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BRIDGE

Skew Placement of Arches with respect to the Bridge Deck

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Abstract

Designers try to find new ways to make landmark bridges slenderer and distinctive. A new trend for arch bridges is placing the arch not co - linear with the bridge axis, but slightly skew. While visually attractive, this concept introduces a number of design problems which are not normal for arch bridges: the arch becomes subjected to significant out of plane bending moments, a permanent torsional effect develops, hangers are not possible in certain areas because of conflict with traffic and the tied arch concept becomes quite difficult to realize. The aim of this research is to study the skew arch concept using finite element modelling. A parametric study is undertaken to investigate the main design problems and to find an allowable application area in terms of bridge span, bridge deck width and skewness of the arch. Hereby, two different skew arch hanger configurations are considered including also a minimization of the number of hangers.

Keywords: skew placement, arch bridge, buckling, finite element modelling.

1 Introduction

For centuries, bridges have played an important role in the traffic system to allow passage across a body of water, a valley or a road.

The construction material for bridges evolved from timber in the early ages, to stone masonry during the Roman period and the Middle Ages. In those periods, compressive strength of the materials could be relied upon whilst tensile strength could not. Hence, an arch bridge structure was often the logical choice as it transfers the loads towards a horizontal thrust at the abutment by means of compression forces in the arch shape. With the invention of iron during the industrial revolution, larger span bridges became possible containing elements with a significant tension strength. Nowadays several designs of bridges exist. They vary depending on the nature of the terrain where the bridge is located, the function of the bridge, the required span length, the materials used to build it and the available funds for the bridge construction. As a consequence, a distinction can be made between beam bridges, truss bridges, arch bridges, suspension bridges, cable stayed bridges and movable bridges. Concrete and steel are the most frequently used materials for bridges. Steel is preferred for longer span bridges due to a larger strength to weight ratio compared to concrete.

Over the years, several configurations for arch bridges have been developed. Old arch bridges are associated with fairly massive brickwork structures. In this way, the possibility of tension forces could be minimized. The last century, the use of steel and reinforced concrete allowed more slender and elegant arches. Depending on the position of the deck with respect to the arch and the load transfer from the deck to the arch, different arch type bridges can be distinguished. The deck can run below, through or above the arch. A tied arch can be used to minimize the horizontal thrust forces on the abutment. In arch bridges where the deck runs below a single arch, lateral loading of the arch can be critical for the bridge design. Therefore, the single arch is often split in two arches which are interconnected to get a better resistance against lateral loading. Designers try to find new ways to make landmark bridges slenderer and distinctive. A new trend for arch bridges is placing the arch not co-linear with the bridge axis, but slightly skew. Besides aesthetical benefits, the skew position makes the single arch more resistant against lateral loading and the arch abutments do not form an obstruction for the road traffic. Nevertheless, while visually attractive, this bridge concept introduces a number of design problems which are not normal for arch bridges: hangers are not possible in certain areas because of conflict with traffic, the tied arch concept becomes quite difficult to realize, the arch is besides axial compression also loaded by significant bending moments and the arch becomes subjected to a permanent torsional effect.

2 State-of-the-art

Currently, only a few skew arch road bridges have been constructed. This implies the absence of a large number of studies concerning the skew placement of the arch in single span road bridges.

