Arch Bridges
ARCH´04
P. Roca and E. Oñate (Eds)

FATIGUE OPTIMIZATION IN NETWORK ARCHES

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Key words: Network arches, arch bridges, fatigue, hanger details, hanger arrangements, stress concentration factor

Abstract. *Hangers of network arches are subject to variable axial forces. There is a danger of fatigue ruptures in the upper and the lower ends of the hangers.*

Two aspects should be examined: First, the geometry and production of the hanger details, and second, hanger arrangements that reduce the variation in the hanger forces.

Because of the geometry of the welds at the ends of the hangers there will be considerable notch effects. To achieve sufficient fatigue resistance it is necessary to minimize the occurring stress peaks and to try to achieve a homogeneous stress field. The danger of fatigue cracking will be minimized with the help of parametrised shape and topology optimization. Afterwards the fatigue notch factor in the optimized hanger ends will be determined and compared to the corresponding fatigue detail categories of the Eurocode. At the end of the first investigation a geometry function of the stress concentration factor will be developed so that future designers will not have to do a finite element analysis.

In the second part hanger arrangements that give a suitable reduction of the variation of the hanger forces will be sought. The slope of the hangers strongly influences the stress variation. This is one reason for examining a multitude of hanger arrangements.

In railway bridges the reduced variation in the hanger forces will lead to hanger arrangements which give no hanger relaxation due to loads only on part of the span. This might also be the case in road bridges.

1 INTRODUCTION

Hangers in tied arch bridges – especially for railway traffic - are subject to varying strains due to changes in the hanger forces. This can be dangerous in terms of fatigue failure, depending on stress magnitude and number of stress cycles.

In this respect, the connections of the hanger bars to the arch and lower chord should be considered as critical, because alterations in the geometry and notch effects of connecting welds cause non-uniform stress conditions. The maximum stress peak at the notch tip is determined by the depth of the notch and the notch tip sharpness. In order to provide sufficient security against fatigue failure it is necessary to minimise stress peaks that cause cracks and to ensure homogeneous stress distribution within the whole element. With the help of parameter-based shape optimisation and subsequent topology adaptation the aim is to reduce the danger of fatigue failure. For the connection detail developed under these aspects, the notch effect – expressed by the stress concentration factor – is determined and the detail classified into standards according to the nominal stress concept.

This paper is part of the author's research work at Dresden University of Technology.

2 OPTIMISATION OF HANGER CONNECTION DETAILS

2.1 General

Optimisation is the process in which a specified objective function f(x) is maximised or minimised by combination of n independent variables (optimisation parameters) respecting certain boundary conditions. The optimisation task can be expressed mathematically as follows:

$$\text{Minimise } f(x) \quad \text{with } x = (x_1, x_2, x_3, \ldots, x_n)^T \quad x \in \Re$$
$$\text{under consideration of}$$
$$h_k(x) = 0 \qquad k = 1, 2, \ldots, n$$
$$g_j(x) \geq 0 \qquad j = 1, 2, \ldots, p$$

The functions $h_k(x)$ and $g_j(x)$ represent the equality and inequality condition.

First of all, for the iterative solution of the given mathematical problem a starting vector x_{v1} must be chosen. The search direction d_v of the linear optimum search which is multiplied by the increment γ is determined by a sensitivity analysis. By derivation of the objective function with respect to the optimisation parameters $\delta f(x)/\delta x$, the gradient delivers an appropriate functional search direction in the following form:

$$x_{v+1} = x_v + \gamma \cdot d_v$$

The iteration is carried out until a suitable abort condition is met. To make sure that a global extremum of the objective function is found, it is advisable to perform a second calculation with a different starting vector $x_{v2.}$

The defined goal of minimisation of the highest principal tensile stress is carried out with the help of the tool implemented in the computer programme iSIGHT v.7.0[i]. The algorithm used for this special problem will be introduced in section 2.3.

