Towards lifetime optimization of hanger connection plates for steel arch bridges

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Abstract

Deterioration and damage in hanger connection plates of steel arch bridges, caused by wind induced vibrations, often have severe impact on the overall safety of the structure. In this paper, an approach for the shape optimization of such connection plates is presented. Herein, various lifetime oriented design criteria are discussed and some techniques for shape optimization using the *p*-version of finite elements are described. The actual optimization is carried out by using evolution strategies. First design studies show promising results.

Keywords: Lifetime oriented design; Shape optimization; Fatigue; *p*-version of FEM; Evolution strategies

1. Introduction

Various recent damage has proven that connection plates of steel arch bridges are highly sensitive to high-cycle fatigue (Fig. 1). Observed cracks in the plate are often initiated by high-cycle fatigue due to vibrations of the rod caused by vortex induced transverse vibrations [1], occurring at relatively slow wind speeds. Resonance effects cause substantial displacement amplitudes which, together with a large number of cycles, result in severe damage within surprisingly short time periods.

The present contribution is about an ongoing research project in the context of the collaborative research center SFB398 entitled 'Lifetime Oriented Design Concepts' at the Ruhr-University of Bochum. This subproject deals with the lifetime-oriented design of steel arch bridges which represents a multi-scale and multi-level problem in time as well as in space. The multi-level model which is currently under development hereby covers the overall dynamic analysis of the bridge, the time-variant reliability analysis of failure sensitive structural elements as well as the lifetime-dependent optimization.

On the optimization level, the aim is to develop an optimization model for the connection plates which particularly takes into account lifetime critical aspects. This includes (i) the formulation of adequate criteria to assess a design with respect to lifetime and (ii) the

development of structural analysis tools well suited for the optimization of continuous structures.

2. Design criteria

In design optimization, the original design problem is transformed into an optimization problem by expressing the relevant design criteria in terms of functions f_i, depending on the design vector $\mathbf{x} \in \mathbb{R}^n$. Hereby, the choice of adequate design criteria is essential for the success of structural optimization. For the actual connection plates the most relevant design criteria have to be related to lifetime. In fact, the lifetime of the connection plates depends on various aspects which are all of highly probabilistic nature (e.g. wind, traffic, material, etc.). Precise lifetime prediction for the connection plates thus requires a substantial amount of research and computer time. For practical optimization, reasonable design criteria, which lead to an extended lifetime with less effort, would be useful. In the following, potential candidates for design criteria are discussed:

Volume of welds Since the observed damage is often noted at the welds, the total volume of the welds represents a deterioration-relevant design criterion. It is related to the failure probability as well as to production costs.

Maximum stress Damage mostly occurs in the vicinity of areas with high stress concentrations. The maximum value of the equivalent stress within the connection plate

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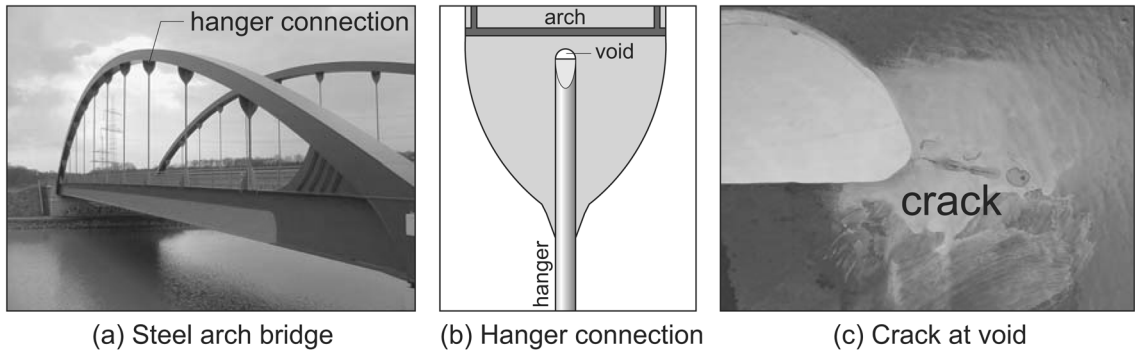(a) Steel arch bridge   (b) Hanger connection   (c) Crack at void

Fig. 1. Hanger connection and crack in connection plate.

therefore matches the failure probability to a large extent.