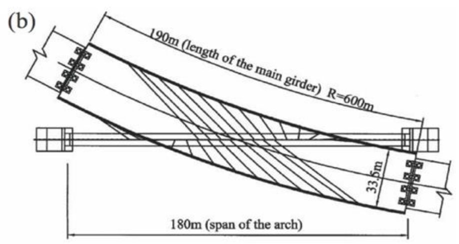

Figure 1. Arch Bridge

Most of the bridges are located in the United Kingdom. The two most known projects are the Hulme Arch Bridge in Manchester and the Clyde Arc in Glasgow. According to [1, 2], both bridges form a gateway into the city and thereby symbolize a plan to increase the quality in the neighboring urban environment. The skew placement of the arch results in an asymmetric cable arrangement. These cables generate significant out of plane bending moments in the arch rib. These bending moments are the most determinant factor for the arch design. Therefore, the arch no longer behaves like a conventional parabolic arch which is in pure compression under a uniformly distributed load. Due to the out of plane bending moments, the arch behaves more like a laterally loaded bending member. Researchers [3] performed a stability analysis of a specific shaped arch bridge (Figure 1), namely a straight arch suspending a curved deck. Therefore, it will exhibit similar properties as a skew placed arch carrying a straight deck. Due to the skew position of the arch compared to the deck, the hangers are placed in a diagonal position contrary to the standard vertical direction in straight arch bridges. They cause large bending moments, compression forces, shear forces and torsion in the arch rib. Nevertheless, the new slanting direction of the hangers tends to resist any deformation of the arch out of its plane and hence increases the structure stability. Similar to straight placed arches, the restraining boundary conditions at the arch spring and the rise-to-span ratio significantly influence the overall structural stability. The stability coefficients for fixed arch springs are more than twice the coefficients for pin-ended arch springs. The stability is found to span ratios. An optimal rise-to-span ratio for the considered bridge is found to be about 0.37. They noted that this value is larger than the optimal ratio for normal, non-skewed arches analyzed in other studies. The more the design of the bridge deviates from a rise-to-span ratio of 0.37, the less reliable the bridge design [3].

3 Reference bridge models

3.1 Design

The aim of this research is to study the skew placement of arches for single span road bridges using finite element modelling. Therefore, a parametric study is undertaken to determine the main design problems and to find an allowable application area in terms of bridge span, bridge deck width and skewness of the arch. The investigated ranges for each parameter are based on existing skew placed arch bridges. All the results are compared to a straight arch bridge configuration (Figure 2) with the same bridge length, deck width and number of hangers as the skew arch bridges.

