Zeitschrift: IABSE congress report = Rapport du congrès AIPC = IVBH Kongressbericht

Band: 2 (1936)

Artikel: Observations on the design of new Belgian Vierendeel bridges of wide span

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DOI: https://doi.org/10.5169/seals-3349

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Observations on the Design of New Belgian Vierendeel Bridges of Wide Span.

Betrachtungen über Vierendeel-Brücken großer Spannweite, die vor kurzem in Belgien gebaut wurden.

Considérations sur l'étude de quelques ponts Vierendeel de grande portée construits récemment en Belgique.

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The Vierendeel girder has been adopted for many road and railway bridges. The most important of its applications under standard gauge railway lines are those recently carried out on the Belgian State Railways at Hérenthals over the Albert canal and at Malines, in connection with the electrification of the Brussels-Antwerp line. These works were completed in 1934 and are now in operation.

I. General description.

Hérenthals Bridges (Fig. 1).

The Hérenthals bridges form two series, respectively with double and single tracks, making three spans separated by concrete piers. In view of the considerable skewness of the crossing of the railway in relation to the axis of the canal, and to the desirability of using normal type of supports for the bridges, it was decided to adopt spans of approximately 90 m for the central opening and of 33 m for each of the side openings. It was also deemed expedient to adopt independent bridges carried on simple supports under each of the spans. The central openings are crossed by two straight bridges having their main girders of the Vierendeel type, the side spans by deck bridges with plate webbed girders under the track.

In order to limit the maximum width of the intermediate piers only movable bearings were provided on these, an arrangement which was only rendered possible by making the deck of the central span monolithic with those of the side spans in order to carry all of the longitudinal reactions onto the end abutments.

Malines Bridges (Fig. 2).

The two bridges at Malines were constructed one with a span of approximately 53.50 m over the Louvain canal, and the other with a span of about 90 m over the Malines-Louvain highway. These structures are in the electrified line between Brussels and Antwerp. They are of single span for double track. The main girders are of the Vierendeel type, those for 90 m span being similar to the corresponding bridge at Hérenthals.

II. Main Vierendeel Girders.

The Vierendeel girders for the Hérenthals and Malines bridges consist essentially of a parabolic arch with a rise of $^1/_7$ divided into eleven panels. Both were designed by reference to the same numerical tables. All the members of

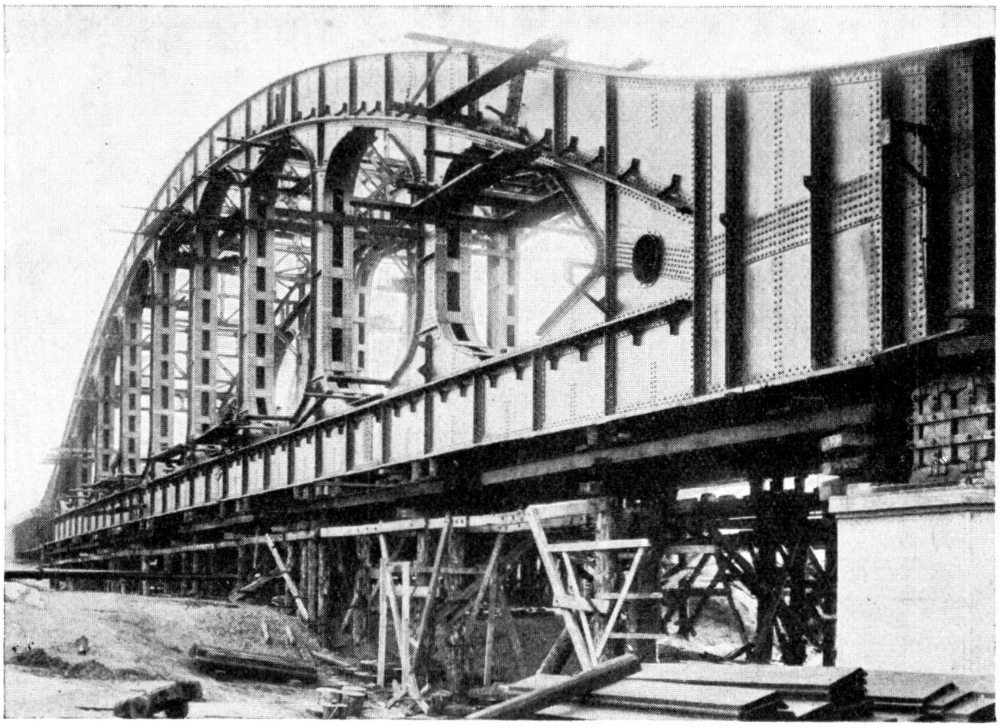

Fig. 1.

