Behaviour of several fatigue prone bridge details

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Abstract. Three fatigue welded bridge joints analysed in this work are the alternative details of the bottom flange connection. This construction detail is mainly used for the erection connection for steel and composite bridges. If applied in the place, where live load is significant, the fatigue becomes the main design criterion. The detail category is thus very important factor. The aim of this paper is to analyse the possibilities of the improving the behaviour of this detail, by various methods. First solution is to modify the shape of the cope hole to the elliptic shape. Second option is to use the “Olemutz” fully welded detail. This detail is often used in bridge designing despite there is no exact information about the fatigue category, and doubts of the performance exists. “Olemutz” is a long web plate slit that is filled by the double bevel weld after the execution of the bottom flange weld. The last detail is the elliptic cope hole filled by the plate-cap welded into an empty hole. The geometry is the same, as in the first case. The conclusion of the numerical analysis and the pilot fatigue experiments is discussed with several practical recommendations for designing.

1. Introduction

Fatigue design takes place in every bridge assessment and the fatigue issue could affect the whole dimension of the main bridge structure. There are many available fatigue details which are verified and recommended in codes, however not all details are covered.

The main purpose of this paper is to analyze the possibilities of the improving the behavior of three specific fatigue details - “Olemutz”, the elliptic cope hole and the elliptic cope hole filled by the welded plate-cap.

The first part describes the parametric study, which was performed in order to optimize the shape of the cope hole fatigue detail. The second part contains experimental pilot tests of the fatigue life of all studied fatigue details.

Bridge designers widely use EN 1993-1-9 [1] for fatigue assessment, where the methodology is based generally on nominal stresses approach. The fatigue strength is then divided into the categories according to the stress range for $2 \times 10^6$ load cycles, that the detail can withstand. The same fatigue details are also described in IIW recommendations [2]. Besides, there is a definition how to determine Hot spot stresses or Effective notch stresses. For the Hot spot method, the mesh performance, mesh density, element usage, and hot spots (points for integration stresses) location are given as well. Numerical Hot spot method is also appropriate in a combination with the experimental hot spot modification. Highly advanced modeling containing notch effect of weld is summarized in the chapter 2.2.4. Effective Notch Stress. A recommendation from this publication was used for numerical and experimental study of the elliptic cope hole detail.
A valuable source of knowledge provides master thesis written by Mohsen Heshmati [3]. There is a very similar cope hole detail study that provide series of new shapes that improve a standard using circular R=50mm hole. A portion of effort is put into observing a combination of shared and normal stresses.

The post welded treatment is also an alternative way how to increase a fatigue life of the cope hole. There is an experiment that follows this topic in the part [3]. Illustrative Figure 1 shows how burr grid of weld toe looks on the specimen. According to [3], the test results show an increase of 190% in terms of fatigue strength for cope-holes treated with Burr Grinding. The same conclusions can be found in Sung-Min Choi et al. [4].

Figure 1. The cope hole weld toe treated with Burr Grinding [3].

2. Studied details

The common solution for railway bridges is to divide them in the middle, allowing two erection parts to be easily transported to the site and welded only with one weld on the site, as shown in the Figure 2. However, the connection of the tensile lower flange is a subject of mainly live load stresses and thus the fatigue loads. To perform a transversal butt weld well even in a location of the web, the cope hole is usually placed, as shown in the Figure 2. The highlighted part shows the area that is exposed to the dynamic load and sensitive to the fatigue. Also, fatigue can limit the whole design of this structural element.

Figure 2. An example of the application of studied details. Cross section of the railway bridge with the lower deck.

Generally, three solutions were studied here.

- The standard fatigue detail with the cope hole R=50mm of category 71. Here, the detail was improved in order to increase the fatigue detail with usage of modern FEM tools.
- An alternative solution, used by designers, is called “Olemutz”, see the Figure 3. However, standard codes or literature give no information about this fatigue detail. Designers apply this detail to aim higher fatigue strength but without any exact knowledge. A significant
longitudinal weld of a narrow slit could seriously affect the zone around weld where the fatigue failure could begin. The slit allows the transverse butt weld of the flange to be welded.