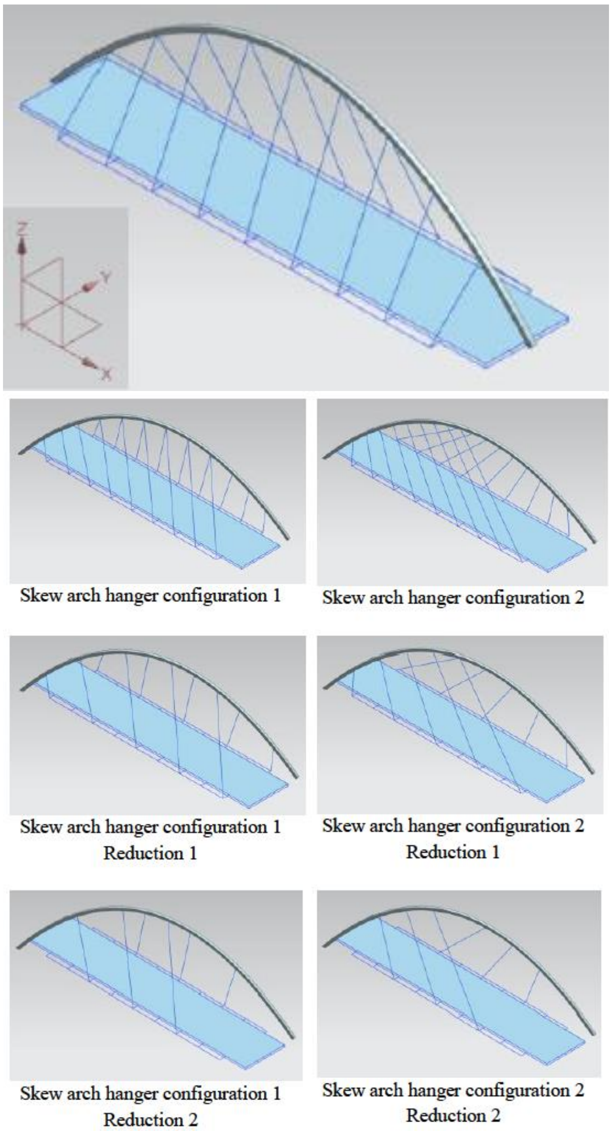

Figure 2. Straight arch bridge model and the different variations

When the arch in the straight arch model is placed in a skew position the hangers would come in conflict with traffic. Hence, the hanger configuration for straight arch bridges is not practically applicable for skew arch models. Therefore, for the skew arch bridge concept, appropriate cable configurations need to be developed. Hereby, the cables inclining across the bridge deck have to provide enough headroom above the carriageway in order to allow the largest design vehicles to pass safely below the hangers. Therefore, a minimum free height of 5 m is assumed, based on guidelines in EN 1991-1-7. Even with special developed hanger arrangements, outriggers for hanger connection and pedestrian provisions are a necessity to avoid vehicle-cable impact. It can be concluded that the required clearance has a significant influence on the overall design of skew arch bridges. It imposes criteria to both the bridge dimensions as to the hanger configuration. Therefore, it indirectly has an effect on the internal force distribution and hence on the structural behavior. A hanger configuration which limits the out of plane bending, the determining design factor for skew arch bridges, has a disadvantageous effect on the provided clearance and vice versa. This resulted in two configurations: skew arch hanger configuration 1 inducing minimal bending moments in the arch and skew arch hanger configuration 2 providing the largest possible vehicle clearance (Figure 2). Based on aesthetical preferences the number of hangers is often chosen as small as possible. Therefore, the effect of reducing the number of hangers in configuration 1 and 2 is investigated (Figure 2). A second reduction in the number of hangers is also considered, as for the removed outer hangers often problems arise with vehicle-cable conflict.

The skew arch reference bridges have a span length of 100 m, an 18 m wide deck and an arch skewed over 16° with respect to the bridge axis. The arch has a parabolic shape and its crown is located 30 m above the deck. The arch has a square box section with a side of 1 m and a thickness of 50 mm. The arch is modelled using 2D elements and is considered fixed at its ends. The deck is made up out of a 20 cm thick concrete layer supported by longitudinal and transverse steel girders. The four longitudinal girders are spaced 6 m while a transverse girder is foreseen each 10 m. The girders are modelled as I profiles with a height of 1500 mm, width of 750 mm and web and flange thicknesses of 50 mm. The transverse girders extend 2 m outwards of the longitudinal girders to provide a connection with the hangers. To avoid locally high deformations at the connection, the outriggers are interconnected by 500 mm diameter tubes with a thickness of 50 mm. The bearings at the bridge deck ends restrain vertical motions. Moreover, at one side also longitudinal motions are resisted. The deck is fixed in the transverse displacement direction at one of the outer points for each of the two edge transverse girders. The hangers are implemented as rod elements without compressive strength. They have a diameter of 100 mm and a tensile strength of 1500 N/mm². Each time a cable is connected to the arch, a diaphragm is provided in the arch cross section. The steel for the deck and arch is S355 and the concrete used in the deck has a quality of C40/50 (f_{ck}=40Mpa, $f_{ck,cube}$=50MPa).

3.2 Analysis of the reference models

In comparison to straight arch bridges, uniform loads in combination with a skew arch position and skew arch hanger configuration lead to out of plane bending moments in the arch rather than the development of axial compression forces. Hence, the arch is used more as a beam then as an arch. Hereby, the self weight of the bridge components and the uniform traffic loads dominate the bridge design. The presence of significant bending moments illustrates that the arch is not used efficiently in skew arch bridges. Based on the occurring stresses and deformations, skew arch configuration 1 and 2 use the arch material less efficient than a straight arch model, respectively with a factor 1.35 and 3. The most loaded arch section is located at the crown for the reference model with configuration 1. On the other hand, it is positioned horizontally a distance 0.33 times the span length from the arch ends when configuration 2 is considered. An opposite behavior is observed for the critical deck section. The middle of the deck deflects the most for configuration 2, while for configuration 1 the critical deck section is situated 10% of the span length more towards the abutment. The arch behavior is determined by the X, Y and Z force components that each cable transfers to the arch. The magnitude of each component is determined by the geometric arrangement of the cables and by the load distribution on the deck. Hence, the bridge design is rather limitedly affected by the skew arch position but by a larger extent determined by the hanger configuration which accompanies the skew arch. The Y and Z force component create respectively out and in plane bending moments. As the cables insert their forces into the bottom plate of the box section, the resulting force component works with some eccentricity with respect to the center of gravity of the arch cross section. This develops some torsion in the arch. The arch in the reference model with skew arch hanger configuration 2 is subjected to at least three times larger in plane, out of plane and torsional moments than the arch in configuration 1. Hereby, the out of plane bending moments dominate the design of the arch. The importance of the out of plane bending moments is much more pronounced for the arch in the model with configuration 2. While the arch for the skew arch configuration 1 remains nearly completely in compression, the arch for the skew arch configuration 2 is subjected to significant tensile forces. As the out of plane bending moments are the critical internal forces, the lateral deformation is the dominant deflection component. Skew arch bridges with configuration 1 are much more resistant against asymmetric mobile loads than straight arch bridges. The arch deflections under asymmetric loads in the reference model with skew arch hanger configuration 1 and 2 are respectively 0.5 and 0.85 times the deformations in straight arches. As a consequence, skew arch bridges work, based on the arch deformations, more efficient than straight arch bridges if the proportion of the live to dead load is rather large. This is because the live load can induce significant load differences on the two deck halves. It can be concluded that configuration 1 is a more structurally efficient skew arch bridge concept than configuration 2. Nonetheless, configuration 2 is less prone to vehicle-cable conflicts than configuration 1 and therefore corresponds to less stringent requirements to provide enough clearance.

