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FORCE VARIATIONS AND SLACKNESS IN TIED ARCH BRIDGES WITH CROSSING HANGERS

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Abstract. *In the design of some tied arch bridges, the hangers are arranged with a certain inclination and are crossing. If the hangers intersect each other at least two times the resulting structure appears as a rather dense hanger web. This configuration is used for the so called "network arches", where the angle between hangers and deck varies along the length of the bridge and for the "Nielsen-Lohse arches", where both sets of hangers remain parallel. The arch and the lower chord of these bridges are kept very slender, resulting in a delicate structure, aiming for an aesthetically pleasing design. In this paper, the different reaction of the hanger rods to compressive or tensile stresses is taken into account, through the use of FE-element models. The hanger elements allow for a relaxation of the hangers, once compressive stresses occur. The paper examines the behaviour of these types of tied arch bridges, as well as a classical tied arch bridge with vertical hangers as a reference point, for total strength as well as for fatigue strength. It is found that the fixed loads introduce a pretensioning effect in the hangers, resulting in much fewer hangers relaxing during the crossing of the moving loads. Other factors, influencing the number of relaxed hangers are the inclination angle of the hangers and the rise of the arch. This same effect results in extremely favourable fatigue behaviour, because of the small stress range. The structural performance, as well as the fatigue behaviour, is thus at least as good for a classical tied arch. The paper concludes that the network arch, as well as the Nielsen-Lohse arch, is a possible and valuable alternative for a tied arch bridge, especially when the slenderness of the design can add aesthetic value to the bridge.*

1 INTRODUCTION

For some types of tied arch bridges, the hangers are arranged with certain, possibly varying inclination angles. These types of bridges try to find configurations of the hangers resulting in a reduction of the displacements of the arch bridge itself. The theory behind the behaviour of this bridge type states that it is possible to find a specific hanger solution for every possible load configuration resulting in minimal displacements. By combining several hanger systems with different inclinations in one arch, thus introducing a cable web of possibly crossing hangers with varying inclination in each arch plane, this bridge type tries to find acceptable values for the deformations under all possible load configurations[i]. This should result in a significant reduction of the necessary steel volume of the bridge. One possible variation on this principle is the “Nielsen-Lohse” arch, where two sets of crossing, but parallel hangers are used in each arch plane.

These types of arch bridges are mostly designed using very slender arch sections and with bridge decks with a very low construction depth. Often bridge decks of high performance concrete are used, in combination with slightly more voluminous side girders, necessary for the anchoring of the hangers [ii].

The network of hangers in each side plane of the bridge consists of cables crossing each other several times. The crossing cables are joined together using soft plastic connectors. The purpose of these connections is not to transmit forces between the hangers, but to avoid damage when the cables of the intersecting systems bump against each other.

2 CALCULATION METHOD

2.1 Finite Element Model

All results in this paper were obtained using the multi-purpose finite element software SAMCEF. The bridge deck of all considered bridges was modelled using 2-dimensional Mindlin shell elements, following the median of the cross section and incorporating the varying thickness. The arches themselves were built up out of simple, 1-dimensional Mindlin beam elements. The hangers however are modelled as Mindlin rods, using a specific, user-defined material model allowing for a relaxation of each individual hanger once compressive stresses occur.

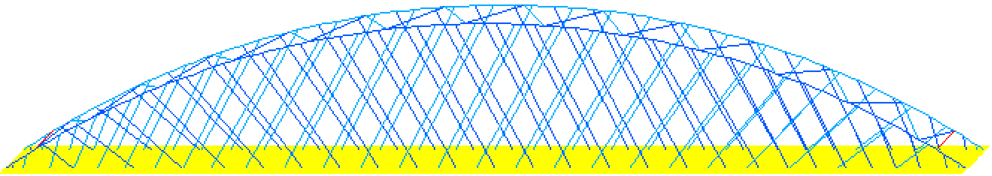

Figure 1: FE model of a bridge with intersecting hangers with varying inclination

The reference model for the calculations in this paper is a 200m long bridge, the arches of which consist of slender I-girders. The deck is designed as a concrete plate with a variable thickness[i]. A bridge with intersecting hangers and varying inclination, a network arch as shown in figure 1, is studied along with a model with intersecting, but parallel hangers (figure 2) as well as a reference tied arch bridge with a vertical hanger configuration (figure 3).

