Arch Bridges
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STEEL TIED ARCH BRIDGES WITH FAN HANGER ARRANGEMENT

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Abstract. *In most designs of steel tied arch bridges the hangers connecting the arch to the lower chord are vertical. In the case of 2 bridges near Antwerp (Belgium) a particular arrangement with hangers converging radial to a centre located outside and below the structure's perimeter was developed. The concept has been evaluated and compared to the vertical hanger arrangement. A fundamental difference results from the fact that in a vertical section of the structure, both the lower tie chord tensile force and the horizontal arch compression force are unequal, since a portion of converging hanger forces contribute to the horizontal equilibrium. This results in unbalanced normal force and bending moment distribution. While varying several design parameters of the structure, and within the conditions of Eurocode design loads for road bridges, it is shown clearly that the unequal distribution increases with the bridge span, but stays moderate below 60 m span. No particular difference of this behaviour is obtained by varying the ratio of arch rise to its span. In addition, for a given value of the arch span, the number of hangers does not significantly affect the behaviour of the structure with radial hangers. However, the variations of stresses with traffic load in the hangers and tie chord of the radial arrangement are not significantly different from the vertical hanger arrangement. Hence, if fatigue resistance is becoming an important design criterion, as is often the case for medium size railway bridges, the converging radial hanger arrangement may be an interesting alternative. These conclusions enabled to design two bridges built near Antwerp. The arches and hangers are extremely slender, adding increased aesthetic value to both structures. After construction, the bridges are tested by highly-sensitive strain mesurements.*

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1 INTRODUCTION

Recent designs of tied arch bridges[i] show many variations of arrangements for arches as well as hangers, adding aesthetic value to these structures. One particular arrangement may be of interest for railway bridges. In this, the hangers are converging radial to a centre located outside the structure's perimeter, suggesting that the arch geometry would be circular. This will be referred to as the fan arrangement, in opposition to the classical vertical hanger arrangement. The centre of convergence where the axes of all hangers intersect is located below the lower chord of the bridge. In fact a tied arch with vertical hangers may be considered as a special case of fan hanger arrangements, the convergence centre being located at infinite distance and the radius of converging hangers being infinite. A small inquiry among interested people shows that a majority prefers this to vertical hangers, although this may be an instantaneous opinion among a technically interested audience. However, the fan arrangement introduces a rotating effect, obtaining a more dynamical view of the tied arch structure.

In the following, the effects introduced by fan arranged hangers, compared to the vertical hanger system are studied, while other bridge characteristic parameters are varied. All structures being considered are less wide than the bridge span, since only 2 traffic lanes or double track railway line will be considered. However, the extent of fan geometry must be quantified previously, since it determines the general view of the structure.

Considering circular arches, 2 radii may be distinguished, the first one being the radius of the circular arch R_a and the second one R_c the radius of converging hangers. By varying the ratio of R_a / R_c it is noticed rapidly that any visual effect of the radial orientation requires at least $R_a / R_c > 0.5$. The hangers may now be placed with constant central angle or at constant distance of intersection points with the lower chord. If the first system is adopted and R_a / R_c exceeds 1.3, the distance of hanger fixations to the lower chord becomes excessively unequal. These assessments were made for ratios varying from 0 to 1.5. In the application, described in section 3 the value of R_a / R_c was taken as 1. Fig. 1 shows various hanger arrangements, including vertical hangers and a negative value of the ratio R_a / R_c .

