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Timber arch bridges with V-shaped hangers

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Abstract

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Abstract

The arch is a very efficient load bearing structure, especially when its shape is affine to the funicular of forces. However, if live loads are predominant as compared to permanent uniformly distributed gravity loads, the arch will be subjected to substantial bending moments, thus losing a great part of its structural efficiency. In traditional arch bridges with hangers arranged in a vertical manner, asymmetrical loads would cause a substantial deviation of the pressure line from the axial line of the arch. In this paper, an innovative concept for timber arch bridges is introduced where V-shaped hangers, rather than vertical hangers, are used. The adoption of V-shaped hangers significantly contributes to the reduction of the eccentricity between the pressure line and the axial line of the arch, thus decreasing the magnitude of bending moments in the arch. The paper discusses the advantages of using V-shaped hangers as an alternative to vertical hangers, both in terms of statics, in-plane stability and dynamic efficiency. Moreover, the design and the recent construction of a parabolic three-hinged arch made of timber, with a steel V-shaped hanger is thoroughly discussed in the paper.

Keywords: Arch bridges; timber structures; V-shaped; buckling; vibrations

1 Introduction

During the last centuries, different types of arches have been widely used. Statically arches are among the most efficient structural forms. Moreover, the undisputable aesthetic qualities of arches and the way they often assimilate into a landscape are additional characteristics that make arch bridges a rather common choice, especially when the span is such that beam bridges would not be suitable. Arches are often built out of timber and/or steel, even though members made of these materials tend to be slender and thus prone to instability when loaded in compression. Hence, concrete would appear to be a more appropriate material for arches. However, timber and steel possess other advantages; in particular, their low self-weight and speed of erection are indisputably advantageous during construction. The low self-weight allows the cranes that are needed on site to be relatively small, easily manoeuvrable and inexpensive. Moreover, timber has the advantage that it can be economically shaped into curved shapes – unlike steel and concrete. The choice of deck position is largely dictated by the local environment in which the bridge will be placed. An upper deck is often advantageous when crossing a deep gorge, against the sides of which the arch can be supported, while for crossing a river, a road or a railway in a relatively flat terrain, an arch with a lower deck is often more appropriate.[1] Timber arches are typically designed with three or – at times – with two hinges. From the structural point of view, two-hinge arches are superior to similar three hinge systems because the former are stiffer and also statically more efficient when subjected to asymmetric loads. Yet, the three-hinge arch is the most common among timber arches, due to its easy erection and insensitivity to movements, such as those provoked by support settlements or/and moisture changes. Timber arch bridges are typically designed with single rectangular massive members for spans up to 50-60m. However, single massive members would become unsuitable for larger spans because the cross-sectional dimensions would become too large. Therefore, for spans larger than 50-60m trussed arches are typically used because of their higher structural efficiency. Moreover, due to their particular geometry, trussed arches with two or zero-hinged configurations can be manufactured in a relatively straightforward manner.[2] For all forms of arches - other than those that are tied- a large horizontal thrust must be taken by the foundation. This is the reason why arch bridges are most suitable when the ground has good strength properties, particularly when the arch can be founded on rock.[3] When the stress conditions of the foundation need to be improved, a composite structure can be selected, as for example, a V-shaped rigid frame composite arch bridge. This type of structure balances the horizontal thrust of the skewback by adjusting the dip angle of the outside inclined leg. [4]

The ratio between the total rise of the arch and the span is an important parameter. The lower the ratio, the greater the flexibility of the bridge. However, a too high rise would increase the usage of materials and thus the cost of the bridge. Moreover, it would often indulge the appearance of an arch bridge. A rise-to-span ratio between 1/7 and 1/5 is often chosen, for both pedestrian and road timber arch bridges. The depth-to-span ratio of typical timber arches lies between 1/50 and 1/40, but it can be significantly reduced for particular arrangements of the hangers, as the one presented in this paper. Most timber-arched bridges are designed with vertical hangers typically consisting of steel rods. Each rod is attached to the arch at its top and to a cross girder at its bottom – the cross girders having the function of supporting the bridge deck. This paper discusses the advantages of using inclined hangers rather than vertical ones, with particular emphasis on vertical stiffness, in-plane buckling and vibration issues. A practical example of a recently erected timber arch bridge with inclined V-shaped hangers is thoroughly debated.

2 Increasing the efficiency of the arch by using inclined hangers

The spacing and any inclination of the hangers are important parameters to consider during the design of an arch bridge. In addition to affecting the appearance of a bridge, these parameters also influence the stiffness and the dynamic properties of the bridge as well as the resistance of the arches to in-plane buckling.

