Comparative Study of Fatigue Life Assessment Made by Different Approaches

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Abstract. The fatigue life of steel elements is usually predicted by classical nominal stress method. Such approach is very convenient, when design model of structure is based on bar elements. But the level of analysis in steel structures is still increasing. There are used more and more sophisticated FE packages, which offer shell and 3D elements instead of classical bars modeling. They allow to include real shape of elements and existence of welds, bolts and other joining components. Results obtained from such analysis contain many stress raising effects and can be easily utilized in modern approaches of fatigue life based on local stress values, e.g. structural (hot spot) stress method. Development of modern computational FE packages make prediction of fatigue life using local approaches possible and easier. Major obstacle in wider application of numerical methods for the fatigue assessment of steel structures is apprehension of designers about accuracy of local approaches. The focus of presented research has been on comparison of fatigue life predictions based on nominal stress method and on structural stress method, made for a couple of constructional details. Paper presents influence of geometrical parameters on stress concentration factors and also highlights a wider flexibility of structural stress method.

Keywords: Fatigue life · Nominal stress method · Structural stress method

1 Introduction

Failure caused by fatigue is one of the ultimate limit states, that should be verified during designing of steel structures (EN 1990). The most widely used method to check this conditions is nominal stress method (EN 1993-1-9). It is characterized by a large computational simplicity, because the determination of the stress range at the considered point of the structure (notch) is calculated for nominal stresses, so it can be carried out using elementary formulas. However, simplicity of stress range predictions forces designer to scrupulously determine category of a given constructional detail. A huge variety of constructional details (notches) appearing in the steel structures were pressed into the framework of fourteen fatigue curves for normal stress range and two fatigue curves for shear stress range. In such approach a particular structural detail is assigned to a particular fatigue class with a given fatigue curve. But in many cases, details of real

Z. Blikharskyy et al. (Eds.): CEE 2019, LNCE 47, pp. 428–435, 2020.
https://doi.org/10.1007/978-3-030-27011-7_54

structures are more complicated than basic structural details gathered in standards or recommendations, so it can lead to conservative estimations.

In the recent years the level of analysis in steel structures is increasing. There are used more and more sophisticated FE packages, which offer shell and 3D brick elements instead of classical bars modeling. They allow to include real shape of elements and existence of welds, bolts and other joining components. The stress results obtained from such analysis contain global stress raising effects and can be easily utilized in structural (hot spot) stress method. For this reason only three detail categories are given in standards and recommendations for the application of the hot spot method (Hobbacher 2016; Niemi et al. 2018; EN 1993-1-9). In many cases approach based on local method offers advantage of wider versatility.

2 Aim of the Study

The aim of this study is to compare fatigue life predictions made by nominal and structural stress methods. Structural (hot spot) stress calculations were made by appropriate FE modeling. Range of this study is limited to welded joints with longitudinal attachments and bolted tension flange connections.

3 Method

Two groups of details have been selected to analysis. First one was longitudinal welded attachment (Fig. 1a), with its variable length *L*. Second group was bolted tension flange joint (Fig. 1b), with variable number of bolts *n* and flange thickness t_f. The summary of the study is given in Tables 1 and 2.

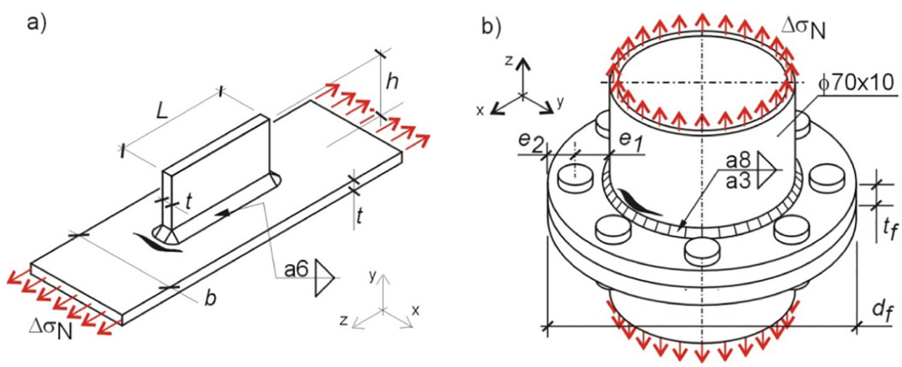

Fig. 1. Investigated structural details; (a) longitudinal welded attachment, (b) bolted flange joints