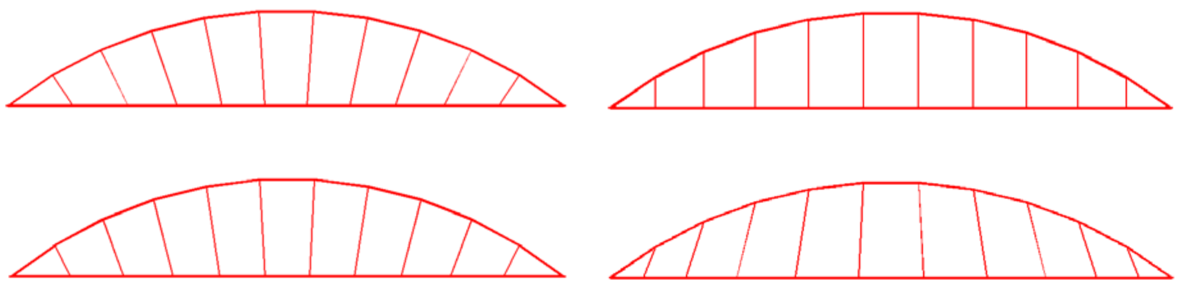

Fig. 1 : Various hanger arrangements and values of R_a / R_c

2 BEHAVIOUR OF ARCH WITH CONVERGING HANGERS

The case of a tied arch with vertical hangers is well known. The most critical section is located at a section at 25% of the arch span. Comparing the arch and the lower chord with converging hangers to the equivalent vertical hanger system shows clearly that the maximum bending moments are larger in the former case. In fact, the distribution of bending moments is significantly more unequal as in the case of vertical hangers. This fundamental difference results from the fact that in a vertical section of the structure, both the lower tie chord tensile force and the horizontal arch compression force are unequal, since a portion of converging hanger forces contribute to the horizontal equilibrium. This results in unbalanced normal force and bending moment distribution. Both quantities reach maximum values at sections close to the fixing points of the shortest hangers, whereas at mid span stresses are considerably lower than for the vertical hanger arrangement.

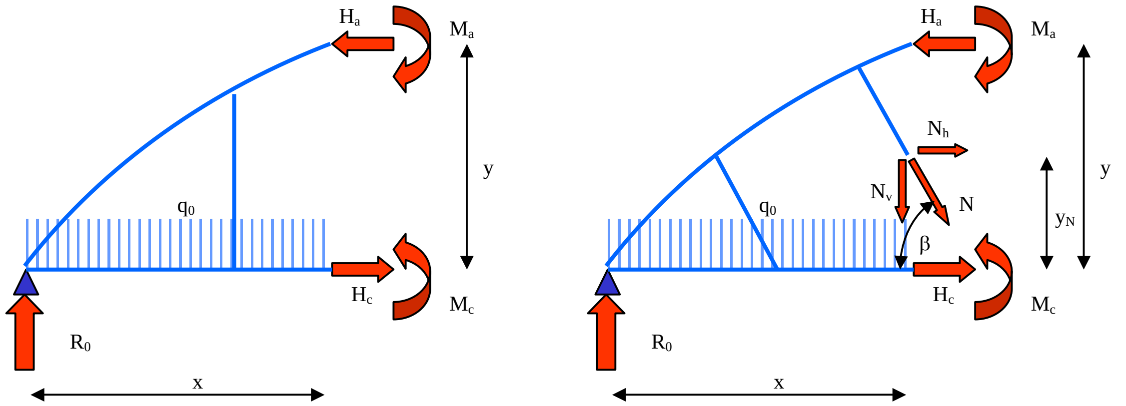

Fig 2. Equilibrium vertical hanger arch (left), fan arranged hangers (right)

Fig. 2 shows the equilibrium in a section through the second hanger. For the vertical hanger system and if H_a is the horizontal component of the arch compression force and H_c is the lower chord tensile force:

$$H_a = H_c \tag{1}$$

In the case of converging hangers:

$$H_a = H_c + N_h = H_c + N \cos\beta \tag{2}$$

Equally and assuming a homogeneous load q the total bending moment at section x equals:

$$M = R_0\, x - q_0\, x^2 / 2 \tag{3}$$

For the vertical hanger system the bending moment in the arch becomes:

$$M_a = M - M_c - H_c\, y \tag{4}$$

Whereas for the converging hangers:

$$M_a = M - M_c - H_c\, y - N\,(y - y_N)\cos\beta \tag{5}$$

From this expression follows that the bending moments for the fan arranged system are larger than for the vertical hanger case. This is displayed in figs 3 and 4, showing the normal force and the bending moments for uniform loading. Evidently, for this uniform loading, the tensile force in the lower chord varies as each node introduces a supplementary portion and the smooth pattern as for vertical hangers is disturbed. In addition, the bending moments in the lower chord have the opposite sign as for vertical hangers. The maximum values are slightly larger, whereas the minimum values are lower than in the case of vertical hangers. If more accurate design loads are used, the maximum bending moments are certainly larger for the fan arranged hanger system.