When subjected to a uniformly distributed load, the structural behaviour of arch bridges is not significantly affected by the inclination of the hangers. However, the discrepancy in behaviour becomes obvious when the load has an asymmetric character, as it is in the case of typical traffic loads. Asymmetric loads will make one side of the bridge to deflect more than the other, creating an antisymmetric deformed shape of the arch. In order to reduce excessive deflections and relative rotations of the arch – and consequently to reduce the bending moments – inclined hangers can be adopted. Typically, arch bridges with inclined hangers have been designed according to two structural systems: *i*) the Nielsen arch bridge, after the engineer O. F Nielsen, and *ii*) the Network arch bridge, proposed for the first time by the Norwegian engineer Per Tveit, see Refs. [5-7]. The substantial difference between these two systems is the number of intersections between hangers in the "web panel", which is zero in the Nielsen arch bridge and up to four in the Network arch bridges (Fig. 1).

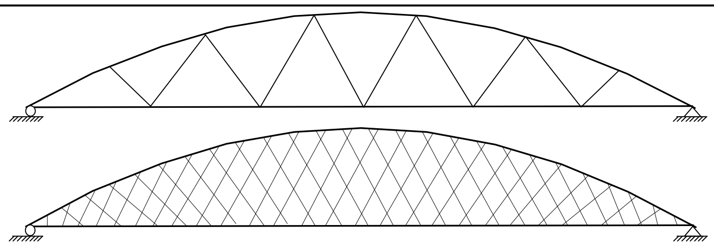

Fig. 1. *(a) Nielsen arch bridge and (b) Network arch bridge.*

Inclined hangers allow for the design of arches with very high slenderness and significant economy of material can be achieved. Erection can also be easier due to the very low self-weight of the structure. However, although arch bridges with inclined hangers are very efficient from the structural point of view, they present some shortcomings, the most important being the large number of attaching points at the end of each hanger. The devices used at these attaching points – which substantially behave as pins – tend to be rather costly, thus reducing the competitiveness of arches with inclined members. For the timber bridge discussed in this paper, a compromise between economy, efficiency (and aesthetics) was chosen. The proposed structure is an arch with four "V-shaped" hangers that are anchored *i*) to the timber arch at their top and *ii*) to a steel cross girder in the lower part. For a uniformly distributed gravity load, the behaviour of this system is practically identical to both that of all the previously discussed arch types. However, for asymmetric loads, larger bending moments occur in the proposed arch than in similar Nielsen or Network arches. Yet, these bending moments are significantly lesser than those that occur in a traditional arch with vertical hangers.

The main reason why bending moments in arches with V-shaped hangers are lesser than in similar arches with vertical hangers is illustrated in Fig. 2, where for the sake of uncomplicatedness, the asymmetric traffic load is simplified by a single concentrated load. For both cases of Fig. 2, a part of the concentrated load acting on the deck is transferred to the arch. Note that the part of the concentrated load that is taken by the arch depends on the ratio between the vertical stiffness of the arch and of the deck respectively. Typically, the deck of a timber arch bridge is rather flexible as compared to the arch, which means that the major part of the concentrated load is, indeed, taken by the arch. The main difference between the two cases is that, in the bottom part of the V-shaped hanger, a horizontal force "R" is generated because the deck tends to counteract the rotation of the hanger around an axis perpendicular to the plane of the arch. Considering the rotational equilibrium about an axis through a point of an arbitrary cross section of the arch located at a distance x from the springing point, it is obvious that the horizontal force "R" generates a bending moment (R·y) that lessens the bending moment generated in the same cross section by the external load "F". Understandably, the horizontal force "R" cannot occur in the case with vertical hangers. Thus, the bending moment in a generic cross section of the arch will be greater in the case of an arch with vertical hangers when compared to the case of a similar arch with V-shaped hangers.

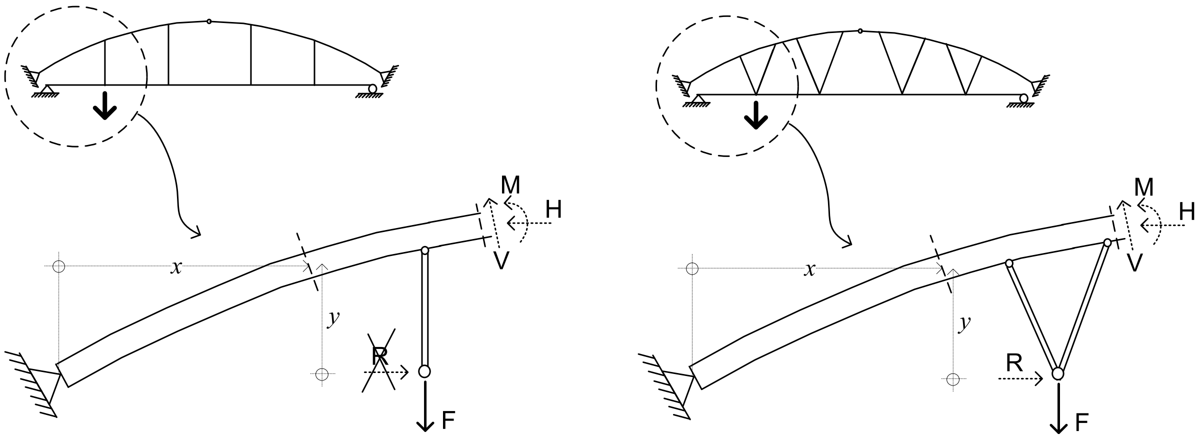

Fig. 2. *Bending moments generated in the arch by a concentrated load. Two cases: vertical hangers (Left) and (b) V-shaped hangers (Right).*

