Numerical investigation of the cope hole shape impact on fatigue life of welded joints in steel bridges

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Abstract. Holes in the bridge girders are usually made at the joint of strips. In most cases, they are made when there is a need to make double-sided butt welds and in order to avoid welds crossing. Size of the hole is selected in order to allow full penetration of the strips across their whole width and also to ensure free access to the welds during NDT. Welded joints with holes, due to low fatigue life, are critical elements affecting durability of large-span steel bridge structures. Low fatigue life of joints with holes results mostly from high concentration of stresses near the weld toe caused by local reduction of cross-section. The paper covers parametric studies based on finite elements method in order to determine the impact of geometrical changes of the hole shape on distribution of stresses within probable areas of cracks initiation and durability of such joint. With reference to experimental studies results, four different holes geometries were analysed: semi-circle (conventional), triangle, parabola of second degree and oval. Assessment of the fatigue was performed using the so-called hot spot method, i.e. geometrical stresses. Results of the studies show that geometrical change of the hole shape affects the stresses concentration change, but it does not translate to the increase of fatigue life of such joint.

1 Introduction

For dozens of years, structures of large-span steel bridges have been made as prefabricated elements, outside the construction site. Due to transport limitations and changes in the cross-sections, this is a few or even a few dozens of segments, which are assembled together at the stage of construction. The assembly process involves regular bolts, friction grip bolts and first and foremost welding. Elements of many bridges, being operated for forty, fifty and more years, have been connected with each other using rivets, however today, this kind of connection means is practically out of use [1].
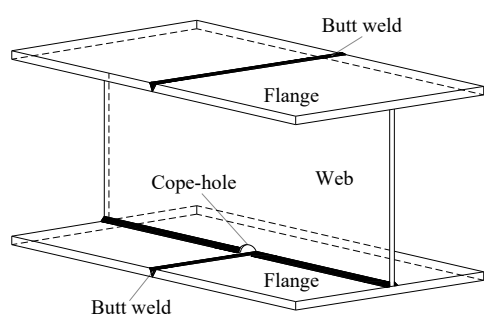

Fig. 1. Location of the hole [2].

In case of the welded joints, in order to facilitate implementation of transverse double-sided butt welds connecting the strips of webs and to avoid welds crossing, holes are made at the installation joint (Fig. 1 [2]). The

hole in the web allows not only to provide full penetration of the strips across their whole width but also ensures equal distance from the weld during NDT of joints quality [3].

Note that from the strength standpoint, the hole causes local reduction in cross-section, thus its rigidity leading in consequence to significant stresses concentration near the toe of longitudinal weld connecting the strip with the web. Therefore, fatigue life of such joint is considerably lower, comparing to other structural details [4, 5].

It is a common practice to fill the hole with weld metal after execution of the welded strip joint. As the studies [6] results show, this operation does not improve fatigue life comparing to the life of the hole itself.

Relatively low class of the detail with simultaneous presence at the place, where significant loads are transferred, causes reduction of durability of the whole structural element [5]. Therefore, it is necessary to increase the fatigue life of such joint [7]. Current studies were mostly focused on different methods of post-welding machining [8, 9]. Among them, the following common techniques are used: grinding, shot peening, TIG weld toe melting, pneumatic hammering and ultrasonic pressing [10]. Even though in most cases significant increase in fatigue strength was noticed, usually there is considerable difference between obtained levels of improvement [11].

Number of studies oriented at assessment of the hole shape geometrical changes impact on joints life and/or distribution of stresses in probable areas of crack initiation

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is negligible [12, 13]. Usually, authors in their studies considered conventional shape (semi-circle) of different radius values [12]. This allowed for determining the dependency between hole diameter and thickness of the strip – it is required that the radius value is as small as possible. However, due to the structure of the examined elements (considerable height to span ratio amounting 1/3), application of these results, especially when it comes to bridge girders, which are much more rigid, may be doubtful.

This paper presents results of studies based on the finite elements method, concerning typical welded joint of steel bridge structural elements with various holes shapes. The analysis includes four geometries: triangle, parabola of second degree, oval and conventional shape, i.e. semi-circle. Assessment of the fatigue life is performed using the geometrical stresses method, i.e. hot spot [14]. The analysis, except for the hole geometry and its impact on the distribution of local stresses, included the impact of shear forces on the fatigue life of such joint. The analyses results were compared with experimental studies [15].