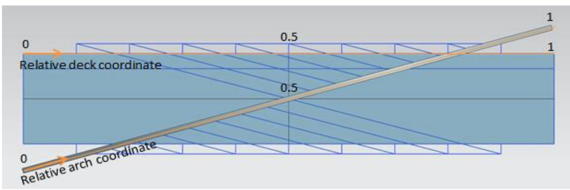

Figure 3. Definition of relative arch and deck coordinate

4 Parametric study

When a bridge parameter is investigated, all the other parameters are considered to be fixed to the corresponding value in the reference bridge design. In this way, all the resulting changes in bending moments, stresses and deformations are completely dedicated to that single parameter adaptation.

4.1 Influence of the span length

As the bridge span increases, the distance between two successive hangers enlarges, the cable inclination changes, the rise-to-span ratio diminishes, the ratio of the lateral distance between the arch abutments and the bridge length decreases, the relative stiffness of the deck and arch reduces, the application area of the mobile loads enlarges, the effect of the dead load increases and the clearance below the hangers reduces. As a consequence, the bending moments increase quadratic when the bridge becomes longer. As the span length increases, the relative importance of the out of plane bending moments compared to in plane bending reduces. This indicates a more efficient use of the arch structure.

For longer bridges with configuration 1, the critical arch section shifts horizontally from a location 0.3 times the span length separated from the abutment towards the arch crown. The critical deck section shifts from the middle of the deck towards a distance 0.3 times the deck length from the deck ends. The shifts are illustrated in Figure 4 and Figure 5, respectively for the arch and the deck. The graphs display a relative coordinate which is defined in Figure 3. For all the investigated span lengths for the model with skew arch hanger configuration 1, the first reduction in number of hangers has only a limited influence on the bending moments (Figure 6), stresses, deformations and hence on the global arch behavior. The second reduction for the number of cables on the other hand has a much more pronounced influence (Figure 6), leading to unacceptable arch stresses and deck deformations. The outer cables, which are removed for the second reduction in number of hangers, tend to restrain lateral arch deflection and only limitedly affect the vertical arch motion. It should be noted that although the most outer cables play an important role to minimize the deformations and stresses, they cause problems with respect to clearance for driving vehicles on the other hand. Contrary to the results for configuration 1, a first reduction of the number of hangers in configuration 2 causes already a significant increase in critical bending moments in both the arch (Figure 7) and the deck.

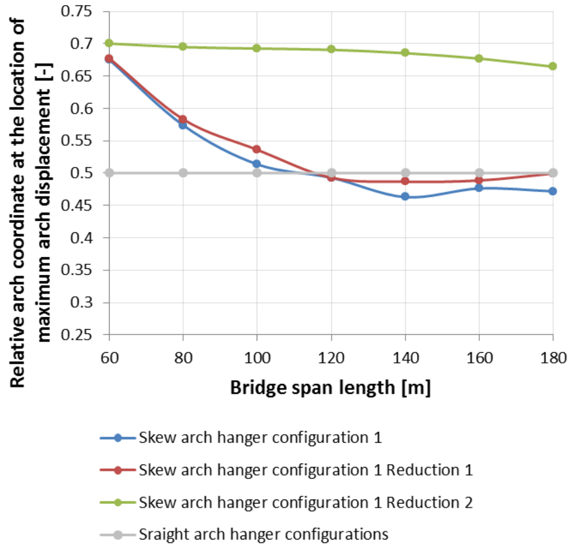

Figure 4. Relative arch coordinate of maximum arch displacement in configuration 1 for varying span length