There is also another positive effect of using V-shaped hangers rather than vertical ones. In fact, in V-shaped hangers, the concentrated load "F" spreads out into two smaller loads, which have reduced the impact on the bending moment in the arch. Other important benefits of using inclined hangers involve buckling and dynamics issues. Figures 3 and 4 show schematic illustrations of the first (in-plane) vibrational mode and the first (in-plane) buckling mode, respectively, of two similar systems, namely two arch structures - one with vertical hangers and the other one with V-shaped hangers. In order to compare some mechanical properties, it is also assumed that both the arch and the deck of the two systems are identical both in terms of cross sectional dimensions and material. The span is L = 20 m and the rise is f = 3 m (i.e. 0.15 L) for both cases. Figure 3 shows schematically the first vibrational mode for the two systems. Considering only the self-weight of the structure in the computation, the first eigenfrequency of the system with V-shaped hangers is approximately 50% greater than the eigenfrequency of the arch with vertical hangers, indicating the better suitability of the V-shaped system for e.g. pedestrian comfort.

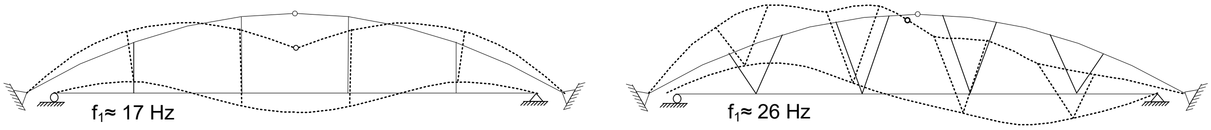

Fig. 3. First (in-plane) vibrational mode in the case of an arch structure with vertical hangers (a) and with V-shaped hangers (b).

Figure 4 schematically shows the first buckling modes of the two systems described above, when subjected to a uniformly distributed load.

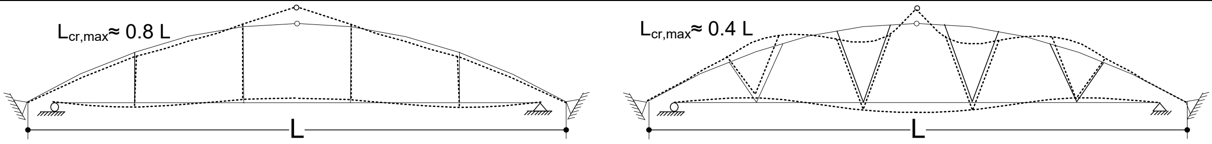

Fig. 4. First (in-plane) buckling mode in the case of an arch structure with vertical hangers (Left) and with V-shaped hangers (Right).

The critical buckling length of the system with V-shaped hangers is approximately one half the buckling length of the traditional system with vertical hangers. This results in a buckling load which is approximately four times greater in the system with V-shaped hangers as compared to the system with the arrangement that makes use of vertical hangers. Structurally speaking, the fact that the arch with V-shaped hangers is superior to the arch with vertical hangers could be predicted by looking at either the first vertical vibrational mode or the first buckling mode. In both cases, the modes related to the arch with V-shaped hangers, show a higher number of points of contraflexure than the corresponding arch with vertical hangers. The higher the number of points of contraflexure, the larger the strain energy needed to bend the structure - which in other words means: *i)* stiffer structure and *ii)* greater buckling load. The vertical stiffness of the two systems above also show large discrepancies. For example, for a concentrated load applied in the deck, at the attachment of the hanger closest to the support, the vertical stiffness of the system with V-shaped hangers is approximately 4.5 times greater than the stiffness of the system with vertical hangers. Regarding stiffness, vibrational and buckling properties, it is evident that the system with V-shaped hangers is significantly more efficient than the one with vertical hangers, thus allowing for slender geometries. Structural slenderness is not only advantageous in terms of material economy; it is indeed often pleasant from the aesthetical point of view. There are also some shortcomings in arches with V-shaped hangers, such as the slightly more complicated attachment devices, the introduction of axial forces in the deck, and the fact that compression forces may occur in some hangers for some particular asymmetric loading. However, the design compression forces in the hangers are generally small, especially when a heavy bridge deck is adopted.