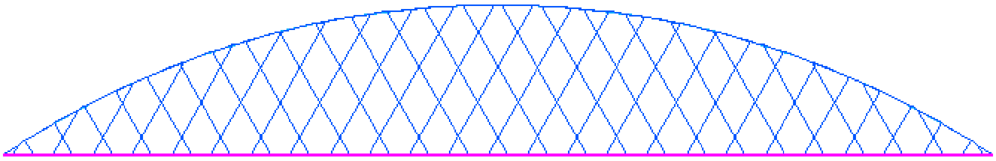

Figure 2: FE model of a bridge with intersecting but parallel hangers

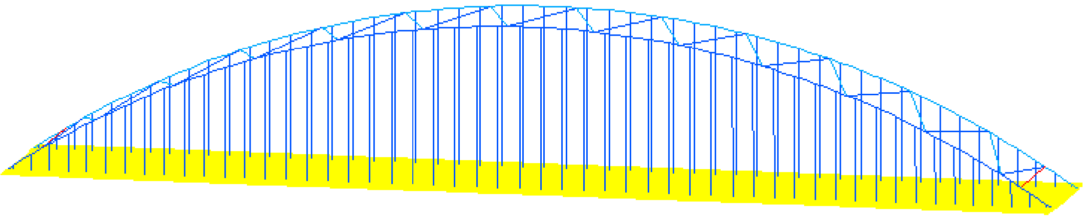

Figure 3: FE model of a bridge with vertical hangers

2.2 Non-linear behaviour of the hangers

The varying inclination of the hangers in this type of tied arch bridges has as main effect that during certain positions of the live load model on the bridge deck, a number of hangers will not be subjected to tensile stresses, resulting in slackness of these particular hangers. When this occurs, these hangers will no longer take part in the structural behaviour of the bridge structure

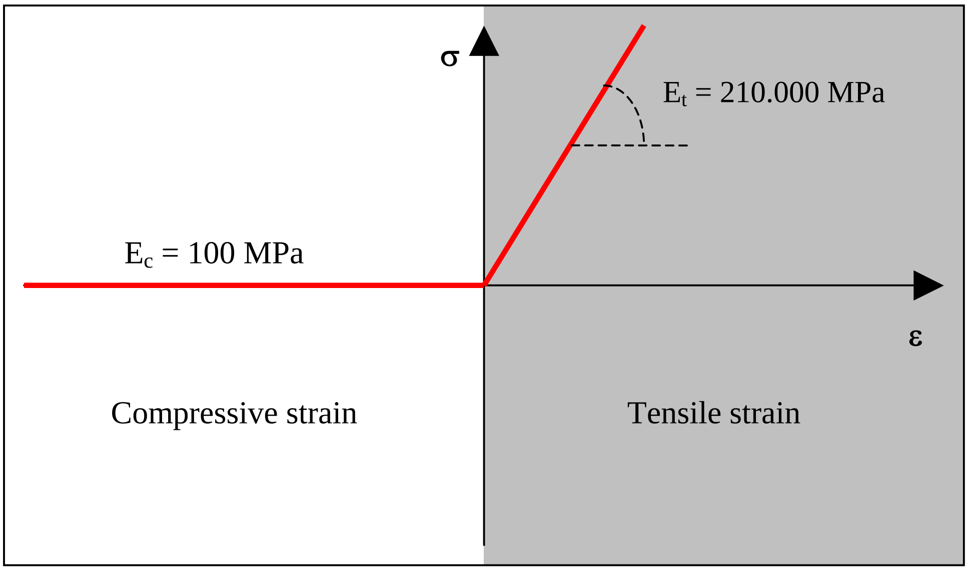

Figure 4: Hanger material model incorporating possible slackness of the hangers

At first glance, the obvious solution to this problem would be to simply remove these hangers from the calculation model and afterwards recalculating the entire bridge. However, since the location and number of the slackened hangers will vary during the passage of the live load model over the deck, this becomes a time-consuming and labour-intensive task. Because of this, a special material model was developed, automating this entire calculation procedure.