Railway bridge with Vierendeel main girders: movable bearing.

these girders are box shaped in section and are made sufficiently large to allow access to a workman for purposes of maintenance. In view of the necessity to take up bending moments in either direction the cross sections are double T; they are built up in the usual way from web plates, angles and flats. In the case of the 90 m bridge girders for the double track it was necessary to make use of special angle sections with legs 180 mm wide. As in ordinary box sections for lattice girders, cover plates have been provided only on the outside of the box, but in view of their width they are inserted between the two angles attached to the web plates and the free end is butted against the web to eliminate any tendency to bulging of the angle legs.

The verticals are, of course, run through the boxes which form the arch and the lower boom, thus making an exceptionally rigid framework. The erection joints for the verticals are made near the ends of the curved portions top and bottom and their exact position is fixed by the effective maximum width of the gusset plate. The web of the vertical is made continuous through-out the depth of the girder. It should be remarked that the arch sections and the tie sections are continuous from end to end of the girder, an arrangement which is justified if the whole is regarded as acting like a simple bowstring girder under a continuous uniform load.

The box bracing, interior diaphragms and cross bracings were subjected to very close study in detailing, in order to ensure the greatest possible rigidity without wastage.

The girder ends connecting the arch with the tie called for particularly careful investigation in view of the large sizes of plate to be used; it was necessary

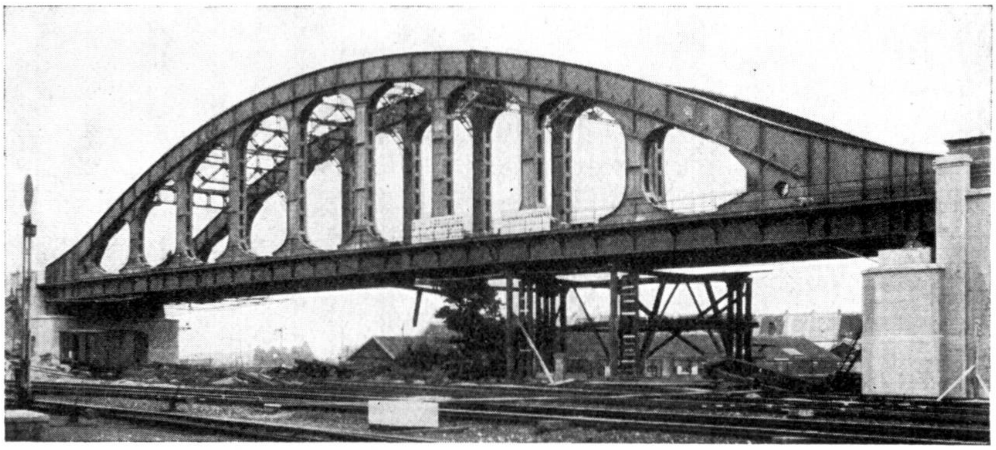

Fig. 2.

Railway bridge over the Louvain road at Malines. Elevation.

to limit the number of joints and provide a sufficient number of stiffeners, while at the same time allowing access for maintenance if required. The principle adopted is the provision of a horizontal diaphragm at an intermediate level with a series of vertical diaphragms pierced by manholes allowing access to any of the internal spaces.

Calculations.

The caracteristic of the Vierendeel girder with simple verticals is the absence of any diagonal members and the consequent elimination, according to its inventor, of those secondary stresses which are so harmful in lattice girders on account of the increase in total stress which they may entail and cause to be excessive. Without again entering upon the vigorous controversy on this subject which has been maintained from time to time it may be permissible to observe that freqently what are described as secondary stresses are merely primary stresses, the term being extended to include stresses due to eccentricities of connection which admit of precise calculation and which are the result of forces acting in the ordinary way. It would be better to reserve the term "secondary stresses" to stresses caused by deformation, such as tend to arise in a lattice system on account of the angular deformations due to extension and contraction of the bars.