3 The arch bridge at Vega-station

In March 2017, a new pedestrian arch-shaped bridge – made prevalently out of timber - was hoisted over the railway in the district of Vega, in the municipality of Haninge, located approximately 40 km south of Stockholm, Sweden. The municipality plans to build some 3,000 homes, supplemented with workplaces and necessary services and a new commuter train station. The homes and offices are located on both sides of the railway track. In order to make the flow of passengers work, it was therefore decided to build a bridge over the railway. The choice of the material was mainly due to issues related to the time needed for the construction, which is a factor that can significantly boost the total cost of the bridge; a long and invasive erection would have indeed caused costly disturbance of train traffic under the bridge. Timber structures can easily be preassembled, with a very high degree of prefabrication, thus allowing for rapid erection, with practically no traffic disturbance in the railroad. The choice of the shape of the bridge was mainly due to the span length. For a span greater than approximately 30 m, trusses or arches are commonly adopted. Here, the arch has the advantage that it can be more easily protected against weather. Besides lateral loads due to wind and longitudinal loads caused by vehicle breaking, the bridge in Haninge was designed to also resist a crowd load of 3.8 kN/m^2 or a service vehicle with a total weight of 120 kN.

3.1 The structural system

The load bearing structure of the bridge in Haninge consists of a Stress Laminated Timber Deck (SLTD) suspended to two parallel three hinge glulam arches via V-shaped steel hangers. The shape of the arches is parabolic with a rise-to-span ratio slightly greater than 0.15. The glulam strength class for all the members of the bridge is GL30c, according to the European standard EN14080.[8] All the steel members have grade S355, according to the European standard EN10027.[9] The main sizes of the bridge, along with the material and the cross-sectional dimensions are shown in Fig. 5.

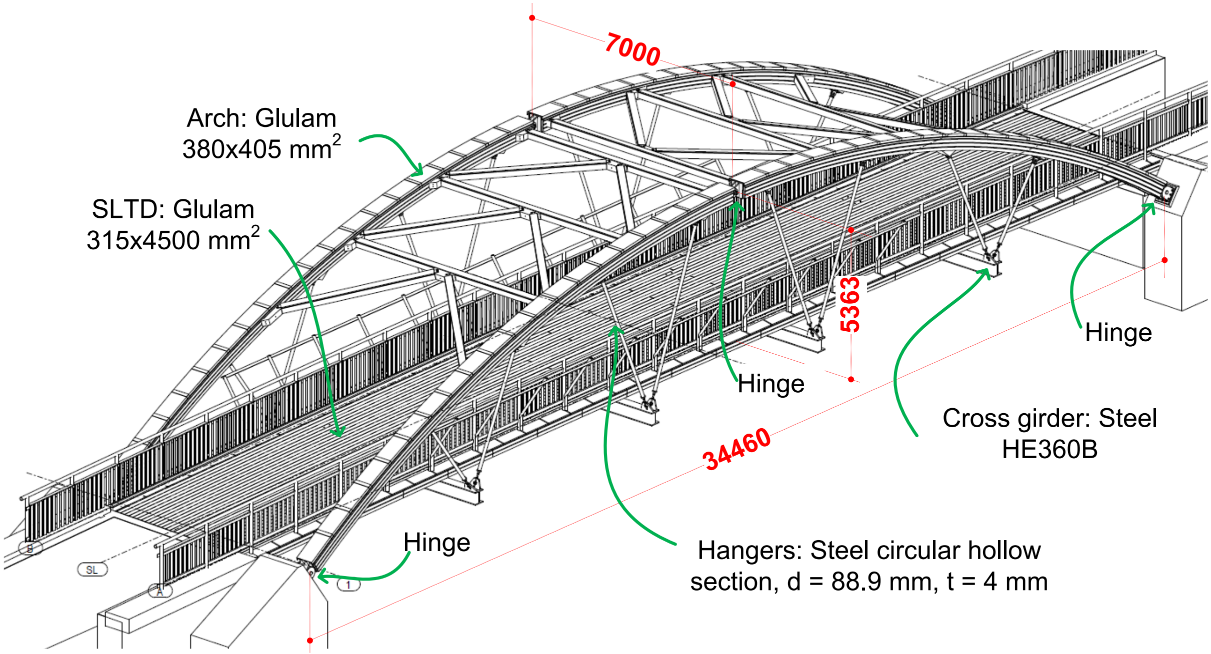

Fig. 5. Geometry, material and cross-sectional dimensions of the bridge.