Table 1. Dimensions of longitudinal welded attachment

Specimen	b [mm]	h [mm]	t [mm]	L [mm]
LA40	100	60	10	40
LA80				80
LA120				120
LA290				290

Table 2. Dimensions of bolted flange joints

Specimen	Flange				Bolts	
	e_1 [mm]	e_2 [mm]	d_f [mm]	t_f [mm]	Diameter	Number [-]
BK 10.4.2	30	30	190	8	M16	4
BK 15.4.2	30	30		15		4
BK 20.4.2	30	30		18		4
BK 10.6.2	35	25		8		6
BK 15.6.2	35	25		13		6
BK 25.6.2	35	25		23		6

It is assumed that both groups of specimens were loaded in the tension range by nominal stress range $\Delta\sigma_N$, with constant amplitude, having pulsating character, i.e. $\sigma_{min} = 0$ and $\sigma_{max} = \Delta\sigma_N$.

Potential crack location was examined in the parent material adjacent to the weld toe of horizontal plate in case of first specimen group, and tube wall in case of second specimen group, Fig. 1. Fatigue checking was done by nominal and structural (hot spot) stress methods. Stress analysis was carried out by FEM. Used numerical models are shown in Fig. 2.

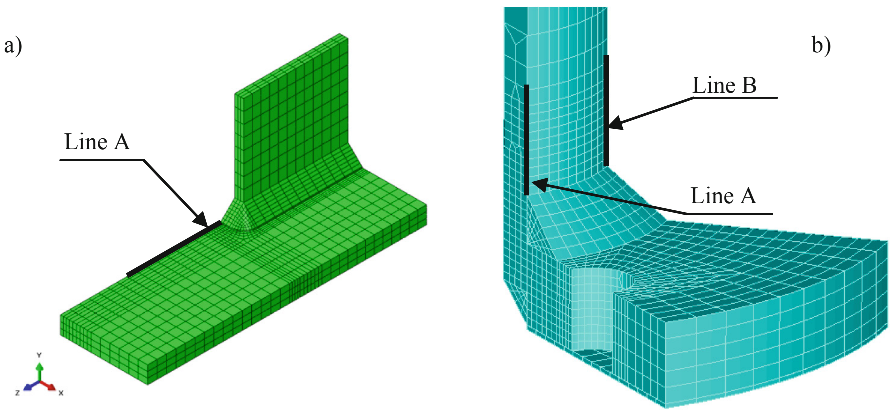

Fig. 2. FEM mesh for structural stress prediction; (a) longitudinal welded attachment LA120, (b) bolted flange joints BK 20.4.2 (the bolt is not shown)

The geometry of the developed numerical model replicated the geometry of the specimens. Due to their shape, symmetry conditions were exploited. Linear elastic analysis was used and no geometric imperfections were applied. Solid model was used and the mesh sizing was chosen according to recommendations (Hobbacher 2016; Niemi et al. 2018).

Two types of stresses were predicted at the potential crack location. Nominal stress range $\Delta\sigma_N$ was directly equal to value of applied load, (Fig. 1). Then hot spot stress σ_{HS} was calculated by extrapolation of the surface longitudinal stress to location of crack site (at the weld toe), Fig. 3. Hot spot is defined as type “a” for both group of specimens, because the potential crack at the weld toe is situated on the plate surface. Extrapolation was done by using linear function. Extrapolating points were chosen according to recommendation (Niemi et al. 2018). In case of bolted flange joints hot spot stresses σ_{HS} were predicted at two locations (Fig. 2). Line A is lying in vertical symmetry plane, which intersect axis of bolt hole, and Line B is situated in vertical symmetry plane, passing along angle bisector between adjacent bolts.