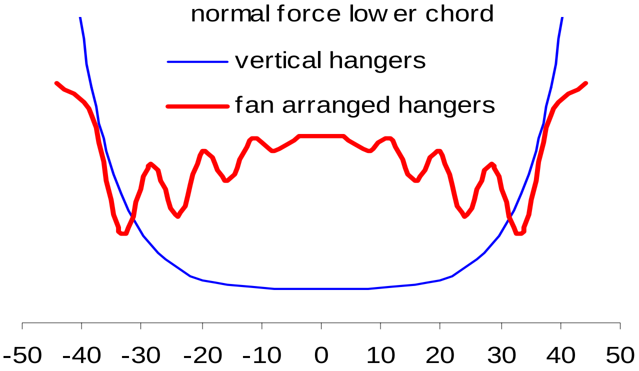

Fig. 3 Lower Chord Normal Force

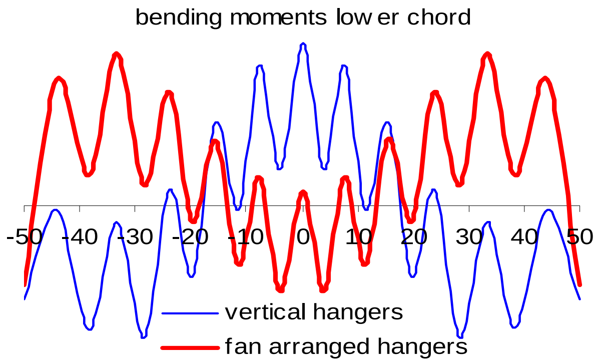

Fig. 4 Lower Chord Bending Moment

3 STRESS VARIATIONS AND FATGUE BEHAVIOUR

Having determined the general behaviour of the fan arranged system, it might be concluded that from the structural point of view, the load carrying capacity is inferior compared to the vertical hanger system. However, as the stress variations would be considered, and these being determined mainly by bending moments in both the lower chord and the arch, the envelope curves of maximum and minimum bending moments are shown in fig 5. Clearly, the vertical distance between the maximum and minimum envelope curves determines the stress variations. There is no apparent difference between the cases of fan arranged and vertical hangers. A series of calculations demonstrates that the fatigue resistance of both systems is almost identical. Consequently, for those structures where fatigue strength determines the structural performance, both types of hanger arrangements are significantly equivalent.

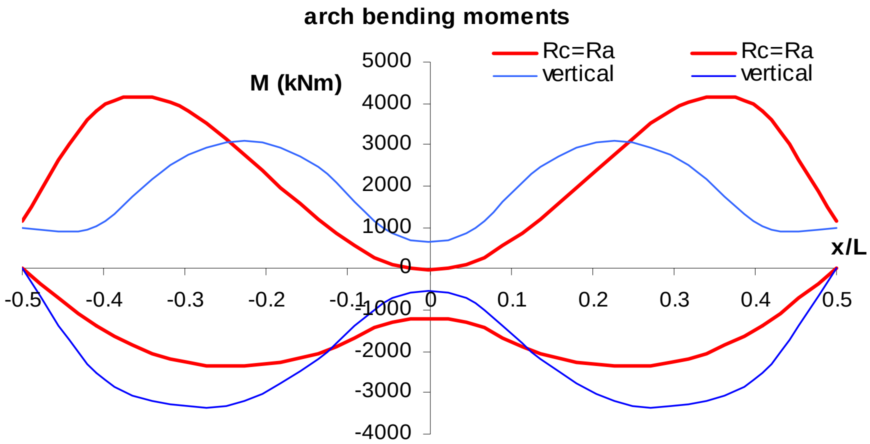

Fig. 5 Arch bending moments envelopes

Fig 6 : Fan arranged hanger system

In the case of 2 bridges, located on the high-speed railway line from Brussels to Amsterdam, at the North of Antwerp (see fig 6), fatigue resistance was the most important design criterion. Following the procedure of Eurocode 3-2[ii] maximum stresses in the lower chord reach 286.6 MPa, which is sufficiently below the acceptable value of 322 MPa for S 355 steel. However, the simplified fatigue verification procedure – the so-called λ-calculation method, shows equivalent stress variations of 113.4 MPa, whereas the detail category is less than 80 MPa. Hence, a detailed rainflow fatigue damage count was necessary. This requires to simulate the crossing of the bridge superstructure by 8 standardised trains as defined by Eurocode 1-2[iii] at appropriate speeds. According to the Technical Specifications for Interoperability of high-speed railway lines, the maximum speed must be increased by 10%. In addition, 12% of trains cross the structure simultaneously, whereas the target value of lifetime is taken as 100 years.