Besides the risk of in-plane buckling, arches are also susceptible to buckling in the direction perpendicular to their plane. In order to reduce the risk of out-of-plane buckling, and also to resist wind loads, a K-shaped bracing was adopted for the bridge in Haninge. The members of the bracing consist of glulam members with a cross section of 190x180 mm^2. It should be remarked that the devices adopted at the arch springing (which indeed works as a hinge for in-plane rotations of the arches) also provides a rather significant degree of restrain for out-of-plane rotations of the arch. The SLTD of the bridge consists of a number of glulam beams with cross-sectional dimensions of 142x315 mm^2, transversally prestressed by means of high-strength steel rods of the same type used in prestressed concrete. One of the two deck bearings behaves similarly to a roller, whereas the other bearing behaves substantially as a fixed one. It is very important that one of the two bearings to be fixed. Otherwise, no horizontal forced would be introduced in the bottom part of the V-shaped hangers (see figure 5), thus resulting in a considerable reduction of structural efficiency. On the top of the timber deck, a waterproofing membrane is applied and on the top of it an asphalt layer. Altogether, the thickness of the paving is 85 mm. This type of paving – which in other bridge projects has proven to be very beneficial from the point of view of the durability of the deck – significantly increases the self-weight of the bridge (for the bridge in Haninge, the paving itself weights approximately 25% more than the STLD). As pointed out in section 1, the ratio between the cross-sectional depth and the span for arches with vertical hangers typically lays in the range 0.02 to 0.025. For the arch bridge in Haninge, this ratio is only 0.012 (i.e. 405/34460), i.e. merely one-half of the ratio typically adopted for similar arch bridges with vertical hangers. The main reasons why the Haninge bridge could be designed so slender are mainly attributable to the inclined hangers which – as explained in section 2 – significantly contribute to the reduction of the bending moment in the arch and also improve both buckling capacity and vibrational properties of the arch.

3.2 The weather protection

The bridge was designed for a service life of 80 years, according to current regulations of the Swedish road and railway administration. According to common Swedish praxis, all wood parts of the bridge consist of untreated glulam made out of Norway spruce. Untreated wood obviously needs to be protected from moisture in order to ensure the required durability. Therefore, a 5 mm waterproofing membrane was applied on the top of the deck to prevent moisture from penetrating into the wood from above. Then, an 80 mm asphalt layer was applied on the top of the membrane. The deck was also given a 2 % cross slope to provide a drainage gradient so that water will run off the surface of the deck. A piece of bent sheet metal that runs along the entire length of the deck on both sides transports the water away from the deck. A ventilated side panel made of 21x120 mm^2 board is used to protect the edge beams of the deck and the prestressing anchorage from rain and sun. The panel is fastened to the deck through wood block spacers. The prestressing bars and nuts are made out of galvanized steel (see Fig. 6).

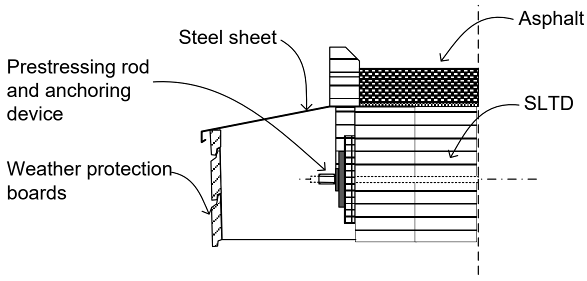

Fig. 6. *Details of the anchoring solution adopted for the prestressing bars and the weather protection implemented.*

The glulam arches were also covered with a ventilated wood panel. The top of the arches was covered with a coated steel sheet, see Fig. 7.

Fig. 7. *Weather protection of the arch. Ventilated wood panels are attached to the sides of the arch, whereas a coated steel sheet is applied on the top (not applied yet at the time when the picture was taken).*

3.3 Some details of the bridge

In this section, some details of the bridge are illustrated, namely: i) the hinge devices at the springing and at the crown of the arch; ii) the attachment devices of the V-shaped hangers. Generally speaking, it is very important that the boundary conditions hypothesized in the structural model strictly correspond to the boundaries of the real structure, otherwise there could be the risk that other load paths than those assumed in the model occur. Discrepancy between assumed boundary conditions and real boundary conditions could lead to severe underestimation of forces and moment in the structure, with risk for possible failure of the connections. This becomes a true issue when spans tend to grow bigger. The bridge in Haninge was modelled as a three-hinge arch. Therefore, the devices at both springing and crown were chosen to reflect “perfect” hinges as meticulously as possible. Figure 8 shows the hinge device at the springing of the arches. The pivot of the hinge is a steel dowel, with a diameter d=90 mm. In order to facilitate the erection of the bridge, the dowel is welded to the part of the steel hardware that is attached to the glulam arch. In order to take uplift forces, “lock devices” (not visible in the figure) are used. The hinge used at the crown of the arch is similar to that used at the springing, the main difference being that the diameter of the dowel is somewhat smaller (d=60 mm at the crown) and it is loose rather than welded to the steel hardware, as in the case of the springing. The steel hardware at the crown of one of the arch-halves, where the steel dowel is to be inserted, is shown in Fig. 8.