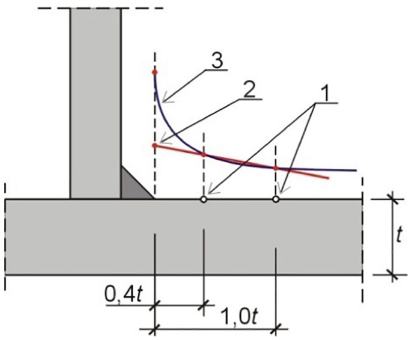

Fig. 3. Linear extrapolation of the structural stress; 1- extrapolating points, 2- hot spot stress; 3-total surface stress

Values of predicted hot spot stresses were used to determine the geometrical stress concentration factor k_f:

$$k_f = \frac{\sigma_{HS}}{\sigma_N} \quad (1)$$

where σ_{HS} is hot spot stress value and σ_N is nominal stress value.

Obtained stress concentration factors are presented in Table 3.

In order to make comparisons, a general criterion, suitable for both approaches, was verified (EN 1993-1-9):

$$\frac{\gamma_{Ff}\sigma_{E,2}}{\Delta\sigma_C/\gamma_{Mf}} \leq 1,0 \quad (2)$$

Table 3. Stress concentration factors k_f

Specimen	Line A	Line B
LA40	1.36	-
LA80	1.43	-
LA120	1.47	-
LA290	1.52	-
BK 10.4.2	5.16	3.11
BK 15.4.2	3.26	2.81
BK 20.4.2	2.54	2.26
BK 10.6.2	4.78	4.50
BK 15.6.2	2.91	2.86
BK 25.6.2	2.20	1.95

where $\sigma_{E,2}$ is equivalent constant amplitude stress range related to $N = 2 \cdot 10^6$ cycles, $\Delta\sigma_C$ is reference fatigue strength at $N_C = 2 \cdot 10^6$ cycles and γ_{Ff} and γ_{Mf} are partial factors for equivalent constant amplitude stress range and for fatigue strength respectively. Assuming, that partial factors $\gamma_{Ff} = \gamma_{Mf} = 1, 0$, Eq. (2) can be written as:

$$\sigma_{E,2} \leq \Delta\sigma_C \tag{3}$$

The results of numerical study obtained for two approaches (nominal and hot spot) were compared in terms of nominal stress ranges $\Delta\sigma_N$ leading to the fatigue failure at $N = 2 \cdot 10^6$ cycles. In such case, for nominal stress method, Eq. (3) can be written as:

$$\sigma_{E,2} = \Delta\sigma_N \leq \Delta\sigma_C \tag{4}$$

where $\Delta\sigma_C$ is reference fatigue strength at $N_C = 2 \cdot 10^6$ cycles, which is equal to detail category according to IIW recommendations (Hobbacher 2016). For first group (Fig. 1a), the detail category varies according to the length of the attachment *L*. For second group (bolted flange joint, Fig. 1b) detail category is constant for each of the studied joints. Reference fatigue strengths for each analyzed joints, considered in nominal method are presented in Table 4.

For structural (hot spot) stress method, Eq. (3) can be written as:

$$\sigma_{E,2} = k_f \Delta\sigma_N \leq \Delta\sigma_C \tag{5}$$

where $\Delta\sigma_C$ is reference fatigue strength at $N_C = 2 \cdot 10^6$ cycles and k_f is geometrical stress concentration factor. Fatigue strengths $\Delta\sigma_C$ using the hot spot stress method depend only on the type of used weld, and were chosen according to EN 1993-1-9 (EN 1993-1-9). Values of $\Delta\sigma_C$ for each considered in this study joints are presented in Table 4.

Table 4. Reference fatigue strengths for nominal and structural stress methods

Specimen	Reference fatigue strength $\Delta\sigma_C$	
	Nominal stress method	Hot spot stress method
LA40	80	100
LA80	71	
LA120	71	
LA290	63	
BK 10.4.2	40	90
BK 15.4.2		
BK 20.4.2		
BK 10.6.2		
BK 15.6.2		
BK 25.6.2		

4 Results

The results of the study, presented in terms of ranges of nominal stress $\Delta\sigma_N$, leading to fatigue at $N = 2 \cdot 10^6$ cycles are shown in Figs. 4 and 5.