train type	nature	Number	speed (km/h)	fatigue damage
1	Passenger train	437406	200	0.110
2	Passenger train	437736	160	0.029
3	high-speed train	182979	330	0.042
4	high-speed train	182353	330	0.024
5	freight train	255556	80	0.210
6	freight train	438155	100	0.423
7	freight train	291787	120	0.086
8	freight train	219324	100	0.047

Table 1 : Fatigue assessment of lower chord

The use of the so-called ‘standard mix’ of types of trains is appropriate for high-speed lines. Table 1 displays the fatigue damage effect of the various types of trains. Evidently, freight trains cause far more fatigue damage than do high-speed trains, in spite of the lower speed. Should all traffic be high-speed trains, the fatigue damage becomes much less. The results of table 1 require previous calculation of mode shapes. In the case of the Antwerp bridges of fig 6, the first mode concerns the lateral displacements of both arches. The second, more relevant mode corresponds to a frequency of 1.57 s^{-1} and shows a full wave pattern of the superstructure. This corresponds to lower deformations at the span centre and lower stiffness at one quarter of the span sections (x = L/4 according to fig 5). In the case of vertical hangers, the mode shapes are closer to half-wave patterns.

4 ARCH STABILITY

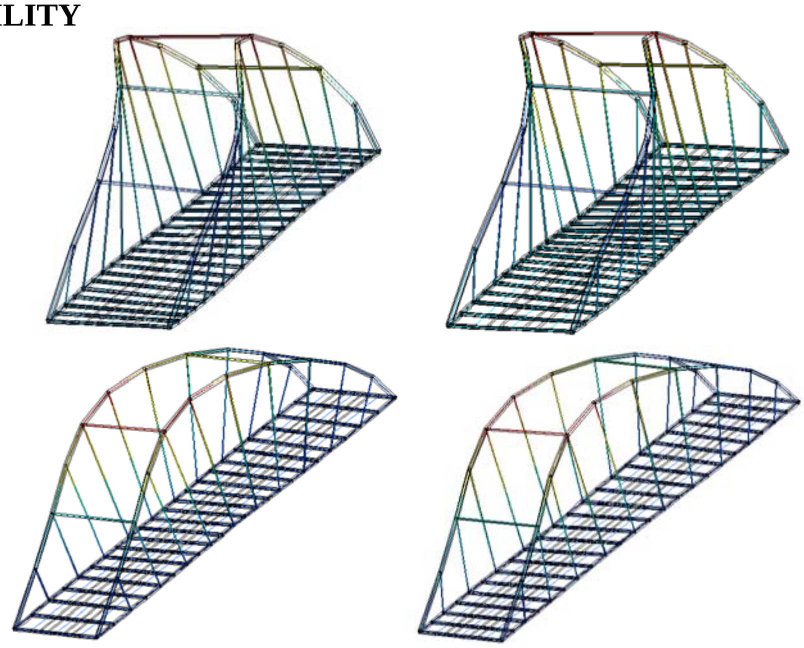

Fig.7 : Arch buckling shapes

Fatigue resistance of the arches is seldom an issue. Adversely, the stress state of arches is highly determined by buckling factors and the stability problem. If the vertical and fan arranged hanger system be compared, the buckling shapes show no fundamental difference for both cases. Fig 7 shows the first two modes for fan arranged (left) and vertical hangers (right). Each mode is determined principally by the lateral buckling of the arches, since the bracing is limited to a small number of tubes, as in the case of fig 6.

R_a/R_c	-0.66	0.00	0.80	1.00	1.06	1.23
N_{crit}	39925	40974	42444	42976	43444	43344
factor	0.97	1.00	1.04	1.05	1.06	1.06

Table 2 : Evolution of critical loads

To assess the influence of hanger convergence, the ratio of R_a / R_c may be varied for an identical arch. The critical arch compression forces from table 2 are then found. Clearly, the arch stability is practically unaffected by any of the adopted fan arrangements. This suggests that the recalling force from the hangers, preventing the arch from buckling, is almost identical. Heavier bracing may influence these results. However, calculations show that the conclusions above are still valid. Although extremely heavy bracing increases the critical arch compression force by a factor of 1.45, the values for fan arranged hangers, even for various ratios R_a / R_c are close to the value for vertical hangers. In addition, the buckling modes are very similar to the patterns of fig 7.