This bilinear material model uses different Young’s moduli for the compressive and tensile part of its material behaviour law, consequently ensuring that once compressive stresses arise in some of the hangers, they loose almost all of their stiffness, guaranteeing that they no longer take part in the structural behaviour of the bridge. As is shown in figure 4, this theory is put into practice by defining the compressive Young’s modulus as 100 MPa, while the tensile Young’s modulus is the normal one for steel, namely 210.000 MPa. The low value of 100 MPa is used instead of 0 MPa to ensure no numerical irregularities arise during the execution of the finite element software

As figures 5 and 6 illustrate, the above described material model for the hangers fulfils its function succinctly. Figure 5 shows the normal tension in the hangers for a load combination consisting of dead load and live load along one halve of the length of the bridge. It appears as if only five of the hangers slacken: two in one arch plane and three in the other one.

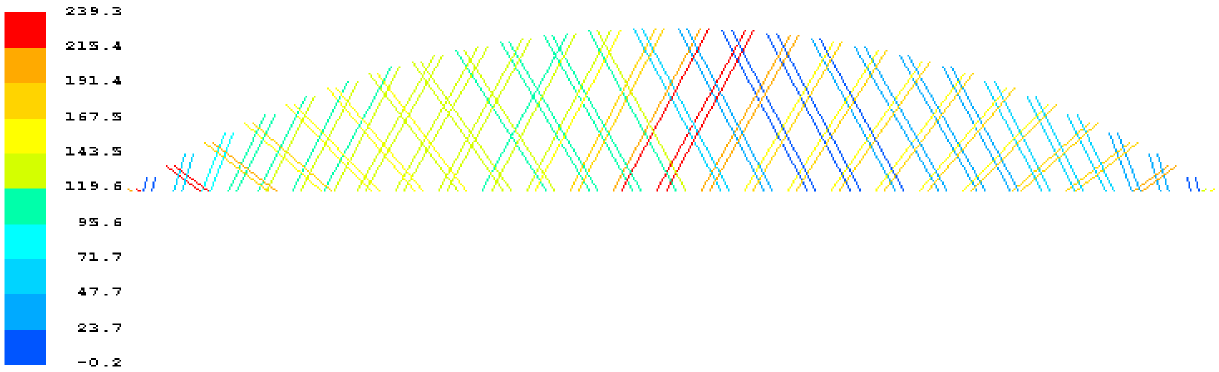

Figure 5: Hanger forces for a bridge model with intersecting hangers (MPa)

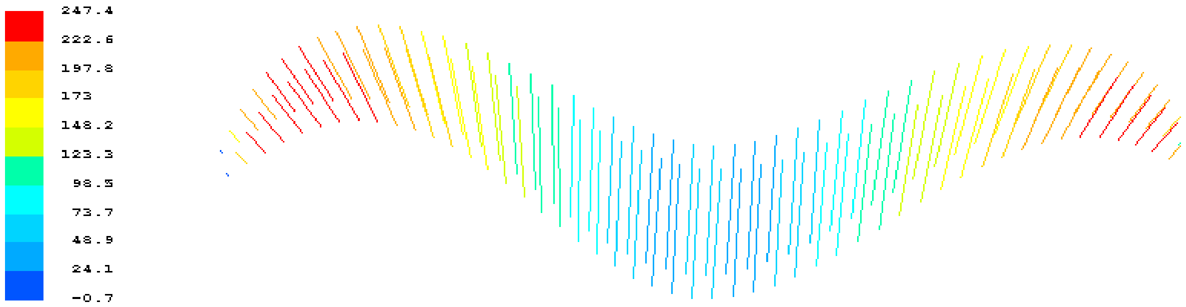

Figure 6: Hanger forces for a bridge model with vertical hangers (MPa)

A study of the different loading combinations shows that for most loads, the same group of hangers tend to slacken: those with the steepest inward inclination at both ends of each arch plane. This can be explained, since all hangers with an outward inclination systematically undergo higher loading than the inwards pointing hangers.

Figure 6 shows the normal tension in the hangers as well as the form of the displacements for a load combination consisting of dead load and live load along the entire length of the bridge. While classic tied arch bridges with vertical hangers normally suffer no slackened hangers, figure 6 indicates nevertheless one cable slackening.

It is important to note that this material model is simply an automation of a calculation strategy wherein all compressed hangers are excluded from further structural calculation of the bridge. It in no way takes into account the possible buckling behaviour of the compressed hangers.

3 INDICATIONS CONCERNING THE FATIGUE EFFECT

3.1 Overall considerations

Fatigue calculations for these types of bridges become exceedingly elaborate because of the sensitive behaviour of the arch bridge to the location of the live load model[iii],[iv]. Possible slackness of the hangers is consequently taken into account for the fatigue calculations.