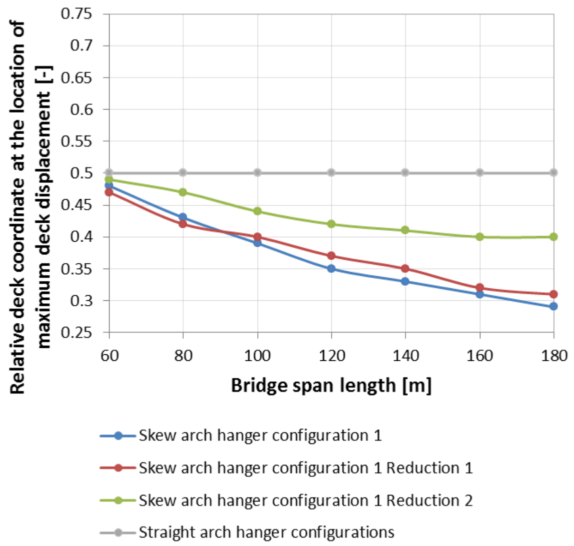

Figure 5. Relative deck coordinate of maximum deck displacement in configuration 1 for varying span length

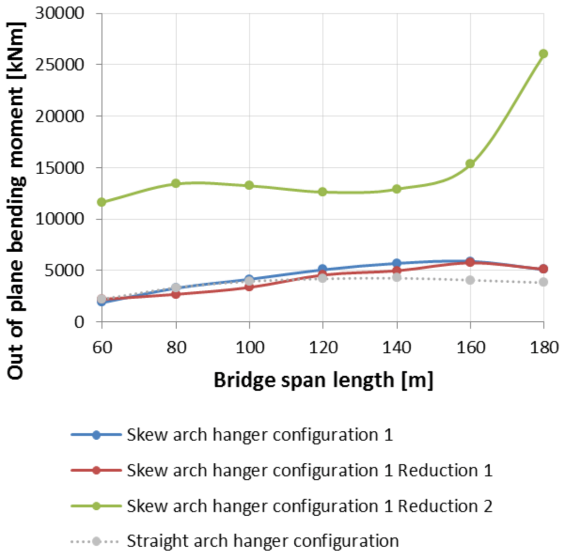

Figure 6. Out of plane bending moments in arch with hanger configuration 1 for varying span length

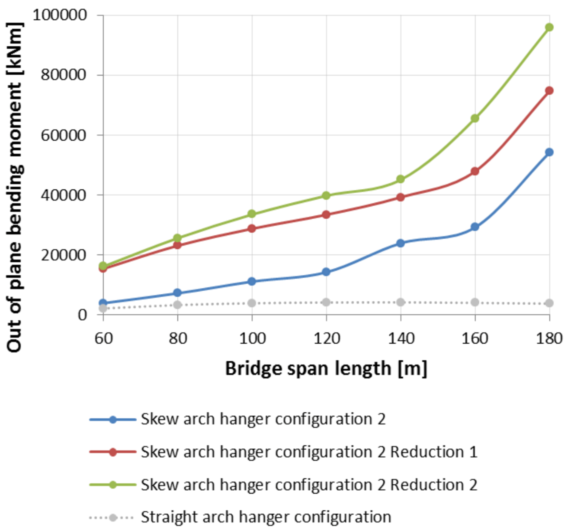

Figure 7. Out of plane bending moments in arch with hanger configuration 2 for varying span length

Similar observations about minimizing the number of hangers in configuration 1 and 2 are valid for changing the deck width or the angle of skewness.

4.2 Influence of the deck width

Compared to the modification of the span length, a more linear increase in bending moment is observed when the deck width is enlarged. As the rise-to-span ratio does not change for varying deck widths, the relative importance of the out of plane bending compared to the in plane bending moment remains large for each deck width. Hence, out of plane bending remains determining for the bridge design.

For increasing deck widths, the position of the critical arch and deck sections respectively shifts from 0.25 and 0.3 times the span length distanced from the deck extremity towards the center of the bridge. On the other hand, for each investigated deck width, the most loaded arch and deck sections in the reference models with skew arch hanger configuration 2 remain respectively 0.3 and 0.5 times the bridge length horizontally separated from the abutment. When varying the deck width, or span length, the bending moments in both the arch and the deck are much more critical when hanger configuration 2 is considered compared to the use of hanger configuration 1. To avoid yielding of the steel in the arch, the bridge deck width has to be limited. For the geometry and arch thickness considered in the reference model, the deck width has to be below 21 m for the models with skew arch hanger configuration 1 or configuration 1 reduction 1 and below 10 m for the models with skew arch hanger configuration 2 or configuration 2 reduction 1. Nevertheless, to prevent vehicle-cable conflict, the deck width should be limited to 18 m in the model with configuration 1. An upper boundary of 14 m and 6 m applies for the model with skew arch hanger configuration 1 reduction 2 and skew arch hanger configuration 2 reduction 2 respectively.