- The last detail represents an “improvement” of the previous detail. After welding of the flange weld, the cope hole is filled and welded by the shaped plate. The cope hole exists no more here, and detail seems to increase its category. However, combination and amount of welds, and related internal stresses creates doubts of this assumption, although designers use this procedure sometimes.

![Figure 3. Investigated fatigue details a) Elliptic cope hole, b) “Olemutz”, c) Elliptic cope hole filled by the welded plate.](image)

The following chapters describe the parametric analysis of the cope hole and the preliminary experimental work focused on these three details.

### 3. Study of cope hole shape

#### 3.1. Parametric analysis

The first stage of the study is focused on a parametric study of the optimization of the cope hole shape. The typical solution a standard cope hole with a radius $R=50$mm. According to IIW and [1], this fatigue detail has a prone spot in a toe of weld. The aim of this study is to try to use different shapes of the cope hole to redistribute local stresses due to geometry of detail. The studied shapes are an oval, a parabola and an ellipse. The parametric study follows these main parameters: width ($W$) and height ($H$). Two general cases are established. For the situation Analysis I – the parameter width ($W$) is changeable and height ($H$) is fixed on the value 50mm. The Analysis II follows the second parameter - height ($H$) - and there are used changeable shapes of ellipse and circle with vertical moving center, see Figure 7.

Hot spot method is an appropriate life fatigue assessment method for this type of problem. This method could take into the account the local geometry of the detail in the sufficient accuracy. Despite that it excludes a notch effect of weld. Hot spot stress $\sigma_{hs}$ is extrapolated from the spots that are in a specific position.

It is necessary to avoid the stress peaks near the flange and the web connection because of the unsuitable meshing. Only if the prescribed, verified procedure of modeling and generating of mash near welded detail is used, the exact hot spot stresses could be reached.
Figure 4. The selected shapes and parameters for parametric study, A) ellipse B) parabola 2° C) oval D) ellipse E) Circle with a moving centre; Red line define a reference circle R=50mm.

Figure 5. The decomposition of hot spots near the weld. The figure describes hot spot application on the sample.

The Ansys FEM software and linear elastic analysis was used here. The spot stresses were taken from nodes in distances 0.4 t and 1.0 t from weld toe. Below is an equation (1) for the hot spot stress $\sigma_{HS}$ extrapolation.

$$\sigma_{HS} = 1.67.\sigma_{0.4t} - 0.67.\sigma_{1.0t}$$

An important condition was an appropriate generation of the mesh because the highlighted nodes in Figure 5 should the keep the same distance from the weld toe in all details. Size of element in numerical model is 3.2 mm.

Figure 6. Results of Analysis I.
Table 1. Results of the parametric study.

| Shape of cope hole | Nominal stress N [MPa] | Hot spot stress H [MPa] | Factor N/H | Predicted fatigue life [cycle] | Fat. life comparison [%] |
|-------------------|------------------------|------------------------|------------|-------------------------------|-------------------------|
| reference circle  | 117.3                  | 195.82                 | 1.670      | 266 358                       | -                       |
| parabola 2°       | 117.3                  | 197.79                 | 1.686      | 258 478                       | -2.96                   |
| ellipse           | 117.3                  | 190.92                 | 1.628      | 287 406                       | 7.90                    |
| oval              | 117.3                  | 195.69                 | 1.668      | 266 897                       | 0.2                     |

3.2. Experimental hot spot analysis

Hot spot method is also suitable for an experimental measurement and stress-strain evaluation. The equations (2) and (3) are used to evaluate the hot spot stress $\sigma_{hs}$. The location of hot spots set in an experimental and numerical application is shown in the Figure 5. The aim of the experiment is to verify FEM model used in the chapter 3.2. and also to get the detail category of the modified cope hole. Totally six weld toes were measured by strain gauges in twelve spots.
\[ \varepsilon_{hs} = 1.67 \varepsilon_{0.4t} - 0.67 \varepsilon_{LOT} \]  
(2)

\[ \sigma_{hs} = E \varepsilon_{hs} \]  
(3)

The fatigue load specification is given here:

- nominal stress range \( \Delta\sigma_n = 117.3 \text{MPa} \) in tension,
- no shear stress applied,
- load frequency 4 Hz.