3.2 Stress ranges in the hanger connections

The behaviour of each hanger is more or less independent. This causes possibly extensive variations in the stress ranges between neighbouring hangers. Because of this, the normal stresses in the hangers for the considered bridge model with intersecting cables can vary from 0 MPa, for the two slackened hangers, to 134 MPa. Stress ranges from 15 MPa up to 45 MPa can occur during the passage of the four standard axles of Fatigue Load Model 3. It is important to note that the slackening of the hangers only happens one time for each concerning hangers during the passage of the load model. This implies that they are not subjected to more than one stress cycle during the passage of the load, resulting in no more unfavourable fatigue behaviour than the not-slackened hangers.

The values derived above are for a passage of Fatigue Load Model 3 along the deck as close as possible to one side of the deck. The discussed values are consequently found with hangers in the most heavily loaded arch of the bridge. While the hangers in the other arch will be subjected to a less heavy loading, a few more hangers will slacken. Nevertheless, the maximal stress in these hangers remains below 128 MPa at all times and the maximum stress ranges equal no more than 27 MPa.

As a comparison, the same calculation was performed for a classical tied arch with vertical hanger configuration. In this case, the maximum tensile stress in the hangers is only 88 MPa with a stress range under 26 MPa for the hangers of the arch plane with the heaviest loading. Stress ranges are consequently only half as large as for a bridge with an intersecting hanger configuration.

4 PARAMETRIC STUDY

4.1 Variation of the hanger inclination

To simplify the comparison of bridges with a different hanger inclination, only Nielsen-Lohse bridges, with two intersecting groups of parallel hangers, are considered in this paragraph. Calculations with different inclination angles indicate that this parameter does not really affect the normal forces in the arches themselves. Only for an asymmetrical placement of the live load combined with the dead load and for higher values of the inclination angle, i.e. an angle larger than 70°, does the inclination appear to make a real difference. While most stress values in each arch remain within pretty strict boundaries, for bridges with a hanger network, the arch starts to act more or less as a tied arch bridge with vertical hangers in this specific case.

When looking at the hanger forces for several inclination angles, it appears that the higher the inclination angle becomes, the more hangers will start to slacken. Systems with lower hanger inclinations have lead to larger variations of the hanger stresses.

The combination of both of these indications for higher and lower hanger inclinations indicates that an optimum value for the hanger angles can be found at a value of about 60°.

4.2 Variation of the span length

Greater span lengths will, quite logically result in greater stresses in each arch. The same conclusion can be found when looking at the hanger forces.

When studying an asymmetrical placement of the live load, the structural behaviour of both sets of hangers becomes quite clear. Figure 7 displays the stresses in the hangers with a left oriented inclination. Two of these hangers in the middle of the span slacken and act as boundary between the heavily loaded hangers at the left side of the span, where the live load is superimposed on the dead load, and the less loaded right side of the bridge.

The right oriented hangers, as shown in figure 8, show the opposite behaviour. Especially the hangers at the right-hand side of the bridge are loaded. Both figures also illustrate that for longer span lengths the tension in the left-oriented hangers increases more than in the right-oriented hangers.

Comparing the results for hangers from both orientations, one could say that the left-oriented hangers in the left side of the bridge carry the live load, while the right-oriented hangers in the right side of the span prevent distortion of the arch bridge due to the asymmetrical loading.

The variation of the span length, maintaining a constant relation between span length and arch height, indicates that the application domain of these types of arch bridges extends to lengths of 200m. The determining position of the live load in this case will be an asymmetrical loading.

