Re-evaluation of weld root fatigue strength for load-carrying fillet welded joints using the notch stress concept

Rohani Raftar Hamidreza, Dabiri Mohammad, Ahola Antti, Björk Timo

DOI: 10.1016/j.ijfatigue.2020.106076

Re-evaluation of weld root fatigue strength for load-carrying fillet welded joints using the notch stress concept.

Hamidreza Rohani Raftar[a, *], Mohammad Dabiri[a], Antti Ahola[a], Timo Björk[a]

[a] Laboratory of Steel Structures, Lappeenranta-Lahti University of Technology LUT, P.O. Box 20, FI-53851 Lappeenranta, Finland

Abstract

The re-evaluation of fatigue strength, applying nominal and notch stress concepts has been carried out, using extracted experimental fatigue data for load-carrying fillet welded joints failing from weld root. Various reference radii, including r_{ref} = 1 mm, r_{ref} = 0.5 mm, and r_{ref} = 0.3 mm are applied to investigate an appropriate reference radius for assessing fatigue strength of weld root using the effective notch stress concept. In addition, a new FAT class with modified slope is proposed to improve the accuracy of the current recommended class for thin joints with r_{ref} = 0.3 mm.

Keywords: Notch stress approach, Root, Fatigue strength, Stress concentration factors, S-N curves.

Nomenclature

FAT	fatigue strength corresponding to two million cycles
IIW	International Institute of Welding
LCFWJ	load-carrying fillet-welded joints
SCF	stress concentration factor
TCD	theory of critical distance
TIG	tungsten inert gas
a	weld throat thickness (without penetration)
a_{eff}	effective weld throat thickness (with penetration)
C	fatigue capacity
f_y	yield strength of material
K	negative inverse slope
K_f	fatigue notch factor
K_t	elastic stress concentration factor
k_1	factor for the calculation of characteristic values
L	leg length
N_f	cycles to failure
Ps	survival probability
Pw	penetration depth
R	stress ratio
r_{ref}	reference radius
Stdv	standard deviation
T_σ	scatter ratio
t	plate thickness
Δ	range
θ	flank angle
ρ	fictitious notch radius
σ	stress
σ_K	notch stress
σ_n	nominal stress
σ_R	reference fatigue strength
σ_w	stress in a weld throat
Indices	
char	characteristic value
mean	mean value

1. Introduction

There is a growing body of literature that recognizes the importance of the fatigue behavior of the load-carrying fillet-welded joints (LCFWJs) [1]–[3], playing a significant role in steel constructions. Fatigue strength of hidden slit notches is an essential feature of LCFWJs principally evaluated by nominal stress [4] and notch stress method [5], [6].

The past decade has seen considerable literature that has grown up around the theme of welded structures evaluation, which has been typically carried out using nominal stress σ_n, computed from sectional forces or moments in the critical cross-section of the structural component [7]. Developments in the nominal stress approach have led to design codes and design guidelines such as the IIW recommendations [8], [9], and European recommendations and codes [8], [9], provided the S-N curves to compare σ_n with endurable nominal stress amplitudes. Present design codes are limited to axially loaded LCFWJs and do not report the consideration of bending stresses. However, Ahola et al. [10] have proposed an analytical method for computing nominal weld stresses under out-of-plane bending. The evaluation of weld root failures using structural hot spot stress methods has not been officially included in design codes, although Fricke et al. [11] and Sørensen et al. [12] have given proposals to assess weld root fatigue strength using the structural weld stresses.

Since fatigue evaluation of welded joints by local methods was reported in 2006, modeling different types of welded joints, including notch and analyzing stress [5], have been attracted a lot of interest [16],[17] and led to feasible guidelines considering different situations such as IIW fatigue design recommendations by Hobbacher [18]. A class of methods based on the critical distances categorized as TCD are also being proposed and investigated in welded components. In a study by Baumgartner et al. [13], [14] evaluating the steel welded joints, critical distances of 0.1 mm and 0.6 mm have been found considering the maximum principal stress hypothesis for the joints in the TIG-dressed and as-welded condition, respectively. Moreover, Karakas et al. [15] determined the critical distance of 0.06 mm for welded joints made by magnesium. The above-referred TCD studies consider weld toe and weld root conditions in their analysis.