2.2 Starting point and analysis of loading conditions

Because of the fact that hangers in network arch bridges cross each other, the fist question to be answered is how to design the hanger connections. The hanger bars should be directed in such a way that they pass each other in order to avoid force diversion and therefore bending. This has consequences in a necessary eccentricity of the connections with the size of the hanger's radius. There are two ways for its constructive realisation. The first possibility is an asymmetrical connection plate aligned perpendicularly to the arch plane. A second possibility is a symmetric gusset plate lying in the plane of the arch and placed eccentrically. In order to reduce the complexity of the shape optimisation, the version with the symmetric gusset plate has been followed up. This form of hanger connection to arch and lower chord has often been carried out in praxis.

The hanger connection illustrated in Figure 1 is used as a starting model. The calculation of the introduced hanger connection model with the FE-programme ABAQUS[ii] leads to the stress distribution shown in Figure 2.

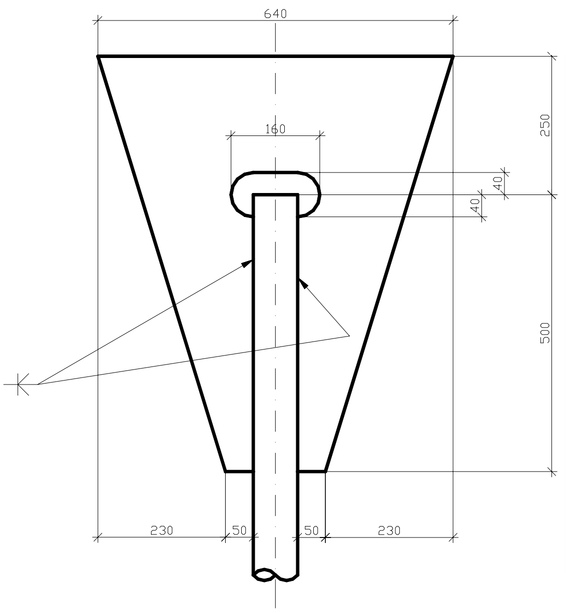


Figure 1: Geometry of the hanger connection

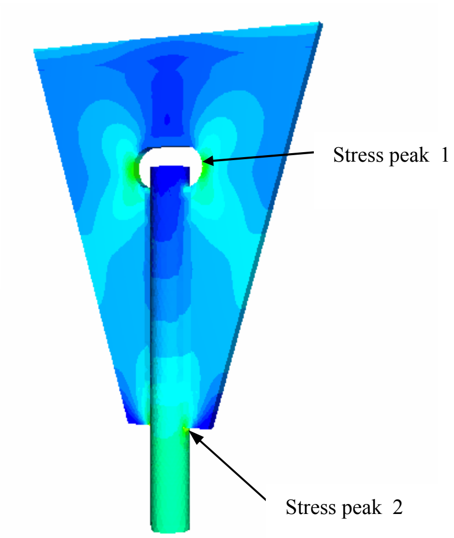


Figure 2: Stress distribution in the connection

This contour plot illustrates the first principal stress which is used for the analysis of the stress distribution. As expected, increased stress values can be found in the vicinity of the cut-out (Stress peak 1) and the transition between hanger and connection plate (Stress peak 2). These values are quantified with a suitable degree of meshing in section 2.5. There is a tendency to higher stress peaks at the transition between hanger and connection plate compared to the cut-out region, because of a higher notch sharpness and therefore a higher notch effect. This assumption is confirmed by the standardised detail categories (see ENV 1993-2, Annex L). In the next step, an attempt is made to decrease the maximum stresses by means of shape optimisation leading to a beneficial connection design in terms of fatigue.

2.3 Shape optimisation

Shape optimisation serves as a tool to determine optimal surface shape of structural elements. For this purpose an adapted algorithm was designed, which suits the present problem (see Figure 4). Under compliance with predetermined boundary conditions a defined goal is achieved by systematic alteration of the outer edges (contour) of a given FE-model. In the present case the objective function is to minimise the occurring stress peaks, whereby only the first principal stress σ_1 (principal tensile stress) is considered. According to the laws of fracture mechanics the fractured surface of a perpendicular fracture is orientated perpendicularly to σ_1. The calculations of the stress values are based upon linear-elastic material behaviour.