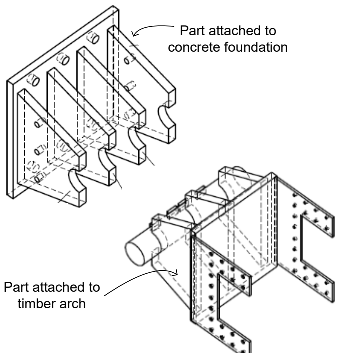

Fig. 8. Hinge device at the springing of the arche.

In the design of hanger attachments – besides striving to adhere to the hypothesized boundary conditions in the structural model as strictly as possible – it is also important to have the possibility of adjustment, especially in the vertical direction. For this purpose, a special attachment device was developed for the V-hangers of the arch bridge in Haninge (see Fig. 9).

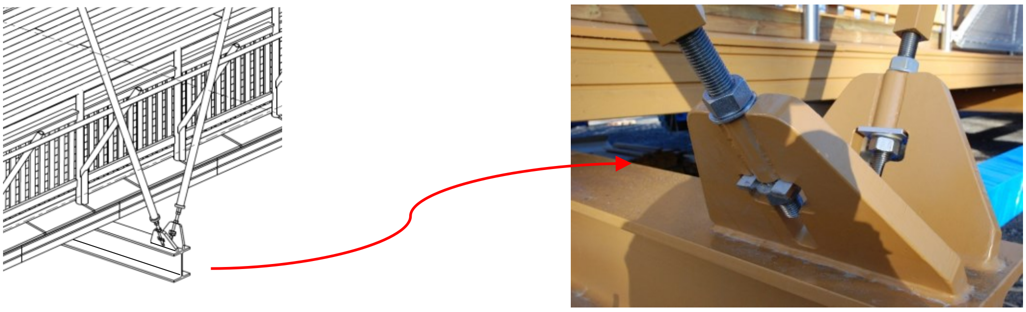

Fig. 9. Special attachment device developed for the V-hangers.

3.4 Erection of the bridge

The bridge was fabricated at Moelven facilities, in Töreboda, Sweden. All steel connections and the timber cleats were attached to the glulam arches at the plant. The parts were then transported to Haninge, which is located approximately 330 km north-east of Töreboda. The bridge was completely preassembled on land, close to one of the abutments. Essentially, every part of the bridge was mounted on land except the asphalt layer. The preassembled bridge was then lifted onto the abutments by means of a truss type mobile crane (Fig. 10). The hoisting took barely 45 minutes.

Fig. 10. Lifting operation of the preassembled bridge.

Dynamic and buckling analysis

Dynamic and buckling analyses using a commercial FE- software were performed on *i*) the bridge discussed in section 3, see Fig. 2, right and *ii*) a similar bridge with identical material properties and nearly identical geometry, the only difference being the vertical hanger arrangement rather than the V-shaped one, see Fig. 2, left. The focus of the comparison analysis was on in-plane modes of vibration and in-plane buckling modes. (Out-of plane behaviour, both concerning vibration and buckling is only marginally affected by the arrangement of the hangers). In the FE-model, all structural elements were modelled as linear beam elements with the cross-sectional dimensions and the materials properties discussed in section 3.1. The arches were modelled with three hinges, one at each springing point and one at the crown. Hinges were also used for the contact points between bracing members and arches, between the V-hangers and the arches and between the formers and the cross-girders. As to the Stress Laminated Timber Deck (SLTD), theory for orthotropic plates should be employed in order to investigate on local stress states . This is often done by choosing adequate shell or solid elements when performing the numerical analyses. However, for global analyses, such as those performed in this paper, the deck can – with sufficient accuracy – be modelled by means of beam elements. In this investigation isotropic beam elements with cross-sectional dimensions of 315x4500 mm^2 were adopted to model the SLTD.[10] The schematic FE- model used for both the dynamic and the buckling analyses is shown in Fig. 11.

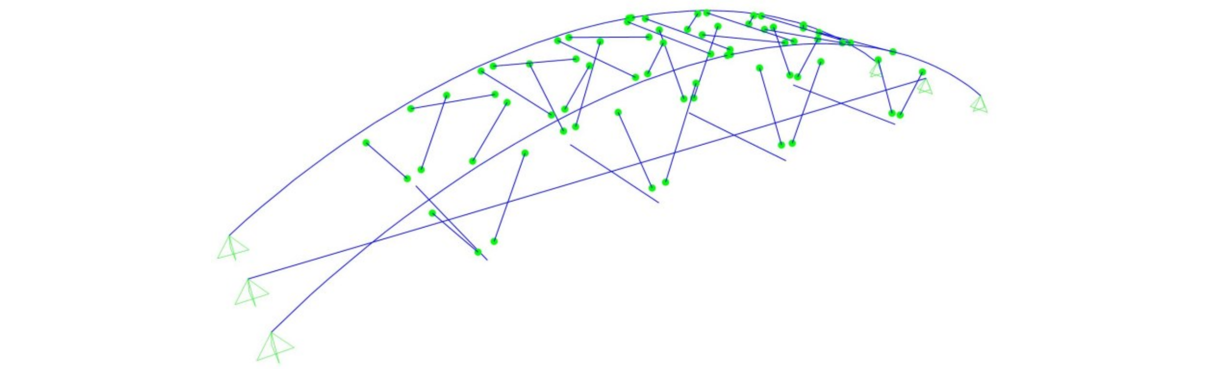

Fig. 11. *The schematic FE- model used for both the dynamic and the buckling analyses.*