To show the application of the notch stress method, Radaj et al. [5] provide a comprehensive background of the effective notch stress method, applying the Neuber's concept of the fictitious notch rounding [20]. Besides, In a study conducted by Karakas [21], the application of Neuber's effective stress approach to determine fictitious notch radius based on microstructural length for magnesium welded joints has been demonstrated. Using the notch stress method, researchers have been able to evaluate weld toe and root failure for each type of welded joints [16]. Generally, for steel with plate thickness $t \geq 5$, the reference radius of 1 mm typically is implemented using finite element models coupled with FAT 225 curve [18] and maximum principal stresses, which is independent of the location of the failure. In 2010, Pedersen et al. [22] conducted a study to re-analyze more than 30 fatigue test series, employing the effective notch stress method, comprising different types of welded joints. They recommended a lower FAT class (FAT 200) for effective notch stress method, to obtain results as safe and conservative as the nominal stress approach. Previous research [19] has established that aluminum welded joints with plate thickness 5 mm $\leq t \leq 25$ mm could be assessed independently from the weld geometries and alloy by the local stress concept. The study has proposed S-N curves considering different stress ratios for the fictitious radius of r_{ref} = 1.0 mm.

There have existed different types of the notch stress approach, providing over the past years such as reference radius of 0.05 mm, combined with FAT class 630 to assess weld root failure in thin plates [17]. However, there is some evidence [23], [24], proving results of weld toe evaluation that apply r_{ref} = 0.05 mm with its FAT class are non-conservative. Karakas et al. [25] and Sonsino et al. [26] were the pioneer of the evaluation of the welded joints made by the magnesium alloy AZ31 using the local stress concept (r_{ref} = 1.0 and 0.05 mm). They carried out research for the welded joints under different conditions to drive FAT classes based on IIW recommendation for comparison with welded steel and aluminum joints. Karakas [27] has also applied the reference radius and Smith–Watson–Topper approaches to examine the effects of mean stress on fatigue life of welded magnesium joints. Moreover, Sonsino et al. [28] have introduced r_{ref} = 0.3 mm and its FAT class (FAT 320) to evaluate plates with a thickness range of 5 mm < t <10 mm. Besides, Bruder et al. [23] have proposed lower endurable stresses for applying r_{ref} = 0.3 mm for evaluating weld toe failure. Furthermore, Baumgartner [29] has conducted a review of the notch stress method considering different radii, including r_{ref} = 1.0, 0.3, and 0.05 mm. Factors found to be influencing the fatigue strength have been explored in this investigation. In 2020, the application of the reference radius of 0.3 mm to assess the fatigue strength of welded magnesium alloy AZ31 joints has been examined [30]. Data from this research show that r_{ref} = 0.3 mm for magnesium is not able to be a definite replacement for r_{ref} = 1.0 and 0.05 mm.

Although the notch stress method is reliable and flexible to utilize for all types of welded joints, the illuminative evaluation of LCFWJs, which considers root failure is quite limited so that a comprehensive assessment of LCFWJ failing from weld root focusing on the effect of yield strength and geometrical parameters have not been performed, despite its extensive application in connection types in shipbuilding or the fixed offshore constructions. Furthermore, the prior studies [31]–[33] have shown that the notch stress approach with FAT 225 might be nonconservative for evaluating the weld root fatigue strength.

The main focus of this paper is to re-analyze the fatigue strength of LCFWJs, failing from weld roots using notch stress and nominal stress approaches and make a comparison between them, considering yield strength of material and geometrical parameters such as the plate thickness, weld penetration depth, and weld throat thickness. To reach this goal, fatigue data is extracted from published literature, and finite element analyses are conducted to determine stress concentration factors to employ in the notch stress approach. Besides, different reference radii in the notch stress approach are investigated to provide a better understanding of its effect on FAT class proposals. Consequently, the reliability of the notch stress method to assess the fatigue strength of LCFWJ is ensured.

2. Fatigue test data extraction

The experimental evidence of the constant amplitude fatigue tests extracted from the literature [3], [10], [12], [34], [31], [35]–[48] is shown in summary form in Table 1 and 2. Furthermore, all data are shown in Fig. 1 using nominal weld stresses.

Table 1

Overview of data collected.