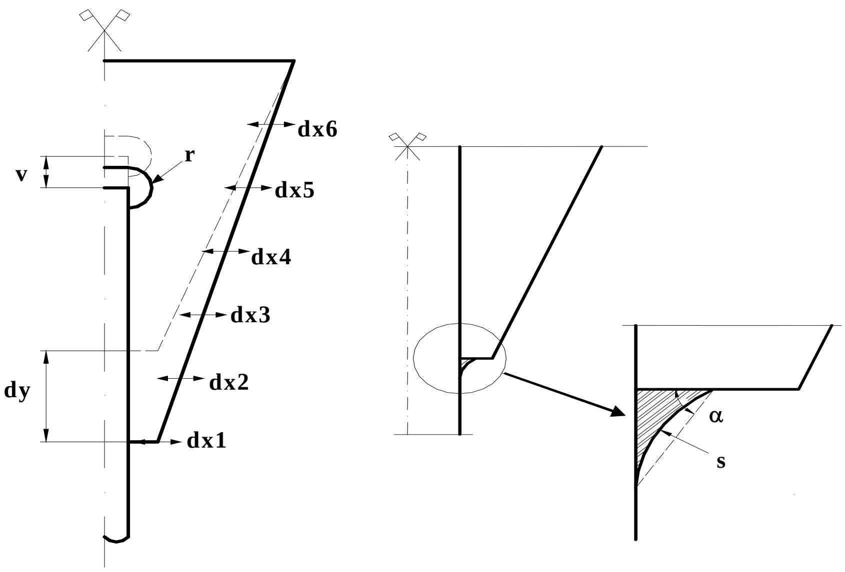


Figure 3: Optimisation parameters

The optimisation strategies used in iSIGHT require a parameterised geometry. Consequently it is first necessary to define the parameters that will be varied by the programme. Number and type of the free values are to be chosen so that the structure of the hanger connection is modelled adequately and that it can be changed sensibly during the optimisation process. Figure 3 shows the parameters required for the alterations to the member geometry. The outside contour of the plate is approximated by a polygon. The contour adaptation is achieved by varying the parameters “dx1“ to “dx6“ in the end points of the polygon lines. Furthermore, the weld length, cut-out radius, distance between cut-out and free edge, the angle of the weld that decays to zero thickness and the fillet radius of the weld are changeable by the parameters “dy“, “r“, “v“, “α“ and “s“.

The optimisation is carried out in two steps. It starts with a sensitivity analysis with the DONLP-method (Sequential Quadratic Programming)[i] in order to verify the influence of the important parameters on the optimisation criterion (output values) and deactivate insignificant values. The values determined in step 1 are used as input information for the Direct-Heuristic-Search-Method (DHS)[i] in the second step. Additionally it is verified whether a global extremum was found. This is done by carrying out the iteration algorithm again with modified starting vectors and varied increment (checking calculation).

Both optimisation algorithms run in an iterative way. The iteration process shown in Figure 4 is performed until a numerical convergence criterion Δ is met. For this the difference in the results of the last two consecutive steps are determined. In the existing calculations the value was set to Δ=0,01 N/mm².