4.3 Influence of the angle

When changing the angle of skewness, nearly all the changes in the arch and deck behavior can be assigned to the modification of the cable inclinations and hence to the force transfer by the hanger arrangement. In the reference models with skew arch hanger configuration 1 and reduction 1, the arch is used most efficiently for angles of skewness larger than 12°. Hereby, an upper boundary of 25-30° applies for practical and realistic applications. Nevertheless, for angles larger than 16°, the minimum required vehicle clearance is no longer present in the reference model. In reality, this translates to arch abutments which will be located next to the bridge deck, indicating that the angle of skewness is often related to the deck width. For angles larger than

12°, the out of plane bending moments are minimal (Figure 8) as are the resulting maximum arch and deck deformations. Nevertheless, the out of plane bending moments remain determining in the bridge design and the contribution of the axial compression in the force transfer through the arch remains limited.

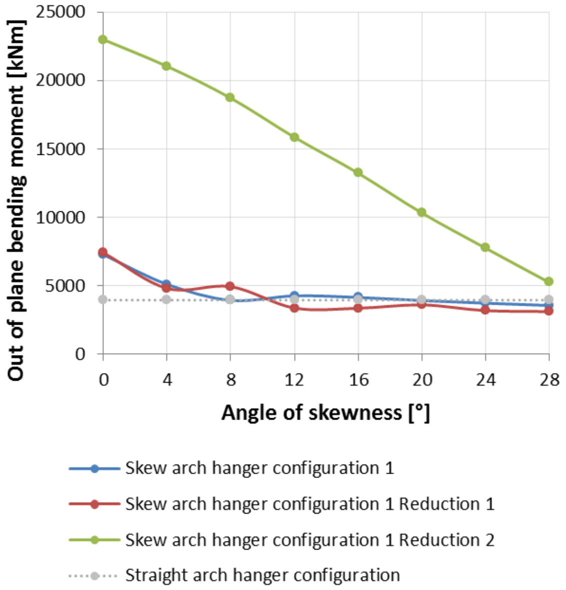

Figure 8. Out of plane bending moments in arch with hanger configuration 1 for varying angle of skewness

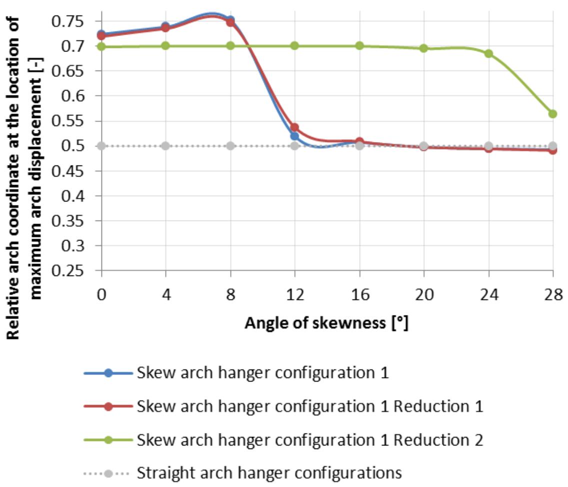

Figure 9. Relative arch coordinate of maximum arch displacement in configuration 1 for varying angle of skewness

For angles in between 12° and 16°, the design out of plane bending moment is similar to the design moment for straight arch bridges with the same dimensions as the reference models (Figure 8).

For the range 12-16° of skewness angles, the location of the critical arch section is situated near the arch crown. This is because the critical section shifts in between an angle of 8° and 12° horizontal from 0.25 to 0.5 times the bridge length separated from the arch end. This is observed in Figure 9. For angles in between 6° and 28°, the critical deck location shifts from the bridge center towards a distance 0.3 times the span length from the abutment.

For the bridge structure where the number of hangers is reduced a second time, the optimum angle of skewness lies beyond practical and realistic angles of skewness (>30° in Figure 8).