Yield strength of material	250 MPa $\leq f_y \leq$ 1157 MPa
Sheet thicknesses	6 mm $\leq t \leq$ 28 mm
Welding procedure	MAG, MIG, TIG, MMA, Laser-MAG, FCAW, MCAW
Number of test series	45
Number of single tests	211

Table 2

Data series of experimental fatigue tests. K_t is defined by means of the notch stress method.

ID	*Ref.*	*Yield Strength (MPa)*		*t (mm)*	a_{eff}/t	K_t *root*	K_t *toe*	*R*	*Process*
		Material	*Filler*						
A1	[3]	315	*	16	0.35	6.5	5.28	0.4	MAG
A2	[3]	315	*	16	0.48	4.46	2.71	0.4	MAG
A3	[3]	315	*	16	0.47	5.62	4.93	0.4	MAG
A4	[3]	315	*	16	0.59	4.47	3.62	0.4	MAG

A5	[3]	315	*	16	0.38	5.83	4.8	0.4	MAG
B1	[35]	413	485	9	0.53	3.73	3.3	0	MMA
B2	[35]	397	485	20	0.48	5.56	4.42	0	MMA
C1	[41]	315	510	16	0.53	4.82	3.88	0	MAG
C2	[41]	315	510	16	0.53	4.82	3.88	0. 75	MAG
D1	[42]	693	*	12	0.46	4.95	3.57	0.1	*
D2	[42]	693	*	12	0.45	5.36	4.72	0.1	*
D3	[42]	693	*	12	0.41	5.3	3.67	0.1	*
D4	[42]	693	*	12	0.52	4.63	3.35	0.1	*
D5	[42]	693	*	12	0.41	5.2	3.31	0.1	*
D6	[42]	693	*	12	0.36	5.71	3.6	0.1	*
E1	[43]	325	*	22	0.32	7.93	6.25	0	MAG
E2	[43]	325	*	22	0.50	4.7	3.76	0	MAG
F	[44]	292	*	16	0.37	4.52	3.5	0	Laser-MAG
G1	[45]	356	460	10	0.55	4.1	3.39	0	FCAW
G2	[45]	356	460	10	0.55	4.1	3.39	0.5	FCAW
G3	[45]	595	550	10	0.64	3.64	3.06	0	FCAW
H	[34]	345	*	12	0.56	4.32	3.51	0.1	MCAW
I1	[46]	392	565	28	0.29	9.02	7.15	0.05	MAG
I2	[46]	392	494	28	0.36	6.25	3.75	0.05	MAG
J	[46]	554	491	24	0.35	6.9	5.42	0.05	MAG
K1	[47]	362	*	15	0.28	6.86	5.84	0.5-0.75	FCAW
K2	[47]	362	*	15	0.38	6.12	4.97	0.5-0.75	FCAW
L1	[48]	534	407	16	0.45	5.07	4.26	0.05	MAG
L2	[48]	534	665	16	0.42	5.2	4.53	0.05	MAG
L3	[48]	534	407	16	0.66	2.89	2.78	0.05	MAG
L4	[48]	534	665	16	0.50	4.13	3.51	0.05	MAG

L5	[48]	534	407	16	0.71	2.55	2.47	0.05	MAG
L6	[48]	534	665	16	0.65	2.9	2.7	0.05	MAG
M	[36]	306	*	16	0.40	4.97	4.02	0.1	MMA
N	[37]	744	*	16	0.56	4.81	3.79	0.2	MIG
O	[38]	395	530	14	0.43	4.62	3.85	0.5	MAG
P	[12]	345	*	10	0.50	4.35	3.62	0.1	SMAW
Q1	[39]	297	425	6	0.33	4.27	3.14	0	TIG
Q2	[39]	297	425	6	0.48	3	2.69	0	TIG
Q3	[39]	297	425	6	0.55	2.67	2.35	0	TIG
Q4	[39]	297	425	6	0.62	2.18	2.06	0	TIG
R	[40]	250	*	10	0.71	3.4	2.9	0	*
S	[10]	960	930	9	0.52	3.77	3.31	0.1	GMAW
T	[31]	1157	930	8	0.50	4	3.44	0.1-0.5	GMAW
U	[49]	370	*	8	0.71	3.1	6.65	0.5	*