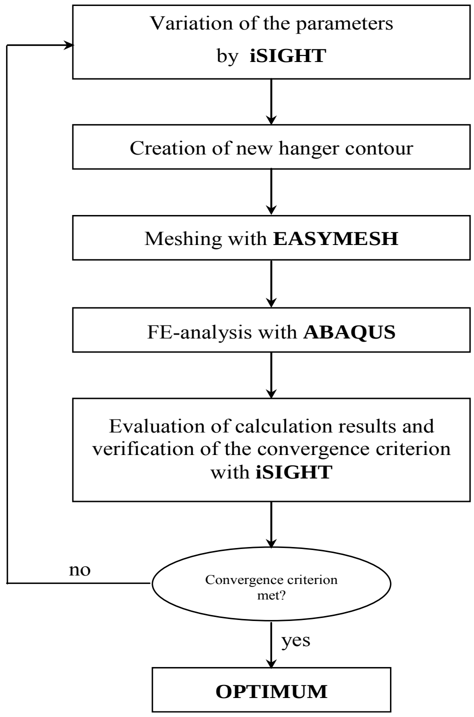
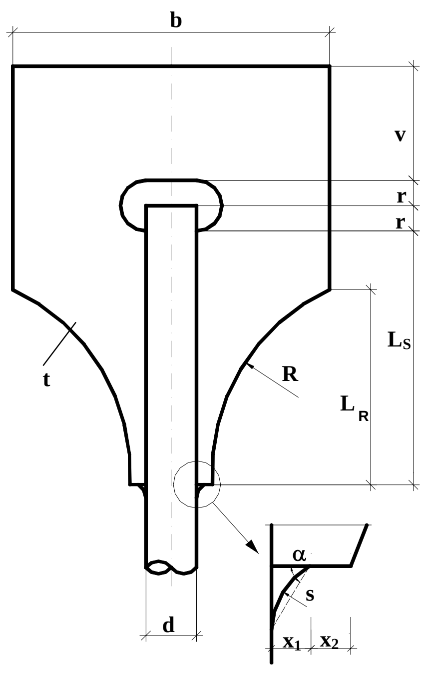


Figure 4: Optimisation algorithm



- b....connection width
- t.....plate thickness
- d....hanger diameter
- $L_S = 2...2{,}5 \cdot \frac{N}{zul\tau \cdot 2 \cdot t}$
- $L_R = 0{,}5...0{,}8 \cdot L_S$
- $R = \frac{B_R^2 + L_R^2}{2 \cdot B_R}$

  mit $B_R = b/2 - d/2 - x_1 - x_2$
- $r \approx d/2$
- $v = 0{,}3...0{,}5 \cdot L_S$
- x_1...depending on the gap between plate and hanger as well as the chamfer angle of the plate

  x_2...to be chosen according to constructive considerations (as small as possible)
- $\alpha = 60°$
- $s_{min} = \frac{x_1^2 + (x_1 \cdot \tan\alpha)^2}{2 \cdot x_1} < s < s_{max}$

  with $s_{max} \approx s_{min} + 3...10\text{mm}$
  depending on the values of x_1 and α

Figure 5: Results of the optimisation

The eventual result is the hanger geometry shown in Figure 5, which is a compromise between calculation results as well as constructive and esthetical requirements. The numerically extensive process shown here is not suitable for everyday design praxis. Therefore, based on the research done, recommendations are given for engineering applications how to improve the fatigue behaviour of hanger connections with little effort.

2.4 Topology optimisation

Topology optimisation means in this case the variation of the gusset plate thickness and the hanger diameter in the connection area. In the investigations performed the influence of these two values on the stresses at the transition between hanger and gusset plate σ_S and at the cut-out σ_f was verified and conclusions drawn.

In the first step the plate thickness t was varied whereas the hanger diameter d was kept constant. As expected, the value of the maximal stress at the cut-out decreases with increasing plate thickness due to the increase of provided sectional area. The stress decay is hyperbolical, analogous to the nominal stress. The ratio of the maximal stresses σ_{max} to the nominal stresses σ_{nom} is constant for all plate thicknesses, which means that the notch effect in this area is unchanged. The rise of the function of the stress decrease is significantly smaller for high values of t than for lower values. Therefore it is reasonable to increase the plate thickness up to a certain value above the static requirements. A thickness of about $1{,}7...2{,}1 \cdot t_{req}$ is recommended. At the same time it is necessary to verify that the ratio of t/d fulfils constructive and aesthetical demands. Considering the influence of the variation of t on the maximal stress at the transition between hanger and gusset plate shows that the stress value changes only very little, the plate thickness consequently has no influence.