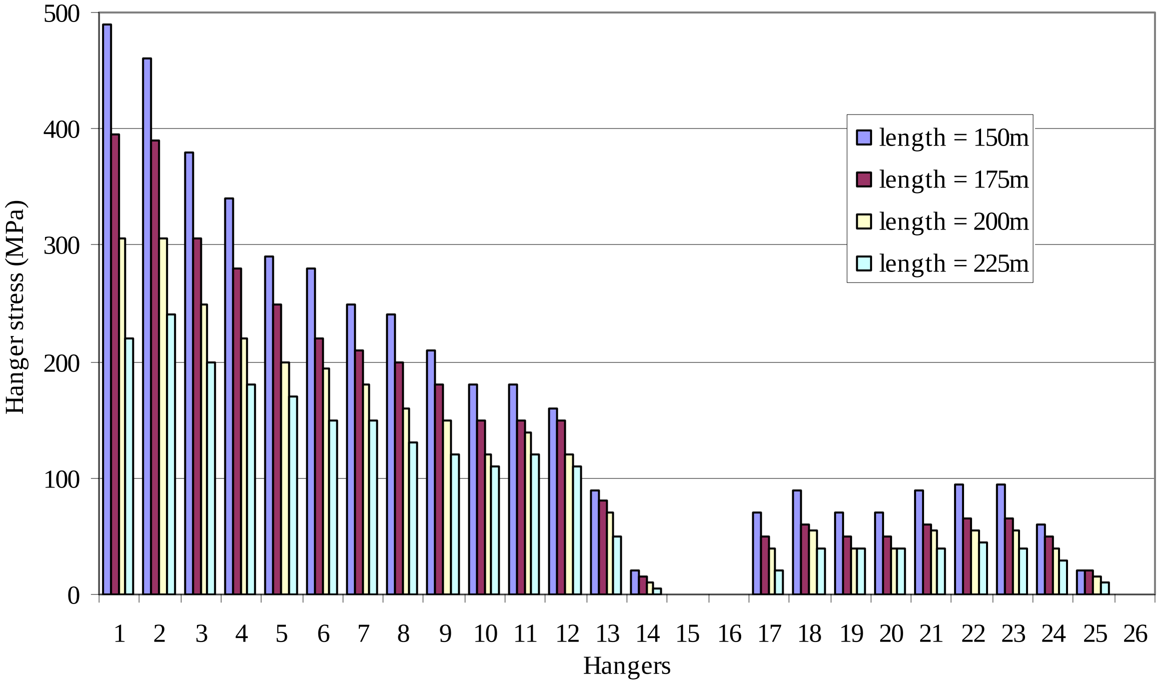

Figure 7: Hanger forces in the left-oriented hangers under asymmetrical live load (MPa)

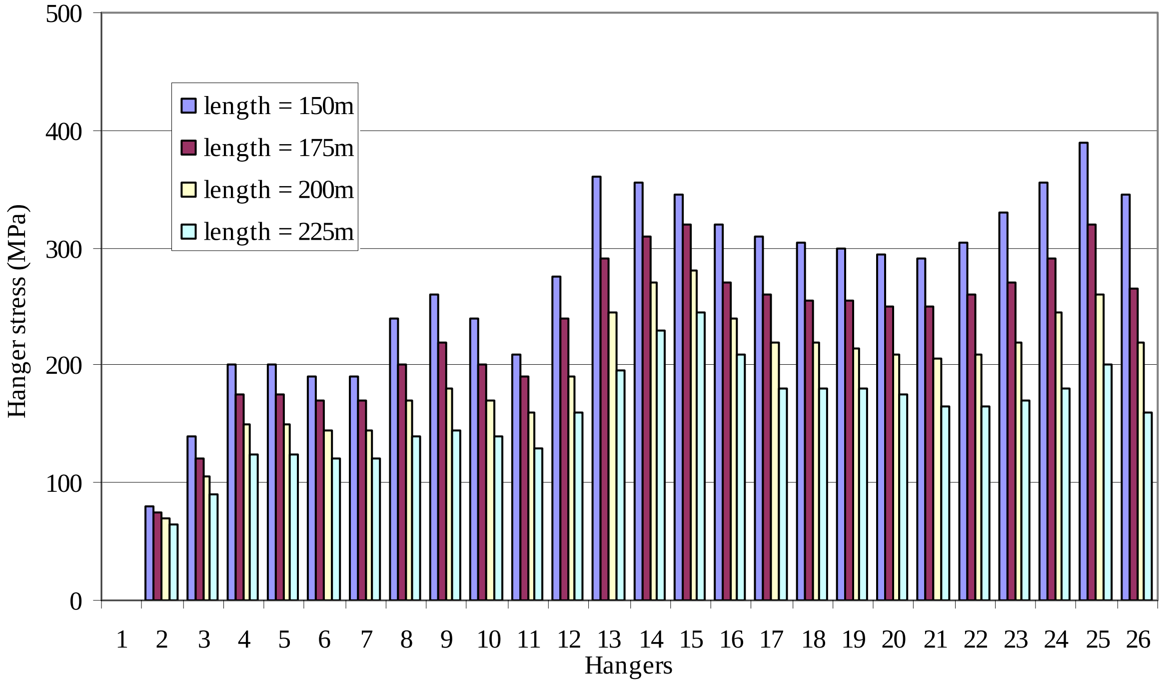

Figure 8: Hanger forces in the right-oriented hangers under asymmetrical live load (MPa)