5 PARAMETRIC VARIATION

5.1 Fan radius

If the centre of converging hangers is varied, the radius also changes. The ratio R_a / R_c continues to be a relevant standard for comparing results. If R_c decreases, the effects described in section 2 tend to increase. Lower chord bending moment distribution becomes more unequal, whereas the bending moment variations in the arch decrease. In addition, the hanger force increases since at equal value of a vertical load V the hanger force follows the relation (referring to fig 2):

$$N = V / \sin \beta \tag{6}$$

In the former calculations the radial hangers are placed at equal angles on the circle circumference. This seems logical, since the distance between nodes on the lower chord is smaller near the arch springs as in the central part. This compensates the larger bending moments near the arch springs. If the nodes on the lower chord are located at equal horizontal distance, the bending moments increase and the surface below the influence lines of the central hangers increases too. Hence, the hanger force becomes larger. Calculations have shown about 8% larger hanger forces.

5.2 Arch rise

The rise f to span L ratio of arches varies between 0.14 and 0.20. For small values of this ratio, the arch compression increases. Similar to the arch stability, the value of f/L does not affect significantly the behaviour of both systems, as shown in fig 8. As the value of R_a / R_c varies, the curves for two values of f/L give almost parallel lines. This indicates that for a given ratio of arch rise to span, the radius of the fan arrangement has equal effect on the arch compression force and also on the lower chord.

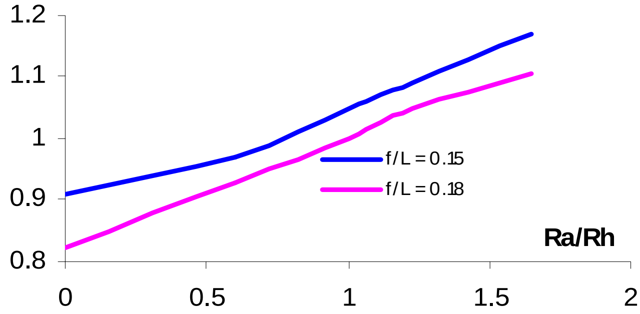

Fig.8 Evolution of arch compression with f/L

5.3 Span value

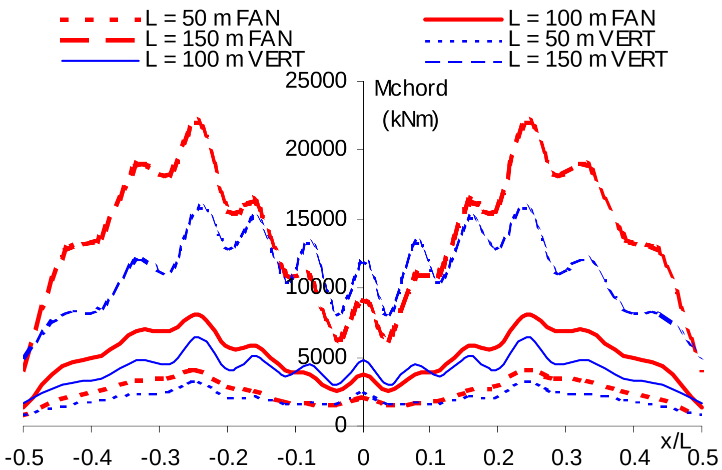

Fig.9 Influence of span value

As the absolute value of the bridge span is varied, bending moments in the lower chord of tied arch bridges increases. Again, comparing values for vertical and fan hangers, the bending moments of fig 9 are obtained. However, these are absolute values of bending moments, without any scaling effect. If the bending moments are divided by L^2, and looking at the results statistically, for the three values of L being considered the bending moments of fan arches is 16 to 20 % higher than for the vertical hanger system. This ratio increases with L. Hence, fan arranged hangers become less interesting for large bridges.

5.4 Numbers of hangers

As can be expected, variation of the number of hangers does not change fundamentally the different behaviour of fan arranged or vertical hanger arches. The stepwise distribution of bending moments and hanger forces still appears, with decreasing magnitude of these steps if the number of hangers increases.