Time variant reliability analysis The most general design criterion is the failure probability for a specified lifetime computed by means of a time variant reliability analysis. Within the SFB, an approach for the damage assessment has been created which is based on the concept of stochastic S/N-curves in association with variants of the Miner-Rule. As the determination of the structural reliability involves time-consuming stochastic simulation procedures during optimization, a distributed approach is needed using a massively parallel computer environment.

Currently, the above-mentioned criteria are evaluated with respect to their applicability for the lifetime-oriented design of connection plates. For that, the time dependency of the optimization problem is neglected at first. It is intended to create a structural optimization kernel which, based upon the numerical feasibility studies currently being carried out, can then be implemented into much more sophisticated lifetime-oriented structural optimization.

3. The *p*-version of FEM for shape optimization

In the *p*-version of the finite element method, the structure is discretized by means of relatively large elements of high polynomial degree. Since elements in the *p*-version are highly insensitive to distorted meshes, this method is especially well suited for the optimization of continuous structures [2,3]. Compared to structural optimization using the *h*-version [4,5], the *p*-approach does not require time-consuming adaptive remeshing during optimization.

3.1. The geometric model

In the *p*-version, usually the blending function method [6] is employed to describe the geometry of the elements.

For quadrilateral elements, the geometry is defined by four curves connecting the four vertices, whereas the mapping is constructed by linearly interpolating between the curves. Non-uniform rational B-splines (NURBS) have proven to be particularly suited for optimization purposes and are, therefore, employed for the description of the edges.

Besides the accurate and flexible description of the domain, shape optimization imposes additional requirements on the geometric model. Primarily, mesh regularity must be ensured even if large changes of the geometry occur during optimization. Figure 2(a) shows the initial shape of the void of a connection plate which is undergoing a remarkable shape in change. The resulting irregular shaped elements in Fig. 2(b) exemplify the need for advanced techniques in parametric geometry description.

Segmented edges Often, a part of the outline can be conveniently described by a single curve whereas intermediate nodes are introduced only for meshing purposes. Therefore, so-called segmented edges are used, where one single curve is shared by several elements. Figure 2(a) shows a segmented edge which is shared among five elements.

Parameter adaptation In order to preserve mesh regularity, the curve parameter t of nodes lying on a segmented edge must be adapted according to shape changes. The employed adaptation criterion hereby is such that the other edge connected to the actual node should intersect the segmented edge by an angle of 90 degrees. This condition can be stated as the one-dimensional minimization problem

$$\min_{-1 \leq t \leq 1} ||\mathbf{E}(t) - \mathbf{P}|| \tag{1}$$

where $\mathbf{P}$ is the other node of the intersecting edge. Problem 1 can easily be solved by any one-dimensional minimization technique, e.g. golden section search [7].
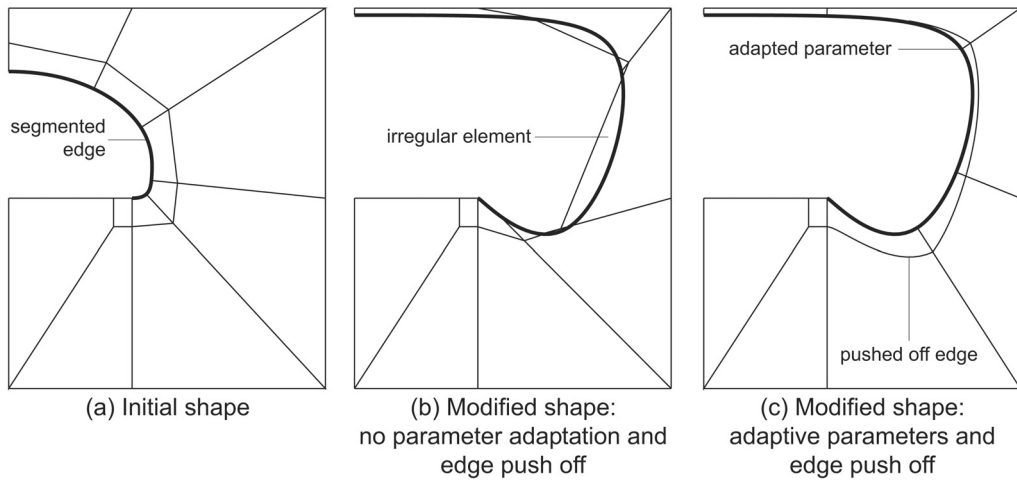
Edge push off In order to avoid self-intersecting