2 Fatigue life

The most common method used to evaluate service life within the structural engineering field is the nominal stress method, which is called the classic method.
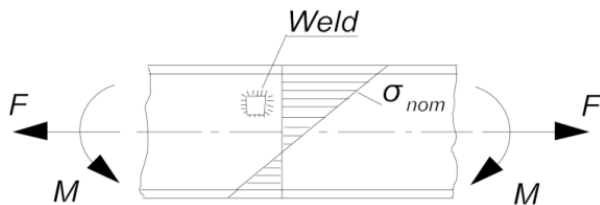

Fig. 2. Distribution of nominal stresses in the cross-section of the bent girder [16].

Fatigue life is determined based on nominal stresses within the joint area. I.e. stresses determined by omitting the effect of accumulation resulting from presence of the weld, considering accumulation resulting from the structure geometry (Fig. 2 [16]). Nominal stresses may change in cross-section and are usually calculated using traditional methods based on linear elasticity of solids. This is a considerable convenience, because determination of actual concentration of stresses in the welded joint is a problematic issue due to geometrical and structural non-uniformity.

The method of nominal stresses may be found especially accurate in case of service life of a structure of simple geometry with minor welding defects, especially of axially loaded joints [17]. Application of this method is problematic in case of complicated geometries. Then, determination of nominal stresses may impose difficulties due to the fact that they idealise the actual conditions. The hot spot approach gets one step ahead and is based on determination of stresses considering also the geometry of specified detail.

Stresses present at the spot of expected fatigue crack initiation (so-called critical spot) are called geometrical or structural stresses. The geometrical stresses method is based on linear distribution of stresses spaced to some distance from the weld toe.

The geometrical stresses method does not take the notch effect into account, caused by the weld profile and includes all other geometrical parameters (Fig. 3 [18]). As shown in [19], elimination of stresses within the notch zone and assumption of the linear distribution of stresses across the slab thickness, mean coherent method of defining structural stresses at the spot of crack initiation, because a solution is obtained with a single value. Because at the design stage, accurate weld profile is not known, elimination of stresses within the notch area seems a reasonable assumption.
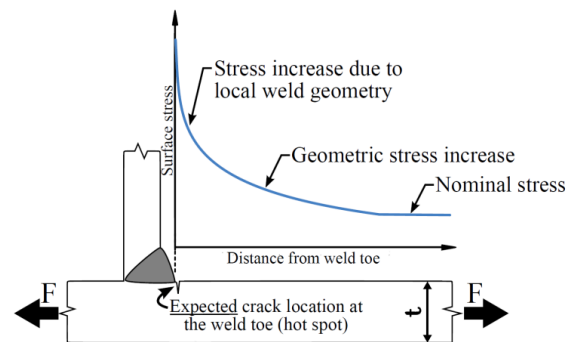

Fig. 3. Distribution of stresses in a welded joint [18].

Stresses at the hot spot are divided to two types: a and b. Structural stresses type depends on location of the critical spot along the strip and direction of main stresses with reference to the weld toe. In Fig. 4. Types of critical spots based on the example of welded girder [18].

[18] presents main concept of hot spots location. In the type a, the critical spot is located on the slab surface wherein the stresses gradient is perpendicular to the initiated crack. However, in type b, the critical spot is located at the edge of the slab, where the stresses gradient is tangent to the initiated crack.
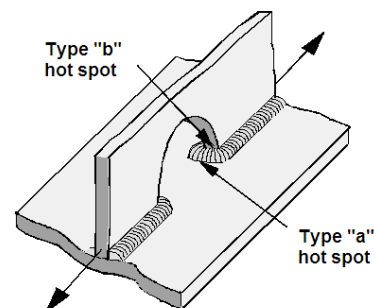

Fig. 4. Types of critical spots based on the example of welded girder [18].

There are a few methods of determining geometrical stresses. Their application depends on dimensions of a structure, necessary calculation accuracy and the degree of complexity of the applied welded nodes. The easiest and most common method is the extrapolation of stresses from specified spots on the sheet surface. The extrapolation may be linear or square in some cases. These procedures are almost the same for both of the methods [20].

Applying FEM, the structural stresses are determined based on stress values obtained at proper nodes spaced from the weld toe by accurately determined amounts, and using similar extrapolation formulas as in the experimental method [21]. However, location of stresses extrapolation spots depends on the type of critical point, as well as on density of the grid in the numerical model.