* Information/data not available

Since the notch stress method takes geometric parameters into consideration, only studies with detailed explanations of specimen geometry are chosen for the re-analysis. Only studies evaluating LCFWJs failing from weld root are considered when specimens are subjected to axial force, and welded joints are in the as-welded condition. The yield strength of materials varies from 250 to 1157 MPa, stress ratios are positive, and between 0-0.75, specimen thickness varies from 6 to 28 mm, flank angles are between 25° to 60° and, moreover, main and cross plates are identical in thickness for all specimens. According to the IIW recommendation [18], it is assumed that the knee point is located at 10^7 cycles, considering the constant amplitude. It is worth noting that this study concentrates on the finite life region of small-scale specimens, and stress ranges after the knee point are not considered. Figure 1 illustrates the extracted fatigue data related to LCFWJ in where the stress range in a weld throat ($\Delta\sigma_w$) and its relationship with fatigue life is provided.

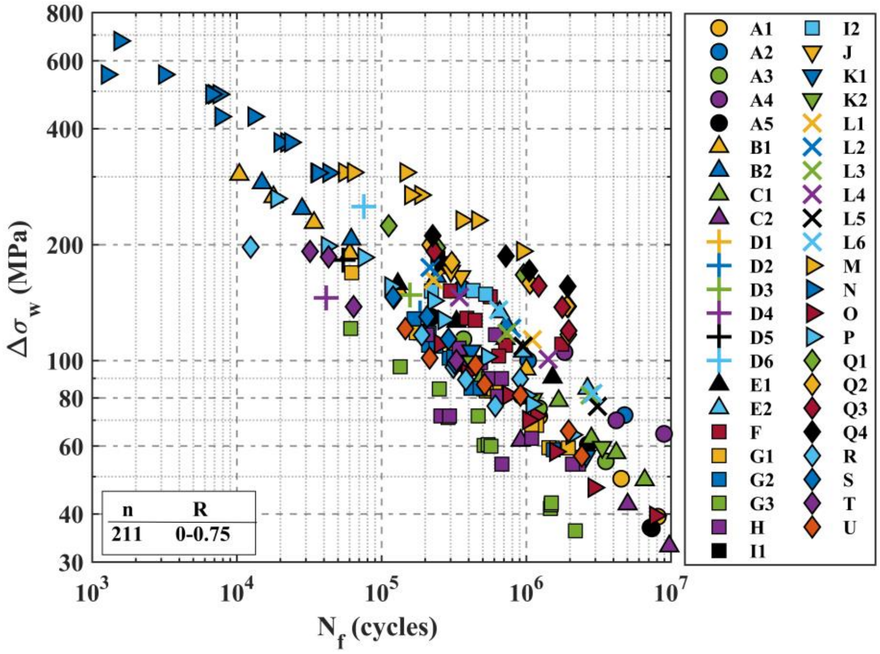

Fig. 1. Fatigue data points extracted from the literature listed in Table 2.

The stress range $\Delta\sigma_w$ is determined, considering the actual weld throat section, including the weld penetration depth based on the design codes [18], [50]–[52] in the following way:

$$\Delta\sigma_w = \Delta\sigma_n \frac{t}{2a_{eff}} \tag{1}$$

Where $\Delta\sigma_n$ is the maximum nominal stress in the cross-section of the adjoined structural component, t is the plate thickness, and a_{eff} is the effective weld throat thickness. Figure 2 shows the geometrical parameters of LCFWJ.

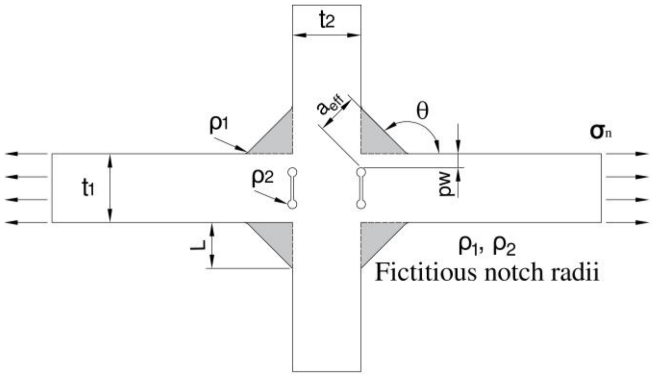

Fig. 2. Geometrical parameters of LCFWJ.

