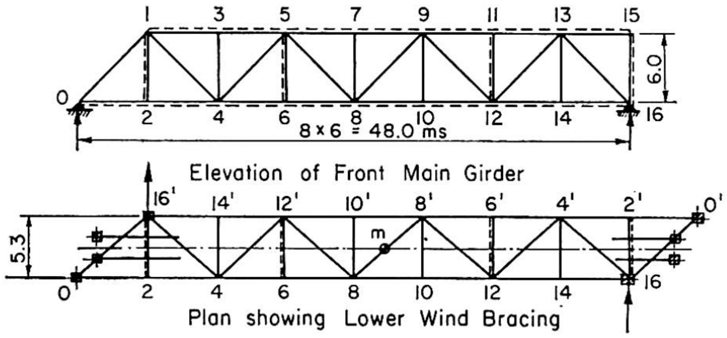

Fig. 1.

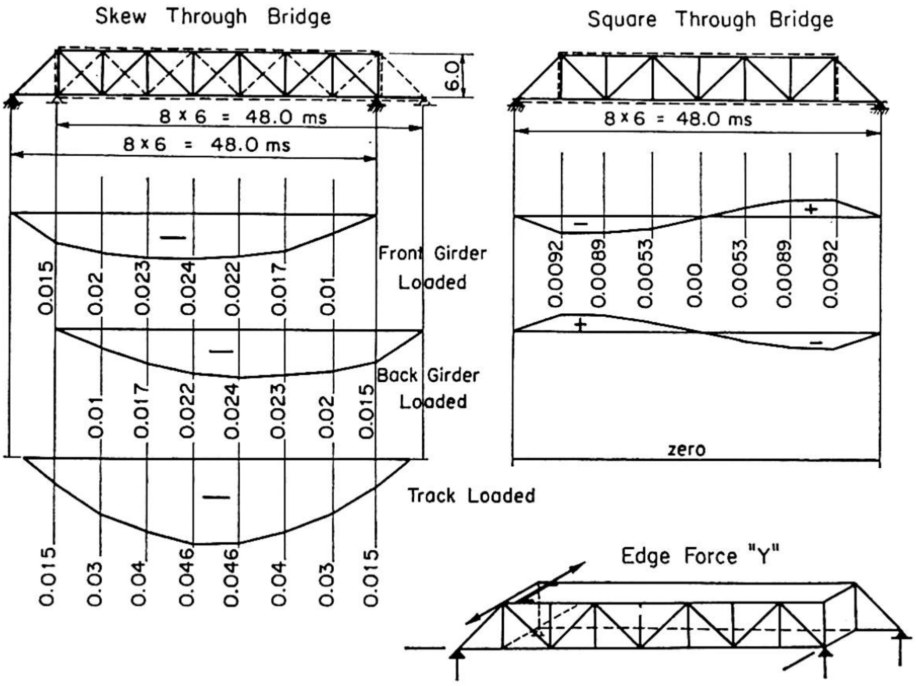

Fig. 2.

therefore zero. In the square deck bridge, the edge force Y for any vertical loading is negligible. In skew bridges, on the contrary, all the ordinates of the influence line for the edge force Y due to a load moving in the plane of one main girder have the same sign, and all the ordinates of the influence line for a load of two tons moving along the centre line of bridge are therefore nearly doubled.

It follows, therefore, that in the calculation of square bridges with two main girders, the space frame action can usually be neglected. It is only of a certain importance in double track railway bridges and roadway bridges subject to eccentric loading. On the contrary, in all skew bridges the actual forces in the main girders, wind bracings, and transverse bracings differ very much from those obtained by the usual method of calculation. In order to obtain a safe structure, skew bridges have to be treated as space frames.