6 FULL SCALE TESTING

In the case of the 2 identical railway bridges earlier mentioned (see fig 6), strain-measurements are done to test the bridge and verify the design. After constructing the concrete deck (as part of the design) and prior to the ballast and track installation, assessments are made with a number of heavy lorries. In both cases, longitudinal and transverse stresses in the arches, the lower chords and the hangers are measured in 10 positions of the heavy lorries (see fig 10). The results of the strain-measurements in the arches of the 2 bridges and in 3 positions of 9 till 10 lorries, are examined.

Fig.10 full scale tests of the railway bridges near Antwerp with heavy lorries

The graphs in fig 11 show the calculated (red column) and measured (blue column) longitudinal stresses on the left and the right side of the upper flange (σ_{upleft} and $\sigma_{upright}$), as well as on the left and right side ($\sigma_{lowleft}$ and $\sigma_{lowright}$) of the lower flanges of the arches. The measured values approach closely the estimated values. Remarkable is the fact that the measured stresses on the left and right side of the upper flange are not equal. In the design calculations, transverse moments can be neglected, thus making equal the stresses on the left and right side of the flanges. The measured stresses in the lower flanges of the arches affirm this conclusion. Obviously, the differences can be explained by the out-of-plane arch imperfection. In this particular case, severe measurements are making it possible to asses a maximum arch imperfection and to verify the design buckling curves according to EC 3-2, taken into account silently the existence of arch imperfections. The authors are starting a research concerning real arch imperfections by highly-sensitive strain measurements.

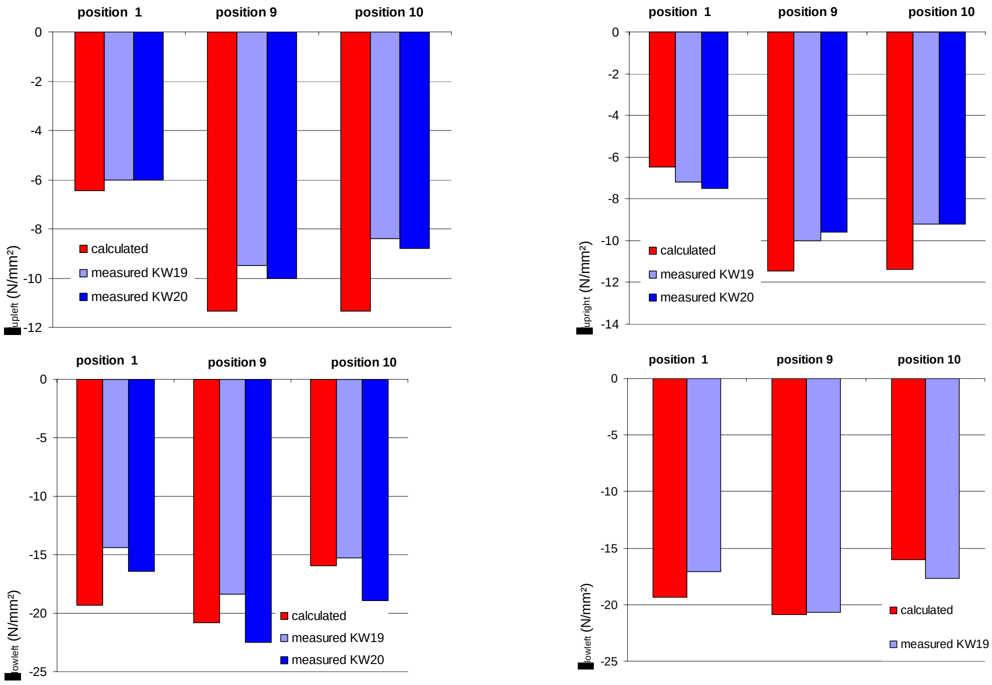

Fig.11 Longitudinal stresses at upper (above) and lower flange of the arches

7 CONCLUSIONS

Arch structures with fan arranged hangers show larger bending moments both in the lower chord and in the arches, when compared to an equivalent vertical hanger system. However, for small to medium span bridges this difference can be neglected, as the stress variations are almost identical. Hence if fatigue becomes an important design issue, both compared systems are equivalent. These conclusions are verified by a wide variety of calculations, with a series of values of R_a / R_c. From the aesthetic point of view, the value of R_a / R_c should be taken between 0.5 and 1.3. The design of the two high-speed railway line bridges near Antwerp was based on the results of this research. After construction, the bridges are tested by highly-sensitive strain measurements.

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