3. Nominal stress approach

In order to assess the weld root fatigue strength of LCFWJs, the nominal stress method is applied. Data points have been statistically evaluated by the standard fitting procedure to achieve the characteristic design and mean strength. First, the least square linear regression in the form of $logN_f = logC - mlog\Delta\sigma$ has been applied to obtain the survival probability at *Ps* = 50% as FAT mean. Where m is known as the slope of the curve in log-log with data points regarding $logN_f$ as a function of $log\Delta\sigma$. $logN_f$ and $log\Delta\sigma$ are corresponded to the response and independent variable respectively. Generally, a calculation of a design curve at *Ps* = 97.7% is made using $logC_{char} = logC_{mean} - k_1.Std$v. A multiplication factor of k_1 is available in IIW recommendation and Stdv is the standard deviation of $logC$ [18], [53].

Based on the statistical evaluation of the test results, the mean stress-life curve is obtained by:

$$N = 2.10^6 \left(\frac{\Delta\sigma_n}{\Delta\sigma_R}\right)^{-1/\mathrm{k}} \tag{2}$$

Where $\Delta\sigma_n$ is the nominal stress range which can be obtained using Eq. (1), *N* is assigned to the permissible number of cycles related to $\Delta\sigma_n$, $\Delta\sigma_R$ is the reference fatigue strength (FAT) at $2{\cdot}10^6$ cycles. *K* is also introduced as the slope parameter of the S-N curve[18].

It can be seen from the fatigue data in the nominal stress system in Fig. 3, the survival probability at P_s = 50%, and 97.7% computed to obtain the characteristic design and mean strength. What is noticeable in Fig. 3 is that the resulting design curve with K = 3.18 obtained from free regression analysis comes to an agreement with FAT 36 coupled with K = 3 recommended by IIW. Besides, the scatter ratio (T_σ) between the fatigue strengths for Ps = 90% and 10% is shown in the Fig. 3.

As the data in Fig. 3 shows, there exists agreement between extracted data and FAT 36, and only very few data points are located below the S-N curves. Stress ratio, various thicknesses, misalignment, as well as weld quality might be given rise to observable large scatter in the results.

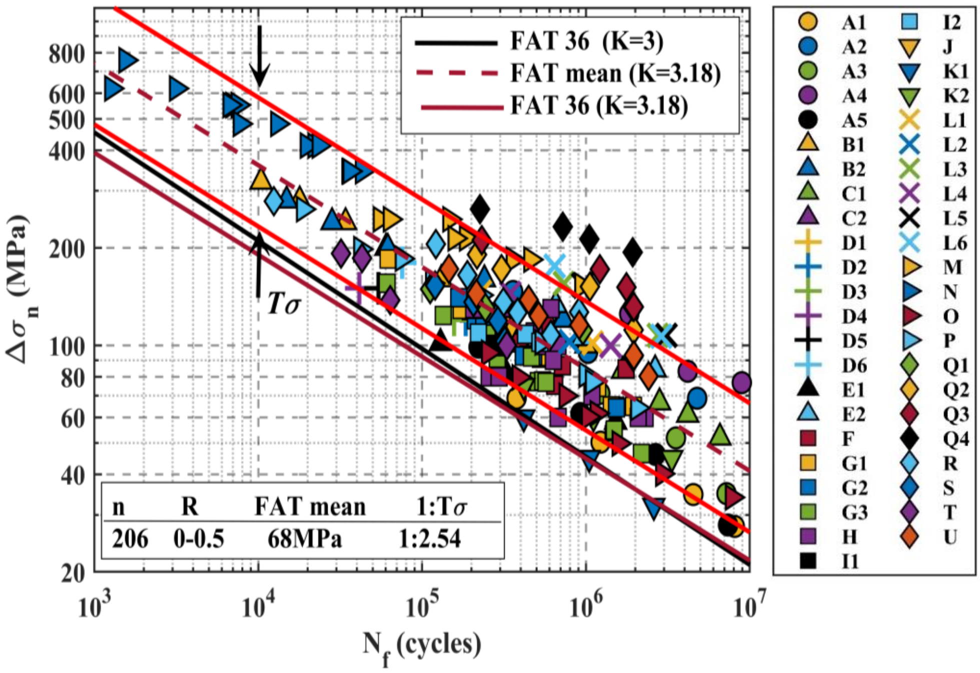

Fig. 3. Extracted data points in the nominal stress system.