In case of type a, the first reference spot, closest to the weld toe, is located at distance 0.4t (t – sheet thickness) or 0.5t in models with dense or loose grid. In turn, the other spot is assumed as the spot, where the effect of geometrical features of the joint will be reduced and is located within a distance 1.0t or 1.5t from the weld toe. Structural stresses (σ_{HS}) are determined based on:

$$\sigma_{HS} = 1.67 \cdot \sigma_{0.4 \cdot T} - 0.67 \cdot \sigma_{1.0 \cdot T} \qquad (1)$$

or

$$\sigma_{HS} = 1.50 \cdot \sigma_{0.5 \cdot T} - 0.50 \cdot \sigma_{1.5 \cdot T} \qquad (2)$$

The same extrapolation procedure may be applied when the critical point is located at the edge of the slab (type b), however distance of reference spots spacing must be different. Here, the stress is uniform across the slab thickness, thus the location of reference spots is no longer the function of slab thickness. Therefore, in case of linear extrapolation, it is recommended to apply reference spots located within a distance of 5mm or 15mm upstream the weld toe, in models with looser grid:

$$\sigma_{HS} = 1.50 \cdot \sigma_{5mm} - 0.50 \cdot \sigma_{15mm} \qquad (3)$$

Note that the finite elements model properties (i.e. size and type of element) affect the stress derivatives within the critical spot area. That is why, the grid, dense or loose, should correspond to the rules of stress extrapolation.

3 Distribution of stresses within area of the cope hole

3.1 Subject of the studies

Fig. 5 presents parameters of the considered system, which is assumed to be the same as in case of the experimental studies [15].
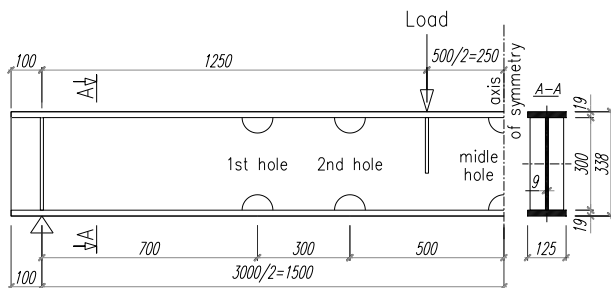
Fig. 5. Parameters of the considered beam (unit: mm) [15].

The spot of applying external loads and arrangement of holes is selected so that only bending forces affect the central hole, whereas the side hoes are subject to combination of shear (τ) and bending (σ) forces. The greatest ratio of shear to bending forces is present at holes located closest to the extreme supports.
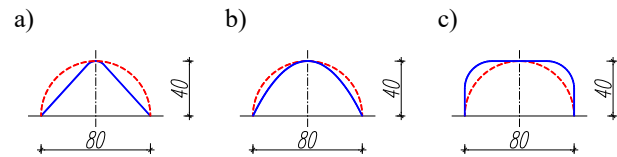
Fig. 6. Tested holes shapes: a) triangle, b) parabola 2°, c) oval; Red line shows reference shape – conventional semi-circle R=40mm.

According to Eurocode 3 [22], the standard hole used at the spot of installation joint is semi-circular or radius R<60mm. In this study, except the conventional shape (R=40 mm), which was experimentally tested, three other geometries were subject to analysis: triangle, parabola of second degree and oval. In case of each of the shapes, constant height (H=40m) and width (W=80mm) were assumed, see Fig. 6.

3.2 Numerical model

Assessment of fatigue life including stresses redistribution at the welded joint with hole may only be tested using the 3D finite elements. Therefore, both, coating and solid elements may be used. The results of studies concerning accuracy of various modelling techniques showed good correspondence of solid models with experimental measurements [18]. However, application of these elements necessitates inclusion of weld into the model [23].

Due to complexity of the considered problems, all calculation tasks have been solved using Abaqus software. Fig. 7 shows the FEM model of the analysed beam. The one-fourth of sample model with 8-node solid elements was created (C3D8R). Young's modulus and Poisson ratio amounted adequately 2.1×10^5 N/mm^2 and 0.3. Material properties have been assigned to the whole geometry together with the welds. Moreover, a gap between the strip and web is introduced to the model, as a special region type, so called *seam*.
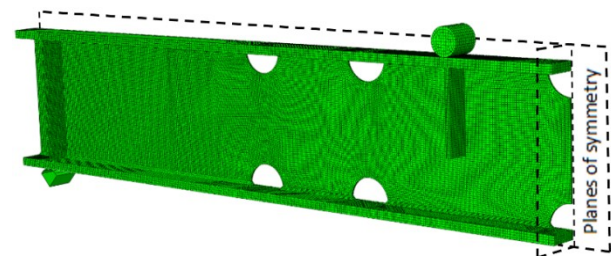
Fig. 7. Exemplary FEM model with assumed boundary conditions.