Results Obtained for Vertical Loads

The influence lines for certain members of the skew deck bridges c) and d) for an axle load of two tons moving along the centre line of bridge, are shown in Fig. 3. The corresponding influence lines obtained by the ordinary method of calculation are also shown for comparison. The investigation of these

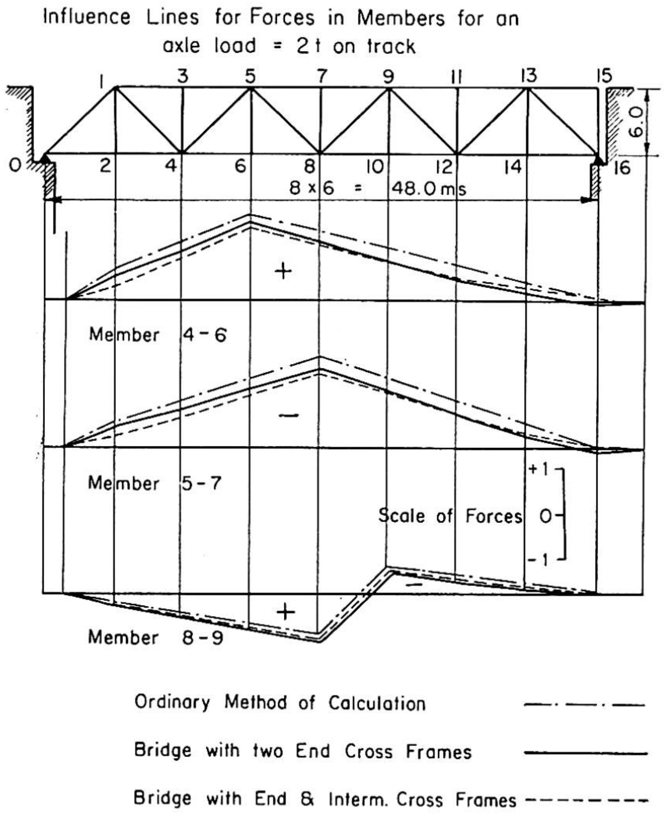

Fig. 3.

influence lines and the calculation of the deflections allow the following general conclusions to be reached.

a) Bridges with Two End Cross Frames

The maximum reactions for the skew deck bridge are increased at the obtuse ends by about 23% and reduced at the acute ends by the same amount. For the skew through bridge this deviation is only 11%. The forces in all the truss members except the diagonals near the obtuse ends are reduced. The greatest decrease is 32% for the deck bridge and 15% for the through bridge. The total forces in the diagonals of the end cross frames of the deck bridge are increased by 130%, while the stresses in the end portals of the through bridge are increased by 290%. A still greater increase takes place for the total forces in the diagonals of the two wind bracings.

By neglecting the space frame action in the calculation of such skew bridges, a considerable amount of material is wasted in the main girders. On the other hand, the wind bracings and end cross frames will not be safe, if they are calculated for wind loads only, as is usual, since they are subject to considerable additional forces due to the twisting moments at the end cross frames.

b) Bridges with Two End and Two Intermediate Cross Frames

The space frame calculation gives an additional reduction of the forces in nearly all the members of the main girders, and a corresponding increase in the middle diagonals of the two wind bracings. For vertical loads acting in the plane of one main girder, the decrease in the forces of that loaded girder is more pronounced than that for loads acting along the centre line of the bridge. The intermediate cross frames reduce the deflections due to vertical loads, thereby increasing the stiffness against vibrations due to moving loads. By increasing the stiffness or the number of the intermediate cross frames this effect can be improved.

Skew Bridges with Several Main Girders Connected Rigidly by Cross Frames and Wind Bracings

Two types of skew bridges with different angles of the skew have been investigated. Both bridges consist of four simple main girders of the plate-girder type, connected together by five rigid cross bracings as well as an upper and a lower wind bracing, Fig. 4. The bridges are symmetrical about the vertical axis through the mid point (m). In the first bridge the skew corresponds to the whole span, $\tan \alpha_1 = 12/7.5 = 1.6$; in the second bridge the skew is about 0.43 of the span, $\tan \alpha_2 = 0.686$. These bridges have been fully calculated as space structures when they are provided with the upper wind bracing only, and then with the upper and lower wind bracings.