In the second step the hanger diameter was varied whereas the plate thickness was kept constant. This analysis is derived from the suggestion in the standards of the Deutsche Bahn (DB) to increase the hanger’s cross section in the connection area. The FE-analysis gives approximately the same results that had already been obtained by variation of the plate thickness. Analogously, the maximal stress and the nominal stress decrease hyperbolically with an increasing hanger diameter. However, in this case the decay is more uniform. Looking at the quotient $\sigma_{max}/\sigma_{nom}$ no change of the numeral value and therefore the notch effect can be reported either. The change in the hanger diameter does not affect the value of the maximal stress at the cut-out. With the obtained results the guidelines of the DB regulations can be confirmed, because the increased hanger cross section caused by the widening leads to lower maximal stresses. However, the fact of a high number of hangers in network arch bridges raises the question of economics. Therefore, the increased expenditure of human labour due to the fabrication of the butt weld between the hanger and the widening at the end is to be balanced carefully against the enhancement of fatigue resistance.

2.5 Results

With the procedures described in sections 2.3 and 2.4 the hanger connection described in 2.2 was optimised. In the following the initial geometry and the optimisation result are compared considering stress peaks. The comparison is mainly focused on the critical notch at the transition point between hanger and gusset plate. The consideration of the geometrically improved connection detail contains ground welds (consideration of the variable parameter “s”) as well as untreated welds ($s \rightarrow \infty$). The reason for this is the intention to weigh the pros and cons of the weld treatment.

The first subject of comparison is the stress gradient along the contour edge of the 2D-model, which is the basis of the optimisation. The path leads from the force transmission point in the FE-model to the bottom corner of the plate (Figure 6). Figure 6 shows the stress gradients of the input geometry as well as the optimised geometry with treated welds (index 1) and untreated welds (index 2). Besides the significant differences of the stress values an obviously earlier beginning of the stress transition can be seen in the adapted models. Whereas the optimised geometry without weld treatment still shows larger local stress peaks (stress at the lower notch is about twice as high as at the upper one), grinding the welds helps to distribute the stress increase due to force deviation to a larger area (homogenisation of stress). It must be mentioned here again that calculations have been performed according to the theory of linearly elastic material.