For the dynamic analysis, the quasi-permanent value of the loads in accordance with EN 1990: 2002/A1 [11], was adopted; eigenfrequencies and the corresponding vibration modes were determined. The first two vibrational modes involve transverse movements. In the first mode –eigenfrequency f ≈ 1.1 Hz – the entire structure shows transverse motion, while in the second mode – eigenfrequency f ≈ 1.8 Hz – the deck does not move although the arches vibrate transversally. The third mode of vibration involves motion in the vertical plane (i.e. motion in the plane of the arch) – eigenfrequency f ≈2.6 Hz, see Fig. 12.

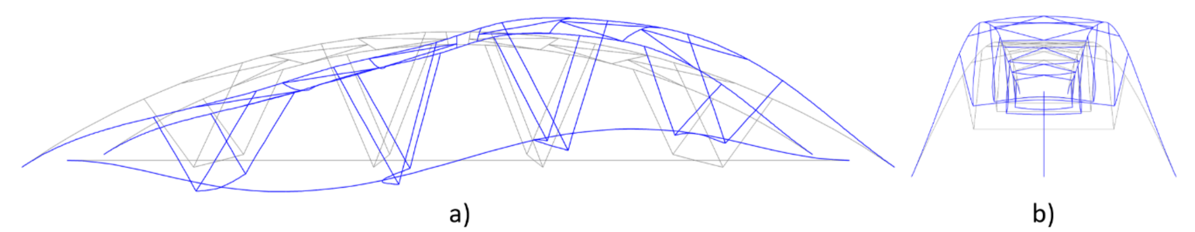

Fig. 12. *First vertical mode shape of the arch bridge with V-shaped hangers, eigenfrequency f =2.65 Hz. a) side view; and b) transversal view.*

It should be noticed that typical vertical frequency range for walking pedestrians on a bridge is between 1.0 Hz and 2.6 Hz. If the first natural (vertical) frequency of a bridge is in this range – with the highest hazard in the range 1.7Hz to 2.1 Hz – there could be a risk for resonance and thus the possibility of a substantial decrease of comfort for pedestrians.[12] In the bridge with V-shaped hangers, the first vertical eigenfrequency is f =2.65 Hz, which is outside the "critical range", indicating low risk for pedestrian discomfort due to vibrations.

For the bridge with vertical hangers, on the other hand, the first vertical vibrational mode occurs at a value of the fundamental natural frequency f=1.75 Hz (see Fig. 13), which, as explained above, could lead to the risk of severe pedestrian discomfort.

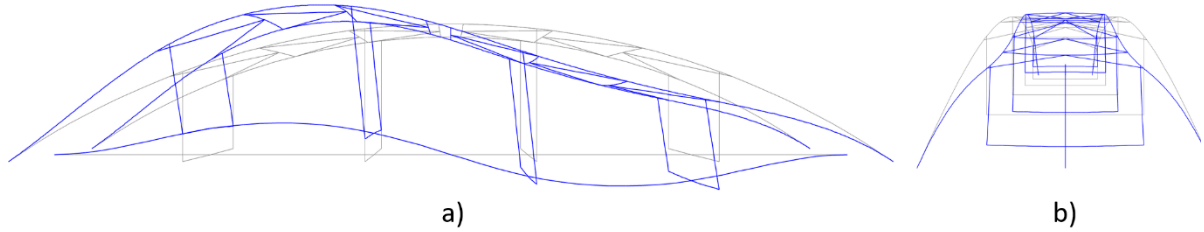

Fig. 13. First vertical mode shape for a model of the structure with vertical hangers, eigenfrequency f= 1.75 Hz. a) side view; and b) transversal view.

The load assumed in the buckling analysis was that corresponding to the Ultimate Limit State combination of permanent loads plus dense crowd uniformly distributed over the entire bridge deck. In Figs. 14 and 15, the first in-plane buckling mode for the arch bridge with V-shaped hangers and the similar arch bridge with vertical hangers, respectively, are shown along with the corresponding buckling load factor k_{crit}.