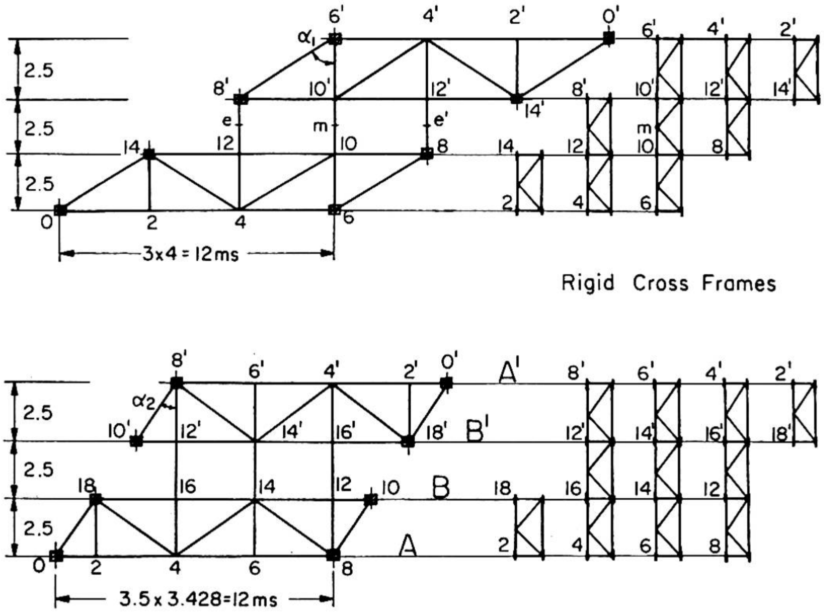

Fig. 4.

Bridge with the Bigger Skew

In this case the bridge is provided with an upper wind bracing only, and can be regarded as consisting of two separate statically determinate bridges $0-6-8-14$ and $0'-6'-8'-14'$ connected together by three intermediate cross frames e, m, e'. The system is statically determinate if the three intermediate cross frames are disconnected and is a nine times statically indeterminate space structure when they are connected. For symmetrical loading, the total number of redundant forces is only five, and for asymmetrical loading, the number of redundant forces is only four.

If the lower wind bracing is added to the above bridge, the structure will be a 13 times statically indeterminate space structure. If we consider the bridge with one wind bracing only as a statically determinate second main system, each of the diagonals of the lower wind bracing will correspond to a new redundant force, and therefore the total number of redundant forces is $9+4=13$. The second main system is four times statically indeterminate for any loading, and twice for symmetrical or asymmetrical loading.

Bridge with the Smaller Skew

The bridge with an upper bracing is nine times statically indeterminate for any loading. It will be five times statically indeterminate for symmetrical, and four times for asymmetrical loadings. In the bridge with two wind bracings, we have six new redundant forces which reduce to three for symmetrical or asymmetrical loadings.

Results Obtained for Main Girders

a) Bridges with one Wind Bracing Only

For the bridge with the bigger skew, for a full loading of the outside main girder (A), the vertical reaction at support 6 increases by 8% and that at support 0 decreases by 16% with regard to those found by the ordinary method of calculation. For the inside main girder, both end reactions are reduced by about 52% for a full loading of this girder. For the critical loading, the decrease in the vertical reaction at the acute end of the outside girder is only 6% while a very great increase of 87% occurs at the obtuse end. For the inside main girder both reactions are reduced by 25% and 18% at the acute and obtuse ends respectively.

The maximum bending moment for the outside girder of the bridge is decreased by 27% for a full loading of that girder, and by 18% for the critical loading. For the inside main girder the reductions in the bending moments are 55% and 27%, respectively.

For the bridge with the smaller skew, the results obtained for the reactions and bending moments range between those found for a similar square bridge and those for the bridge with the bigger skew.

In all bridges considered, the relief in the maximum bending moment due to the loading of one main girder is much greater for the inside girders than for the outside girders, owing to the fact that the two adjacent girders in the first case take a greater part of the load than the one adjacent girder in the second case. It is therefore recommended that the outside girders should be made stronger than the inside girders. This is not only favourable for equal distribution of the bending stresses over the four main girders, but also for the stiffness of the bridge. Furthermore, the maximum deflections in the outside girders will be reduced.

b) Bridges with Two Wind Bracings

The relief in the bending moment of the outside girders for the loading of one of these girders is about one and a half times as great as in the bridge with one bracing, and the inside girders are also slightly more relieved. The effect of the second bracing is much greater in skew bridges than in square bridges.