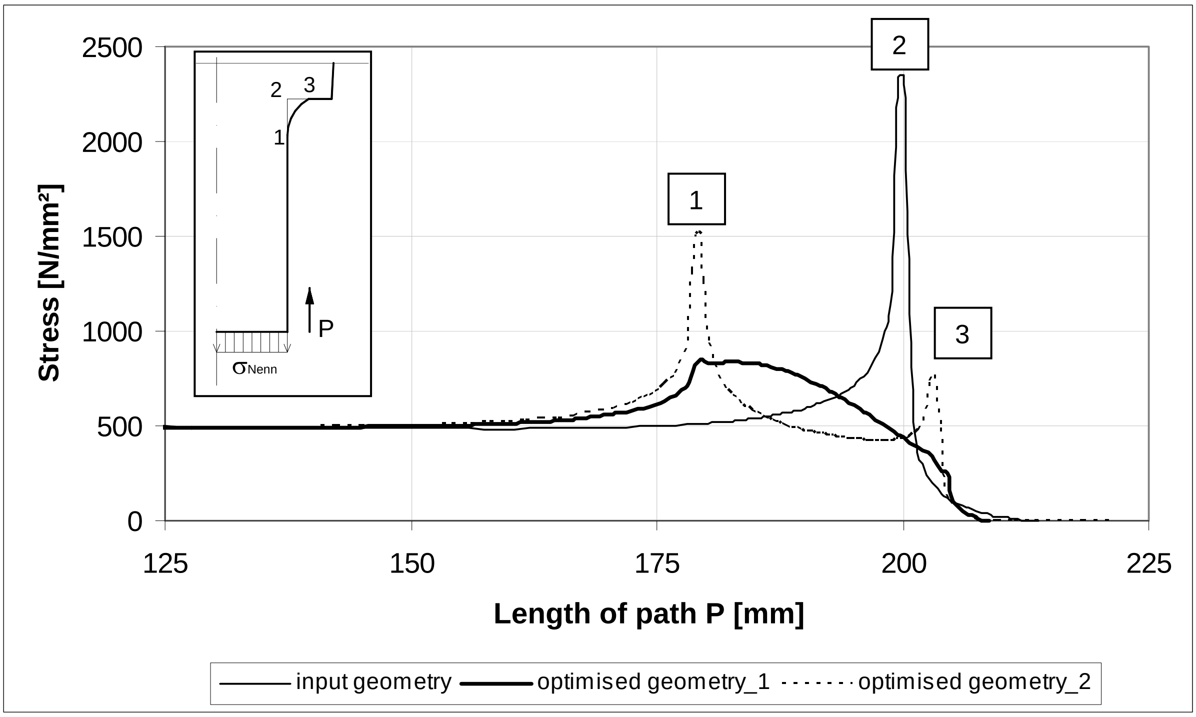
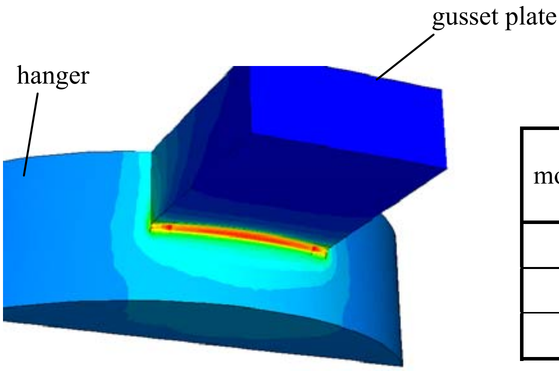


Figure 6: Stress gradient at the outer edge

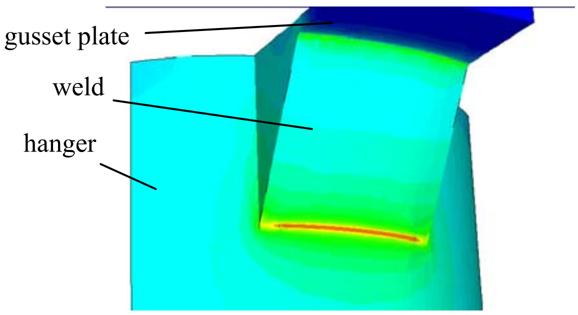
The stress values shown in Figure 6 do not represent the real elastic notch stresses, but they are exemplary results of the FE-analysis of the 2D-model (element size at notch 1 mm) for a load of 1000 kN, which is sufficient for the comparison of the stress gradient. Nevertheless, it is adequate to display the stress gradients qualitatively.

The calculation of the elastic notch stresses was performed with the help of an algorithm for submodelling implemented in ABAQUS. Firstly, a coarse mesh of the whole connection detail was calculated by FEM and secondly the calculated deformation components were applied as boundary conditions to the sections of the sub-model. The submodel incorporates the area directly around the transition of hanger to gusset plate and receives a significantly finer mesh. Figure 7 shows the stress-plots of the submodels of the three connections considered and the results obtained. The conclusions already drawn from the analyses of the stress gradients along the contour edge are confirmed. In model 3 the distribution of the highest stress in a more expanded area caused by the grinding of the weld can be seen clearly, while local stress peaks occur in models 1 and 2. All calculations have been performed with a hanger force of 1000 kN, which means a nominal stress of 198.94 N/mm² taking a hanger diameter of 80 mm. The size of the notch effect can be estimated by looking at the stress concentration factor. It is the ratio of the elastic notch stress to the nominal stress and was determined, in the discussed case, according to the concept of RADAJ[iii,iv]. Comparing the results shows that the notch effect of the ground weld is only half as high as that of the untreated one. This means 3.75 times higher fatigue resistance compared to the input model.