4.3 Variation of the arch height

Just as for arch bridges with vertical hangers, the stresses in the arches decrease for higher arch heights. This is especially the case near the base of each arch. It is of importance to note that when the arch height is changed, this has effect on the hanger inclination as well. The inclination of the most horizontal hangers, which are situated at the bridge ends, is influenced the most. This leads to a larger reduction of the hanger forces.

The enlargement of the arch height has a positive influence on the bearing of the live load, because stress peaks are reduced as well as the number of slackening hangers. However, this has not an overall positive effect in reducing the steel sections, because higher arches are more susceptible to wind loads.

5 PRETENSIONING EFFECT OF THE CABLES CAUSED BY DEAD LOAD

During the initial stages of the development of the finite element model used for this paper, an interesting observation was made. When the model with slackening hangers was tested, initially using only live load on the bridge deck, a large number of hangers seemed to slacken. Later on, when load combinations were used, consisting of dead load as well as live load, the number of slackening hangers was reduced to just a few. It appears as if the dead load of the structure induces some sort of pretensioning of the hanger configuration. Where at first glance bridge models with inclined and intersecting hangers would be highly susceptible to fatigue damage because of their slackening behaviour, this pretensioning reduces this problem.

Figure 9, showing the hanger forces caused by a symmetrical live load, indicates that all outwards inclined hangers are under tension, while all other cables slacken. When looking at a situation where live load is combined with dead load, as is shown in figure 10, only the first one and the last one of the inwards inclined hangers are slackened. The pretensioning caused by the dead load nullifies the expected problem of hanger slackness almost entirely

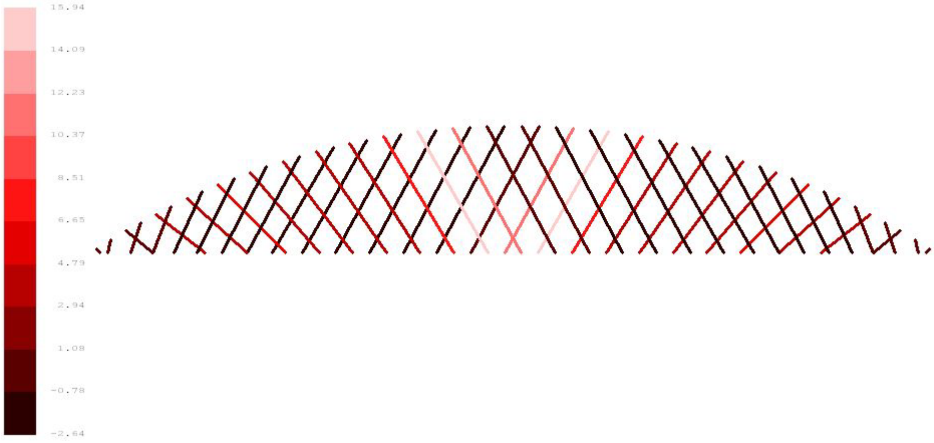

Figure 9: Hanger forces under a symmetrical live load (MPa)

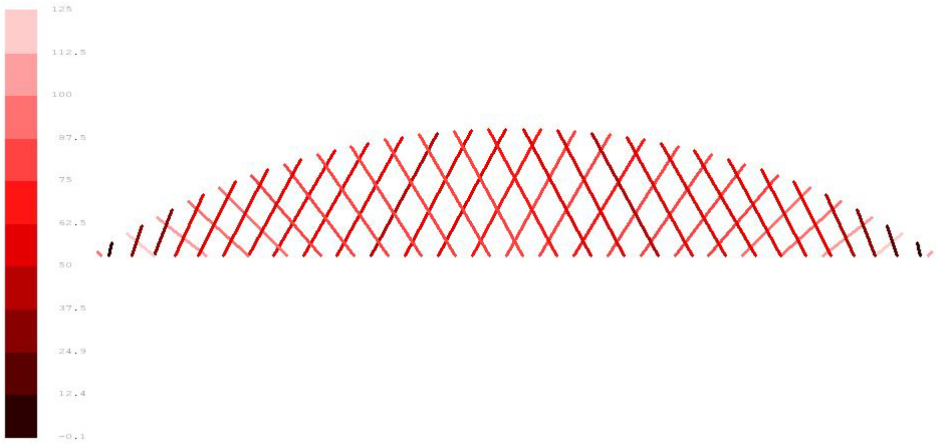

Figure 10: Hanger forces under symmetrical live load combined with dead load (MPa)