(a) Initial shape

(b) Modified shape:
no parameter adaptation and
edge push off

(c) Modified shape:
adaptive parameters and
edge push off

Fig. 2. Detail of the mesh for a hanger connection plate.

(a) Dimensions of initial design
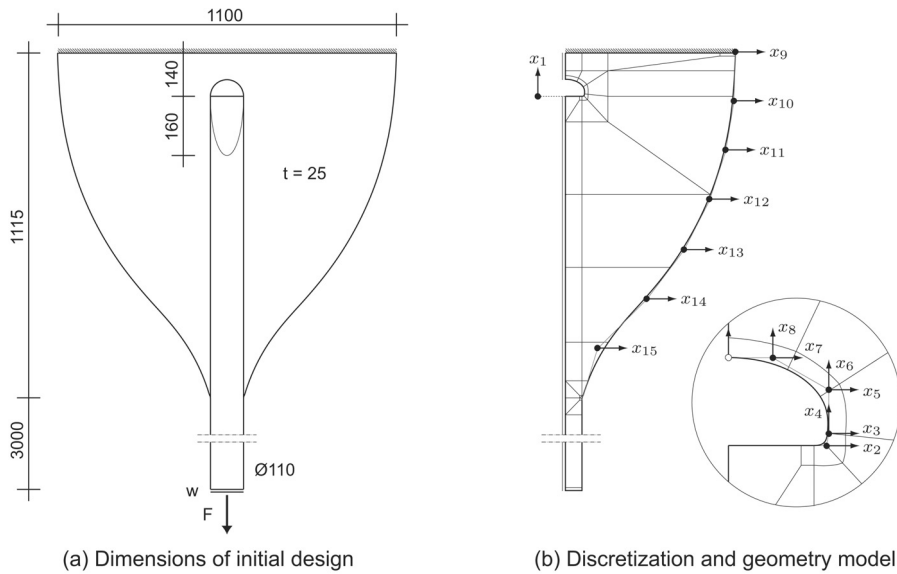
(b) Discretization and geometry model

Fig. 3. System and geometry description in terms of design variables.

elements, it can be necessary to control the shape of one edge by another edge. The pushed off edge $\mathbf{E}_p$ can be described by

$$\mathbf{E}_p(t) = \mathbf{E}_p^s(t) + \alpha(\mathbf{E}(t) - \mathbf{E}^s(t)) \qquad (2)$$

where $\mathbf{E}$ is the controlling curve and α the push-off factor. The straight connection between the end-points of the controlling curve is $\mathbf{E}^s$ and $\mathbf{E}_p^s$ for the controlled curve respectively. Figure 2(c) shows the application of the above techniques.

4. Design study – first optimization results

As part of the ongoing research, the optimization of a connection plate is presented that is similar to the existing plate at the Hiltrup bridge in Germany (Fig. 1(a)). In this design study, however, only time invariant design criteria are considered.