Fatigue crack in the considered joint starts at the slab surface at the weld toe. That is why the spot of crack can be classified as a critical spot of type a. Size of the grid was adopted based on the assumptions of the linear method of geometrical stresses interpolation.

Size of the grid outside the second reference spot (1.0t) need not be as dense and within these areas, looser grid may be used, see Fig. 8.
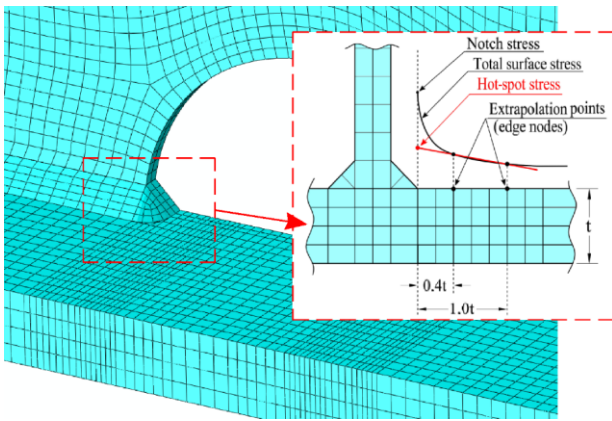
Fig. 8. Configuration of the grid within the area of hot spot.

However, transfer from the dense to looser grid should be smooth. In this specific case, this was achieved by dividing the transfer area to a few small sub-areas and gradual change of the grid density.

4 Results of the analyses

The analysis using finite elements method showed that toe of the weld at the hole is a critical spot subject to substantial stresses which are the combination of first and foremost bending and also then shear stresses.

As it results from Fig. 9, in case of holes located within the shearing areas, stresses clearly increase at one side of the hole (always towards support direction) and decrease on the other. However, the middle hole, which is subject to bending only, has symmetrical distribution of stresses with peak values at the toe of the weld. The same dependency was observed by Choi at al., during laboratory tests [15]. The highest concentration of stresses is present within the area of the second hole.
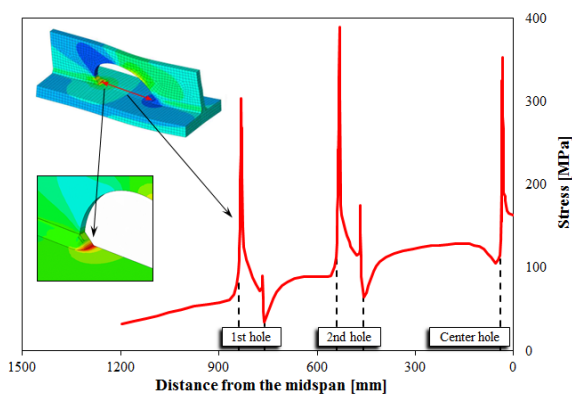

Fig. 9. Distribution of stresses along the girder.

Fig. 10 presents distribution of geometrical stresses depending on the shape, within area of the second hole. The obtained values correspond in quality to the fatigue values during experimental tests [15].

The lowest stresses are present when the hole is triangular and the greatest when is oval. This is the result of cross-section rigidity reduction at the hole. The larger area of the hole the less rigidity of the whole cross-section, leading in consequence to more additional stresses at the weld toe, at the spot of potential fatigue crack initiation.
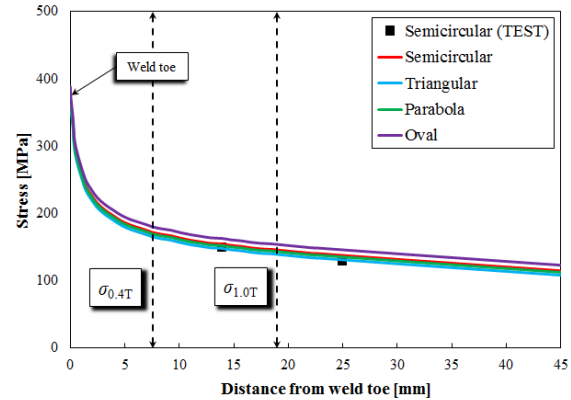

Fig. 10. Distribution of stresses within the area of the second hole in case of its different shapes.