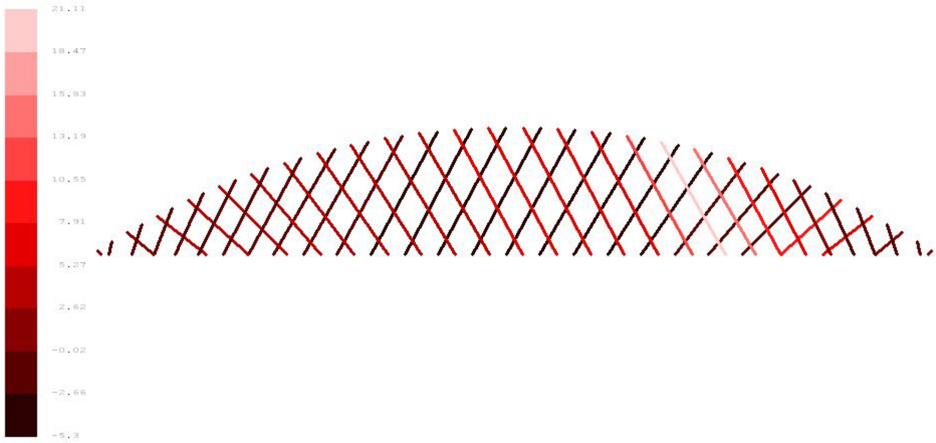

Figure 11: Hanger forces under asymmetrical live load (MPa)

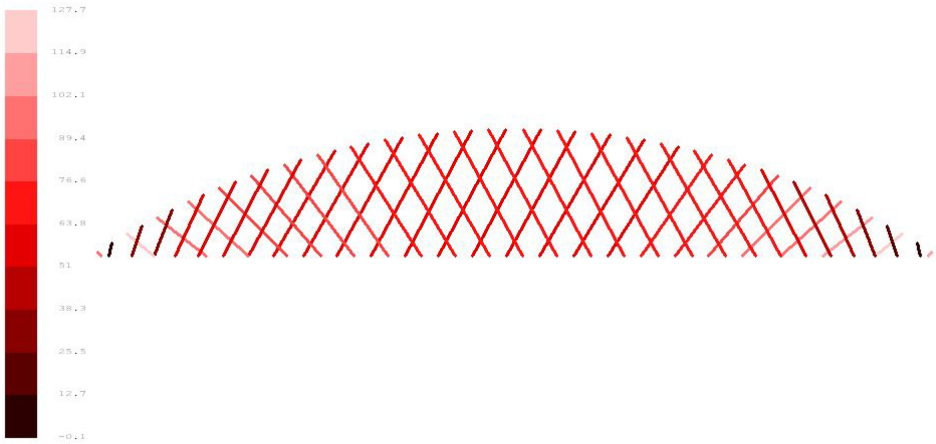

Figure 12: Hanger forces under asymmetrical live load combined with dead load (MPa)

A study of figures 11 and 12 leads to comparable conclusions. The axles of the live load model are placed at one fourth of the span length from the right hand base of the arch. All from this location outwards pointing hangers are tensioned while almost all others become slackened. A combination with the dead load leads to much higher stress values but only a few of the inwards pointing hangers at both ends of the bridge are slackened.

6 CONCLUSIONS

A study of arch bridges with intersecting hangers, network arches as well as Nielsen-Lohse bridges, based on finite element calculations, using a non linear material model for the hangers, proves the value of this bridge type. The high stiffness of the hanger configuration has a positive influence on the displacements. This, combined with a very low mass, leads to a well balanced design. The pretensioning of the hangers, caused by the dead load, solves the problem of hanger slackness and results in a favourable fatigue behaviour. The most fatigue-sensitive detail of the entire bridge is the connection of the hangers, but even there stress ranges remain minimal.

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