Plate with longitudinal attachment is one of the most popular and thus one of the most tested notch, so it can be regarded as a good reference point to compare nominal stress with another approach. It can be noticed, that results obtained from hot spot method in this study are in good agreement with those from nominal stress method. Differences vary between 1÷8% and can be explained by the need to assign $\Delta\sigma_C$ in nominal stress method to certain length ranges of the attachment L. Some allowance is also included in both methods for geometrical imperfections, but levels of stress

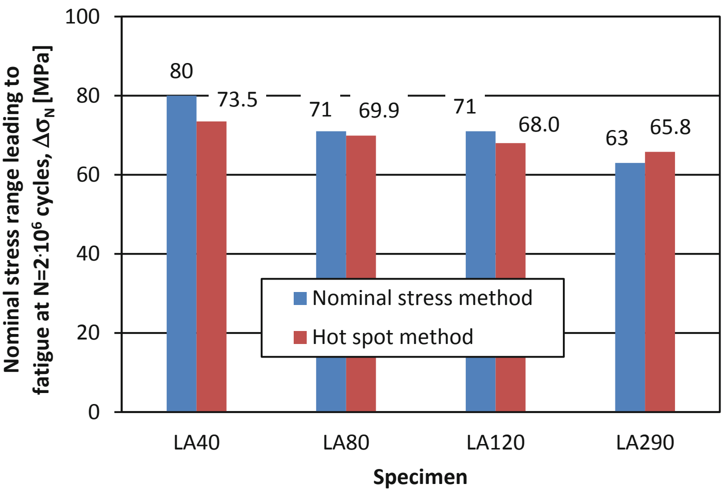

Fig. 4. Longitudinal welded attachments

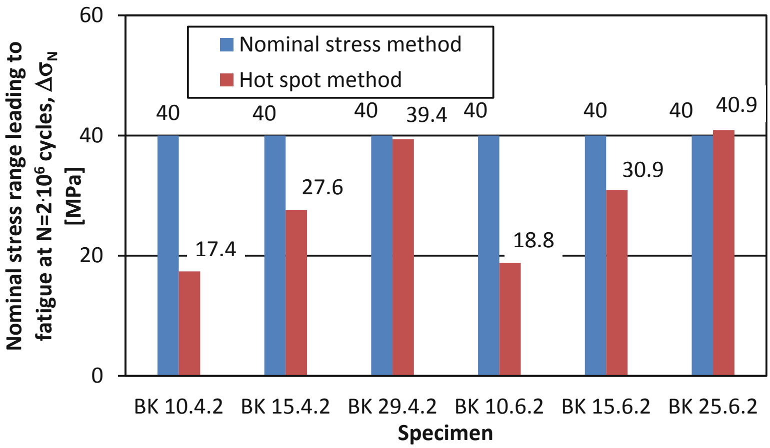

Fig. 5. Bolted flange joints

magnification factors covered in both verification methods are slightly different (Hobbacher 2016).

In case of second group (bolted flange joints) differences between two approaches are significant. However, they probably arise from a noticeable variation of stress concentration factors k_f appearing in the joints (see Table 3), while nominal stress method describe such notch using only one value of reference fatigue strength $\Delta\sigma_C$. An important factors influencing on values of k_f are thickness of flange and number of bolts in joints. So, this example clearly shows a wider flexibility of structural stress method in assessment of fatigue limit state.

5 Practical Significance

In the present study accuracy of hot spot method was tested on two groups of joints, using nominal stress method as a reference point. It has been recognized that the nominal and hot spot methods give consistent results in such cases, where nominal method provides a good representation of the fatigue strength of detail. When nominal method gives rather simplified recommendations, the hot spot method appears to be more appropriate and provide better estimation of fatigue life. Comparisons, using nominal, hot spot and also effective stress method are presented e.g. in (Taras and Unterweger 2017; Aygül et al. 2013; Pettersson and Barsoum 2012) and give information about applicability of different fatigue life estimations and influence of geometrical imperfections.

6 Conclusions

The local approach of fatigue life requires more work in FE modeling. But the level of analysis in steel structures is still increasing and sophisticated FE packages are used to build structural models for the purposes of analysis, design and verification. Obtained results can be easily used to assess fatigue life, by the hot spot method.

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