The initial dimensions of the plate are shown in Fig. 3(a). Two loading cases are taken into account: loading A is an in-plane tension force of $F = 975$ kN acting on the hanger and loading B is a prescribed out-of-plane
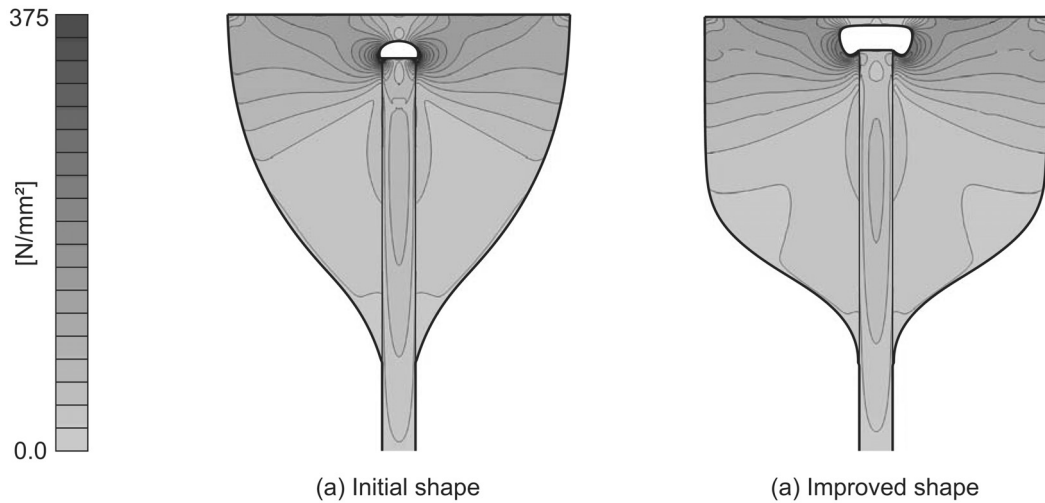
Fig. 4. Initial and improved shape – equivalent stress for loading B (out of plane).

displacement $w = 57$ mm, in the middle of the hanger. The material is steel where $E = 210\,000$ N/mm^2 and $\nu = 0.3$. Linear elastic material behavior is assumed.

The system is modeled by means of two-dimensional elements. Two separate models are established; one for each of the two loading cases (plane elements for loading A and Reissner–Mindlin plate elements for loading B). Figure 3(b) shows the discretization defining 39 p-elements and utilizing the system's symmetry. The structural analysis is performed using an object-oriented FE-system developed by the authors [8].

As a starting point for the investigation of different design criteria, the connection plate is optimized with respect to the maximum stress criterion. The objective function taken is the sum of the maximum stresses of both loading cases where loading B is weighted by a factor of 0.75. The shape of the plate is described by 15 design variables being coupled to the control points of the NURBS representing the outer curve as well as the shape of the void (see Fig. 3(b)). Bounds are imposed on the design variables such that the overall dimensions are limited to the initial ones. The resulting optimization problem is therefore unconstrained.

Gradient based optimization algorithms completely failed to find a good solution for the actual problem.

This is because the max-operator involved in the computation of the objective function ruins C^1-continuity. As a consequence, the optimization was carried out using evolution strategies [9] on a cluster of 37 Linux PCs.

As the results in Table 1 demonstrate, a substantial reduction of the maximum stress for both loading cases has been achieved in the optimization. Figure 4 shows the stress distribution of both the initial and the optimized shape for loading B. Further comparative studies have shown that the maximum stress mainly depends on the shape of the void being relatively insensitive to changes of the outer shape of the plate.

5. Conclusions

Ideas for the lifetime-oriented design hanger connection plates for steel arch bridges have been introduced. As it turns out, the lifetime design problem is a multi-level as well as a multi-scale problem in time and space for which the formulation of meaningful but easily computable design criteria is crucial. First results of the optimization are promising and show that the p-method, along with the suggested techniques for parametric geometry modeling, is appropriate. Further research is necessary to evaluate the optimized design using more sophisticated techniques, such as a time-variant reliability analysis. Also, the long-term optimization requiring time-navigated feedback with respect to design variables is still to be scrutinized.

Table 1
Maximum equivalent stress for initial and improved design [N/mm^2]

Loading	Initial design	Improved design
A (in plane)	311	151
B (out of plane)	780	271

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