It is obvious that if the deformability of the intersection points is increased to an extent which makes these approximate to pin joints such stresses will disappear, and the English expression "self relieving stresses" may properly be applied to them. This result may be attained through the play of the rivets or through the plasticity inherent in the gussets and in the bars. Such stresses, thus defined, play a minor part by comparison with that sometimes attributed to them. It should be added that all structures which deform more or less are exposed to these stresses, within limits that vary according to the degree of restraint imposed upon the free interplay of forces by the rigidity of the component elements. In a lattice girder, for instance, calculations and experiments agree in indicating that these stresses are practically proportional to the inertia per unit length $\left(\frac{I}{l}\right)$ of the element.

The present girders were designed in accordance with the simplified method explained by M. Vierendeel in his course on the stability of structures. From the tables of diagrams in this work the values of the shear forces at the points of intersection of the verticals and those of the bending moments in the booms and in the verticals were read off for each loaded panel point, these elements of calculation being applicable directly to all girders of the same ratio between rise and span and the same number of panels. When the girder is under uniformly distributed load covering the whole span the force in the arch becomes a simple compression along its axis and the tie bar is uniformly stressed in tension between its supports, while the verticals are in simple tension from the weight of the floor.

It is of interest to note that in the prismatic central portions of the boom the stressed calculated on the hypothesis of a live load over the whole span are greater than those which result from partial loading. The latter condition would be less favourable only in the case of curved connections between the verticals and the booms on the assumption that these are of prismatic section. On the other hand the design of the verticals is conditioned by bending stresses when the bridge is partially loaded.

If the bending moment diagram for a panel length of the boom is examined, this diagram having been plotted on the usual hypothesis of constant cross section over the whole length of the panel, it will be seen that for certain conditions of loading the point of zero bending moment may be either within the width of the vertical member or within the covered portion of the connections. Having regard to the great increase in section as between the verticals and the booms, and to the wide extent of these transitions, it seems unlikely that these points of zero bending moment (coinciding with the points of inflection) will be displaced much outside the prismatic central portions of the booms. At any rate it may be inferred that the initial assumption of a constant moment of inertia will lead to conclusions that must be accepted with caution proportionate to the extent of the transition in comparison with the prismatic portions of the verticals and the booms. The limiting case would be reached in a girder consisting of a succession of triangles touching one another at the central points of the booms and verticals. It is, therefore, difficult to ascribe any great accuracy to a method of calculation for a Vierendeel girder which does not take account of the variations of the moments of inertia due to the transitions, and it would appear that a simpler method of fixing the point of inflection in the prismatic portions of the booms *a priori* would give satisfactory results not necessarily more erroneous than are obtained by the method alleged to possess greater accuracy. Such a method has been devised by the German engineer Engesser and described by him in the Zeitschrift für Bauwesen in 1913. Engesser assumes that the verticals possess infinite rigidity, and he deduces from this that the points of inflection on the booms would be situated on the vertical line passing through the centre of gravity of each panel of the girder.

The fixing of fictitious hinges is immediately accomplished, and allows of a simple and rapid calculation of the different isostatic sections of the girder.

Relative calculations carried out to determine the stresses in a girder of about 100 m span for a railway bridge, single track, using the two methods of Vierendeel and Engesser respectively, indicate that the approximate method gives satisfactory results. It is only right to mention that before Engesser, M. Vierendeel himself hat pointed out a similar simplification applicable to girders with parallel booms.