In comparison to configuration 1, no optimum angle of skewness exists for bridges with skew arch hanger configuration 2. For increasing angles of skewness, the inclination of the cables becomes more and more advantageous. Hence, the largest practically applicable angle of skewness that is still realistic should be chosen in order to minimize the bending moments (Figure 10).

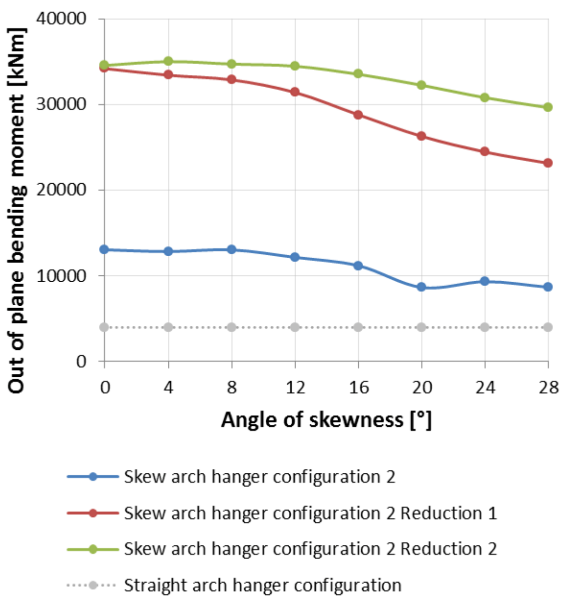

Figure 10. Out of plane bending moments in arch with hanger configuration 2 for varying angle of skewness

Nonetheless, the bending moments in configuration 2 remain always a factor 2-3 larger than the design moments in arrangement 1. Consequently, configuration 2 is at least a factor 2-3 less efficient compared to straight arch bridges. As the arch abutments are in reality often located immediately next to the bridge deck, configuration 2 can be used for relatively wide bridges compared to the span length. The reason is that for those bridges the angle of skewness of the arch is large. For large but realistic angles of skewness, the critical arch and deck section are located at a horizontal distance of 0.33 and 0.45 times the span length from the abutment.

5 Buckling analysis

In comparison to straight arch bridge models which buckle in an out of plane sine wave due to large axial arch compression, no global arch buckling is observed for skew arch bridges. The reason is that no relevant load combinations exist which load the arch mainly in axial compression. Under the effect of the deadweight and uniform mobile loads, the arch is subjected to significant in and out of plane bending moments. At the locations where bending moments are maximal, the arch has the largest deformations and is subjected to the most severe curvature. Due to this maximal arch curvature, critical compression forces develop within the webs of the arch box section. Eventually this compression can induce local plate buckling of a web of the arch box. The most efficient way to prevent the local plate failure is increasing the shell thickness of the arch or adding stiffeners. The difference in buckling behavior between the models with skew arch hanger configuration 1 and 2 and the effect of changing the bridge span length, bridge deck width and angle of skewness is determined by the difference in magnitude and location of maximal arch deformations. For the reference skew arch models 1 and 2 from Figure 2, the loads in the critical load combination can increase respectively with a factor 12.81 and 11.25 before inducing local plate buckling. Hence, buckling will only be observed when the stress levels in the arch steel have already largely exceeded the yield strength. This indicates that buckling is not a stringent requirement for the design of skew arch bridges. Consequently, no sudden failure due to buckling is expected. (Figure 11)

6 Conclusions

Skew arch bridges are less prone to deformations than straight arch bridges under asymmetric live loads and can therefore be useful when the live to dead load ratio is large.

Furthermore, it can be concluded that a skew arch bridge with hanger configuration 1 is structurally more efficient than a skew arch concept with cable configuration 2, as can be seen when comparing the much lower bending moments shown in Figure 8 with those in Figure 10. Nevertheless, the useful deck width in configuration 1 is lower than for configuration 2 due to vehicle-cable clearance requirements.

In bridges with skew arch hanger configuration 1, the number of hangers can be quite low without inducing more stringent design conditions than for a bridge with a lot of cables.

In order to use the bridge material most efficiently, the angle of skewness should be at least 12° when opting for hanger configuration 1 or should be designed as large as possible for a bridge with hanger configuration 2. For both bridge concepts an upper boundary in the range of 16°-30° is assumed for practical and realistic applications. Nevertheless, for configuration 1 the upper limit is often induced by vehicle clearance regulations. Practically, arch abutments next to the bridge deck form a good design.

7 References

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