Results Obtained for Cross Frames and Wind Bracings

For a loading acting in the plane of the cross frame itself, the stresses in this cross frame are about 1.5 times greater than those produced in the adjacent cross frames. It follows, therefore, that all cross frames of the bridge are stressed, whether the load is acting in their own plane or in the plane of other adjacent cross frames, and it is incorrect to assume, that each cross frame is stressed only by the loads acting in its own plane.

The critical loading producing maximum compressive stress in the middle strut of these cross frames consists of a full loading of the inside main girders B and B', while that producing maximum tensile stress in the middle lower strut consists of a full loading of the main girders B' and A'.

These critical loadings are the same for bridges with one and with two wind bracings, but the second bracing has a tendency to increase slightly the forces in the cross frames of square bridges and reduce those in the cross frames of skew bridges. It is more favourable for the load distribution to make the cross frames as stiff as possible.

Comparing the critical forces in the wind diagonals of these bridges, the forces in these diagonals in the case of one wind bracing only, are less than one-half of those obtained in case of two wind bracings.

It follows therefore that the lower wind bracing will relieve the main girders and the cross frames of the bridge from part of the load, but the two upper and lower wind bracings will receive additional forces. The two wind bracings have an effect on the load distribution which is less than that obtained by arranging stiffer cross frames.

Conclusions

1. At the obtuse end of the outside main girders of all skew bridges, the reactions are very much greater than those obtained by the ordinary method of calculation. It is important to take this into consideration in the design of the abutments in order to avoid unequal settlement.

2. The more the skew of the bridge is increased, the greater is the reduction in the maximum bending moment in both main girders.

3. The position of the maximum bending moment is near the centre of the main girders of square bridges, but it is shifted towards the acute ends in skew bridges. The greater is the skew of the bridge, the greater is the shift of the position of the max. bending moment.

4. The deviations mentioned for bridges with one wind bracing are still more pronounced in cases where the bridge is provided with two wind bracings.

5. The bending moment and shearing forces in the cross frames increase considerably when the skew of the bridge becomes greater. In the bridge with the smaller skew, they are twice as great as, and in the bridge with the bigger skew five times greater than, the corresponding values in square bridges.

6. The forces in the wind diagonals are affected when the angle of the skew becomes greater. In the bridge with two wind bracings, the forces in the wind diagonals are five times greater than those of the bridges with one bracing in the case of the square bridge, and twice as great in the case of the bridge with the greater skew.

7. By taking into account the load distribution and space frame action in the design of skew bridges, a considerable amount of material can be saved in the main girders. On the other hand, the additional forces in the cross frames and wind bracings produced by vertical loads must be taken into consideration in the design in order to obtain a safe structure.

Summary

The object of this research is to investigate how skew bridges with two or more main girders, connected rigidly together by cross frames and wind bracings, will behave if they are treated as space structures. The author has found that by taking into account the load distribution and space frame action in the design of skew bridges, a considerable amount of material can be saved in the main girders. On the other hand, the additional forces in the cross frames and wind bracings produced by vertical loads must be taken into consideration in order to obtain a safe structure.

Résumé

L'auteur étudie le comportement tridimensionnel des ponts biais comportant deux ou plusieurs poutres maîtresses, solidarisées par des entretoisements et des contreventements. Il montre que l'on peut réduire considérablement les poids des poutres maîtresses lorsque l'on considère la distribution des charges et le comportement tridimensionnel de la structure; pour réaliser un ouvrage présentant toute sécurité, il faut bien entendu tenir compte des sollicitations supplémentaires des entretoisements et des contreventements dues aux charges verticales.

Zusammenfassung

Der Zweck der vorliegenden Arbeit ist, festzustellen, wie sich schiefe Brücken mit zwei bzw. mehreren Hauptträgern, welche mit Querrahmen und Windverbänden verbunden sind, als Raumtragwerke verhalten. Es wurde bewiesen, daß die Berechnung solcher Brücken unter Berücksichtigung der durch die räumliche Wirkung erzielten Lastverteilung zu einer erheblichen Materialersparnis bei den Hauptträgern führt; jedoch müssen die zusätzlichen Kräfte in den Querrahmen und Windverbänden, welche durch die vertikalen Lasten hervorgerufen werden, mit Rücksicht auf die Sicherheit der Konstruktion berücksichtigt werden.

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