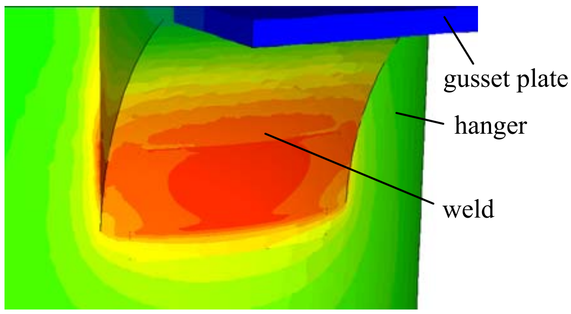


model 1: input geometry

model	elastic notch stress	stress concentration factor
1	359 N/mm²	1,80
2	700 N/mm²	3,52
3	1350 N/mm²	6,78



model 2: optimised geometry with untreated welds



model 3: optimised geometry with treated welds

Figure 7: Results of the stress analysis at the transition hanger-gusset plate

3 STRESS CONCENTRATION FACTORS AND PROSPECTS

For the construction of a fatigue proof hanger connection detail the fatigue resistance has to be assessed by calculation. Possible assessment methods are contained in current standards, such as DIN 4132 and ENV 1993-1-1. They are based on detail categories and nominal stress range classes (FAT-classes). It is difficult to classify the hanger connection detail discussed because no similar detail categories are contained in these catalogues. Another point is the global approach of the normative assessments. Local effects like weld geometry or notch stresses are only considered approximately.

SEEGER, OLIVIER[v] developed a concept for a fatigue calculation without using detail categories. This so called „Mittelwert/Streuungs-Kerbspannungskonzept“ is independent from detail category catalogues and allows the determination of the fatigue resistance by Wöhler curves especially worked out for this purpose. For the assessment the fatigue-relevant elastic notch stress is to be verified against theses special Wöhler curves. It is possible to perform this for every weld and weld connection geometry.

Indeed, for this concept it is necessary to determine the real stress concentration factor K_f representing the ratio of the elastic notch stress to the nominal stress. Besides some standardised details, for which stress concentration factors are listed in the literature (for example PETERSON[iv]) or an analytic solution can be found, only experimental and numerical methods like the finite element or boundary element method are available for calculation. These analyses require high modelling and calculation efforts in order to achieve serviceable results or they are quite costly in the event of experiments. For this reason they are hardly relevant for the structural engineer.

The aim is to develop an analytic formula for K_f at the critical transition point between hanger and gusset plate to help the user to obtain desired results more efficiently. Consequently, the application of the notch stress concept on hanger connection details will be facilitated. Different hanger diameters, gusset plate thicknesses and parameters of the optimised hanger connection geometry (see Figure 5) are considered. Systematic results have not been available before the entry deadline, because they will be elaborated on in the course of the actual research performed at the Chair of Steel Structures of Dresden University of Technology. For further information please contact the author of this paper.

Another important point for the reduction of fatigue strains on the hangers is the variation of the hanger slope and the involved design of the whole hanger net. The stress range changes depending on the hanger slope. For the choice of the hanger’s inclination not only the maximal stress range is relevant but also the maximal hanger forces and bending moments in the arch and lower chord. Remarks on this topic can be found in BRUNN, STEIMANN, SCHANACK[xi]. Investigations based on the discussed aims using a specially developed optimisation algorithm will continue the development towards an optimal hanger arrangement including comparison with already existing bridges.

4 ACKNOWLEDGMENT

Finally, I would like to express my gratefulness to Dr. Per Tveit, Dipl.-Ing. Benjamin Brunn and Dipl.-Ing. Frank Schanack for the outstanding collaboration.

For the programmes iSIGHT and ABAQUS academic licenses were used.

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