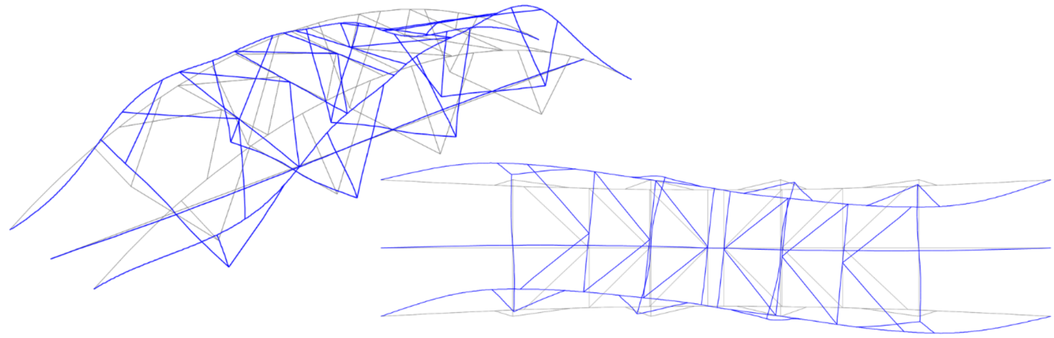

Fig. 14. Buckling shapes and corresponding buckling load factors k_{crit} = 6.94 for the case with V-shaped hangers.

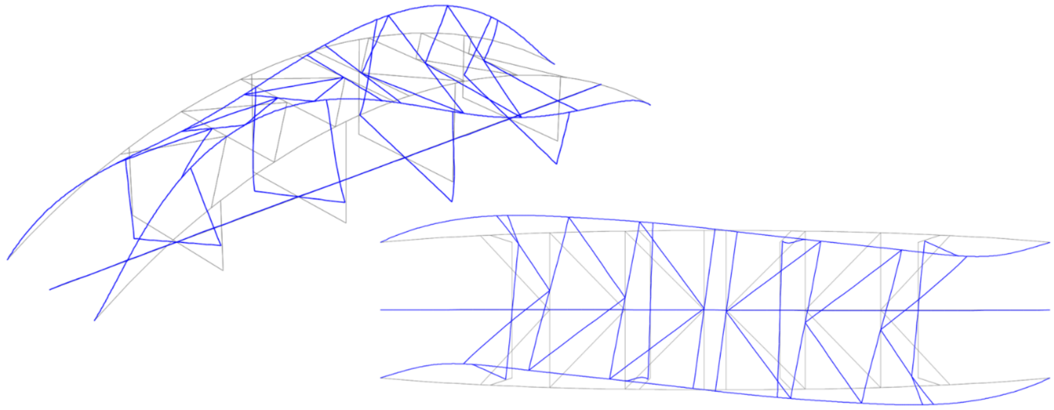

Fig. 15. Buckling shapes and corresponding buckling load factors k_{crit} = 1.81 for the with vertical hangers.

As it can be observed, for the particular geometry and load condition, the analysis shows that the buckling load for the arch bridge with V-shaped hangers is roughly four times greater to that of the arch bridge with vertical hangers.

Conclusions

This paper discussed a new V-shaped arrangement type for hangers in arch bridges. Moreover, a timber bridge with V-shaped arches recently erected in Sweden was thoroughly presented and discussed. It was debated that if the deck is restrained from longitudinal movements, the V-shaped hanger arrangement helps reducing the bending moments in the arch caused gravity loads.

Generally speaking, the arch bridge debated in this paper is rather similar to the Nielsen arch bridge. In terms of statics stability and dynamics - overall - the Nielsen arch has better performance, showing lesser bending moment, a higher buckling load and a higher vertical natural frequency than the proposed bridge with isolated V-shaped hangers. On the other hand, the Nielsen arch type includes a considerable larger number of diagonals and attaching devices than the bridge with V-shaped hangers. The high number of diagonal members and attaching devices increases both the construction cost and the difficulty of construction making the arch type presented in this paper more competitive than a similar Nielsen arch. Simple buckling and dynamic analyses were performed on both arches with traditional vertical hangers and similar arches with V-shaped hangers in order to compare their structural performance. The adoption of V-shaped hangers - instead of traditional vertical hangers - resulted in:

- an increase of the buckling load factor for the first in-plane critical buckling mode from 1.81 to 6.94;
- an increase of the first vertical natural frequency of vibration of the bridge structure from 1.75 Hz to 2.65 Hz.

thus showing a clear pre-eminence of the arrangement with V-shaped hangers, in terms of both dynamic behaviour and buckling. Finally, it should be emphasized that the hanger system of the arch bridge presented in this paper might be to some extent more onerous – thus more expensive – than a corresponding system with vertical hangers. However, the higher price of the former is compensated by the saving of material in the arches, being the cross sectional area of the arches considerably minor in the case of V-shaped hangers than in the case of vertical hangers. Furthermore, apart from the economic considerations, a more slender arch is, in general, considerably more aesthetically appealing than a stocky one. Altogether, the discussed V-shaped hanger arrangement can be a sound alternative to the traditional arrangement with vertical hangers, both in terms of efficiency, economy and aesthetics.

Acknowledgements

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