It should be noticed that the ratio of the linear moments of inertia (ratios of moments of inertia to length) in the elements of the boom, to the corresponding figure for the verticals, is of basic importance in defining the action of a Vierendeel girder. The limiting conclusions can easily be ascertained by making use of the general relationship given below (due to *Keelhoff* in his "Cours de Stabilité"):

$$\frac{(I'c)^3 + I''^3}{(I'c + I'')^3}\left[H^3{}_n \frac{Z_n}{I_n} - H^3{}_{n-1}\frac{Z_{n-1}}{I_{n-1}}\right] = \frac{3\lambda}{2}\,\frac{H_{n-1} + H_n}{I'c + I''}\,(M'_n + M''_n)$$

Here a single panel of the girder is considered, with the heights of the verticals given by H_{n-1}, H_n and the moments of inertia by I_{n-1} and I_n. The normal width of a panel is λ, the moments of inertia of the upper and lower booms are assumed to be constant at I' and I''. The upper boom forms an angle φ with the horizontal for which $\cos\varphi = c$, and the lower boom is itself horizontal. If a section is taken through a panel along a vertical line passing through the centre of gravity, the bending moments in the upper and lower booms respectively are M'_n and M''_n, while Z_{n-1} and Z_n are the horizontal shear forces acting at the points of contraflexure of the verticals.

Recalling the fundamental hypotheses,

$$\frac{M'}{M''} = \frac{I'c}{I''} \quad \text{et} \quad \frac{h'}{h''} = \frac{I'c}{I''}$$

h' and h'' fix the position of the point of inflection in a vertical.

To disclose more easily the limiting conditions we will suppose that $I' = I'' = I$

$\frac{I}{\lambda} = \beta$ is the linear inertia of the lower boom,

$\frac{I_n}{H_n} = \frac{I_{n-1}}{H_{n-1}} = \alpha$ is the linear inertia of the verticals

$$\frac{1 + c^3}{(1 + c)^2} = K.$$

The general relationship takes the following form

$$H^2_n \cdot Z_n - H^2_{n-1} \cdot Z_{n-1} = \frac{\alpha}{\beta} \cdot \frac{1}{K} \cdot \frac{3}{2} (H_{n-1} + H_n) (M'_n + M''_n)$$

wherein the ratio $\frac{\alpha}{\beta}$ between the linear inertia of the verticals and the booms appears as a principal coefficient.

The limiting values of $\frac{\alpha}{\beta}$ are ∞ and 0, the value $\frac{\alpha}{\beta} = \infty$ or, reciprocally, $\frac{\beta}{\alpha} = 0$ corresponding to Engesser's assumption that the moment of inertia of the verticals is infinity. Applying $\frac{\beta}{\alpha}$ to the first member, the hypothesis $\frac{\beta}{\alpha} = 0$ implies M'_n and $M''_n = 0$ and since M' and M'' are of the same sign, $M'_n = 0$ and $M''_n = 0$.

We may infer that the sections of the booms on a vertical line passing through the centre of gravity of the panel are the sections of zero bending moments, whatever the loading. If nothing but the simple bending of the booms is considered, these sections will correspond to points of inflection. In the case of a girder of constant height these points will be situated at the centre of each panel.

The other limiting value $\frac{\beta}{\alpha} = 0$ corresponds to the case where the verticals possess zero inertia, as is practically the case in bowstring girders with thin suspension bars, and as would also be true of two parallel booms of equal inertia connected by vertical pin-jointed rods.

$$H^2_n \cdot Z_n = H^2_{n-1} \cdot Z_{n-1}$$

$$Z_{n-1} = Z_n \cdot \frac{H^2_n}{H^2_{n-1}}$$

Z_{n-1} has the same sign as Z_n the proportion being that of the squares of the height of the verticals.

Under the hypothesis of vertical loads $\Sigma Z = 0$.

In the case of a girder with parallel booms $\Sigma Z = 0$ which may be written

$$Z_n \cdot H^2_n \cdot \sum_0^m \cdot \frac{1}{H^2} = 0$$

and reduces to $Z_n = 0$. All the shear forces in the verticals are zero.

In the case of a bowstring girder with thin suspension bars the summation ΣZ_n includes a term

$$Z_o = Z_n \cdot \frac{H^2_n}{H^2_o}.$$

If $Z_n \gtrless 0$, H_o being zero, Z_o would be infinite.

Now, in this case the value of Z_o is determined and finite, as it corresponds to the horizontal component of the axial thrust in the arch. For Z_o to be finite while H_o is zero it is necessary that Z_n should be zero, a conclusion which brings us back to the ordinary definition of a bowstring girder with thin vertical members pin-jointed to the arch and tensile boom.