3.3. Conclusion of the cope hole study

The summary of obtained numerical and experimental results is in the Table 2. The comparison of the numerical and experimental hot spot stresses provides a good accuracy together and it is indicating that the numerical model used for the parametric analysis was created well and reflects real values. The fatigue life was evaluated according to the mean of the SN curve FAT 137. This curve is recalculated from characteristic SN curve FAT 100, that is recommended in IIW [2]. Also, real fatigue life that was measured for our specimen is shown here.

| Approach of fatigue life determination | Numerical model | Experimental strain gauge | Experiment results |
|---------------------------------------|----------------|--------------------------|-------------------|
| Method based on                       | SN-curve FAT137 | SN-curve FAT137          | Cycle counting    |
| Hot spot stress [MPa]                 | 187.8           | 180.6                    | -                 |
| Fatigue Life [cycles]                 | 778 367         | 875 165                  | 1 077 335         |

The parametric analysis provides these conclusions:

- From the range of the tested shapes, an ellipse with \( a=80 \) and \( b=50 \text{mm} \) was chosen as an efficient alternative of the cope hole. However, the improvement is quite small, 7.9% improvement in comparison with standard cope hole \( R=50 \text{mm} \).
- The wider narrow shapes seem to behave better than the tall narrow ones.

4. Experimental tests of the fatigue details

In the last parts of the paper, a pilot full scale fatigue experiment will be presented. The size of the specimen is taken to be comparable with the standard beams used for bridges. The tested details are introduced in the chapter 2. For each type of the detail one specimen was fabricated. The results should check and compare behaviour of these chosen fatigue details, as a pilot experiment, that can lead to the further wider study. An ultrasonic test and a dye penetrant inspection were used to check the weld defects.

4.1. The experiment specification

The layout of the test is shown in the Figure 8 and Figure 9. A simple supported beam is loaded by a hydraulic device by four-point bending. This layout forms a constant internal moment in the central part of the beam, where three same fatigue details are located without any shear stresses.

The specimens were tested in separate time period and because of the time limitation, the stress ranges were not the same. Despite this, constant stress range was ensued in each single test. Experiments were finished when fatigue crack reached 70 mm.
4.2. Discussion of the test results
Main results of the experiment are summarized in the Table 3, where the approximate fatigue categories are calculated. It is obvious, that “Olemutz” reaches the best fatigue behavior. If we accept assumption that this experimentally determined fatigue category is the mean fatigue category, characteristic fatigue category would be FAT 93. It shows that whole detail is limited by transverse butt weld (of category FAT90 according [2]). This assumption is supported by fact that fatigue crack began and progress exactly in the butt weld, as shown in the Figure 10 and 11.

Table 3. Results of the experiment.

| Fatigue detail                      | Stress range $\Delta \sigma_n$ [MPa] | Experiment Number of cycles | Experimentally determined fatigue category |
|-------------------------------------|--------------------------------------|-----------------------------|------------------------------------------|
| “Olemutz”                           | 225                                  | 360 134                     | 127                                      |
| Elliptic cope hole                  | 117.3                                | 1 077 335                   | 95                                       |
| Elliptic hole filled by plate cap   | 201                                  | 215 288                     | 96                                       |

The results also show that filling of the cope holes by welding of additional plates does not improve the fatigue behavior, compared to the cope hole itself.

Figure 10. Fatigue crack through butt weld of “Olemutz” detail.

Figure 11. View on the lower flange with crack of “Olemutz” detail.
5. Conclusion
The results of the parametric study shows, that the possibilities of the improvement of the cope holes by the geometry modification exist, however are quite small. The elliptic shape with the dimension of main axis $a=80\text{mm}$ and $b=50\text{mm}$ provides $7.9\%$ improvement of the fatigue life.

The second part of the paper shows the experimental tests of two fatigue details in the full-scale test. It is obvious, that "Olemutz" reached the best fatigue behavior. The results also shows, that filling of the cope holes by welding of additional plates does not improve the fatigue behavior, compared to the cope hole itself.

All of those results can be directly applied in the bridge engineering for the design of the fatigue sensitive details.

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