Geometrical stresses (hot spots) are determined using stresses linearisation at critical spot, according to equation (1). In turn, fatigue life is read according to recommendations provided in EC3 [22] and IIW [16] based on fatigue curves S-N FAT100 (Fig. 11 [16]).
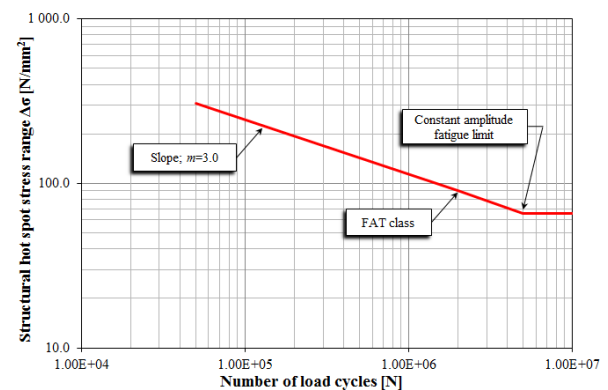

Fig. 11. Fatigue curve S-N FAT100 in the hot spot method [16].

As opposed to the nominal stresses method, when the fatigue life assessment procedure is performed based on the geometrical stresses method, standard structural details are not related to the fatigue curves. Instead, appropriate fatigue classes are assigned to the detail with reference to the weld type.

Table 1. Comparison of geometrical stresses value (σ_{HS}) and fatigue life in case of the middle hole.

Shape of cope hole	Hot spot stress [MPa]	Predicted fatigue life [cycles]	Fat. life comparison [%]
Semi-circular	204.05 (*227.34)	250 231 (*266 610)	-
Triangular	195.72	271 428	+8.47
Parabola 2°	200.37	257 142	+2.76
Oval	213.67	235 714	-5.80
(*values obtained during laboratory tests)			

Results presented in Table 1, confirm unfavourable effect of oval holes application, wherein the lowest fatigue life is attained. The triangular shape can be characterised with the highest expected service life, thus the highest increase in strength. Only the parabola 2° shows properties close to the conventional semi-circle. This is directly related to similar geometry of both shapes.

In order to analyse the impact of local stresses on fatigue life, stresses concentration factor is determined (Table 2) according to the dependency:

$$K_{HS} = \frac{\sigma_w}{\sigma_{HS}} \qquad (4)$$

where σ_w is the maximum surface stress in the weld.

Table 2. Value of the stress concentration factor (SCF).

Shape of cope hole	Hot spot SCF		
	First hole	Second hole	Centre hole
Semi-circular	2.16	1.99	1.73
Triangular	2.21	2.02	1.77
Parabola 2°	2.18	2.00	1.75
Oval	2.12	1.96	1.70

Based on the results, one may observe that the lowest value of concentration factor is always present in case of the middle holes. This is due to presence of pure bending in this area ($\tau/\sigma=0$).

In the remaining cases, there was significant increase in SCF together with the increase in shear to bending stresses ratio. Therefore, holes located closest to the intermediate supports, where the highest shear forces occur – first hole – can be characterised with the highest SCF. This is confirmed by previous analyses, wherein as a result of shear deformation, additional stresses at the weld toe emerge, which must be considered while determining the fatigue life.

5 Conclusions

In the presented studies, the impact of hole shape geometrical changes in the welded joint on distribution of stresses in probable areas of crack initiation and to fatigue stress life of such joint were analysed. Based on the studies of different hole shapes, the following conclusion may be made:
• When assessing fatigue life of welded joints with holes, it is necessary to consider shear stresses, if present;
• Together with the increase in shear stress to bending stress ratio (τ/σ), there is an increase in concentration of local stresses within the hole area;
• Change of the hole geometry affects the improvement of fatigue life of such a joint. However, the attained increase is minor comparing to the conventional solutions within semi-circular hole. The greatest advantage is attained in case of triangular shape;
• Increase in fatigue life of such joint must be looked for in different more effective methods, e.g. in new methods of machining the weld within the hole area.

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