Although IIW recommendations of FAT values are given for R = 0.5, the recent literature [31], [45] on root side failure has revealed that the effect of stress ratio (R) on load-carrying fillet welded joints is not significant compared to those with weld toe failure. Data points obtained from [45] in Fig.4 shows that the difference in the fatigue strength for R = 0 and R = 0.5 is very slight. Besides, the effect of R on welded joints made of ultra-high-strength steel (UHSS) investigated by Ahola et al. [31] demonstrates that UHSS welded joints under load-carrying conditions are not highly sensitive to stress ratio.

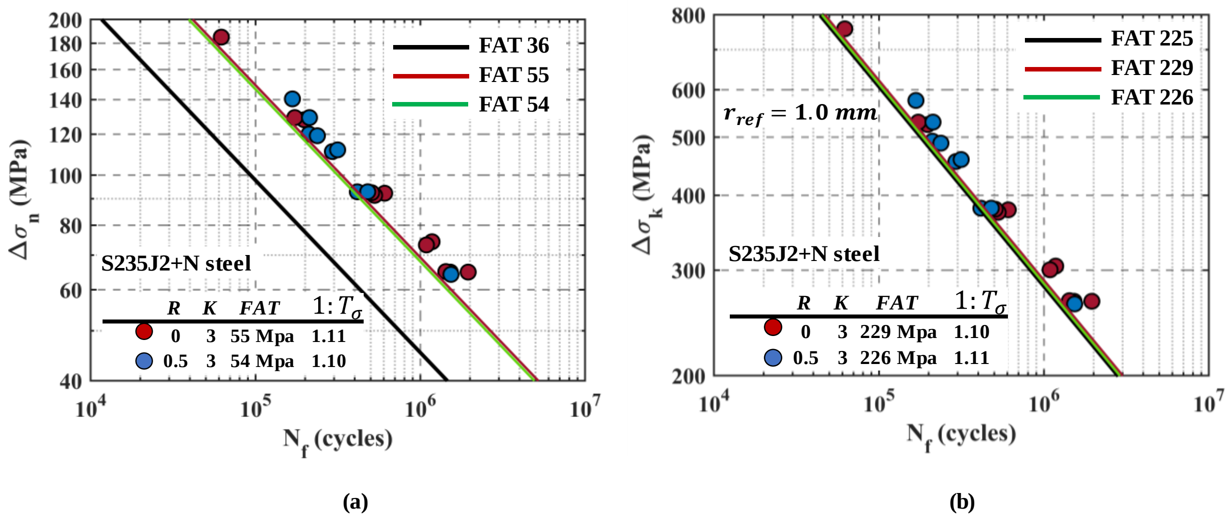

Fig. 4. Fatigue test results extracted from [45] for stress ratio R = 0 and R = 0.5 (a), and the converted data points in notch stress system (b).

4. Notch stress approach

The notch stress method perceives the escalation of local stress at the rounded weld root or weld toe in accordance with the elasticity theory. Averaging linear-elastic stresses on a definite area takes into consideration the micro-structural support effect using a stress gradient on fatigue behavior. The inspiration for this concept is that the decrease in stress in a notch caused by averaging linear-elastic stresses over a certain depth might be obtained by fictitious notch radius ρ [18], [54].

The determination of fatigue-effective notch stress at the weld root, was conducted using finite element analysis employing two-dimensional plane strain element models. The maximum principal stress criterion was applied in the determination of notch stresses. However, the von Mises equivalent stress might be applied if smaller FAT classes utilized since in sharp notches, the equivalent stress generally diminishes [54]. There exist two alternative shapes for modeling the notch root, namely the keyhole and U-shaped notches. Based on [16], comparing the U-shaped notch with the keyhole notch, the high-stress concentration decreases in the U-shaped notch, and a slight underestimation of the notch stress to evaluate fatigue strength in root face could be assumed. The keyhole notch-shape is, therefore, applied in this study.

Mesh of the root side is implemented, considering Hobbacher recommendation [18]. It shows the accuracy of the model is improved by applying the mesh refinement in the region around the weld root. All weld details are uniformly modeled using the finite element method to draws a meaningful comparison between the reference radii. Figure 5 shows the specification of the mesh applied in the root side. The steps of the finite element modeling are as follows:

- 2D finite element models (plane strain)
- the double-symmetry is used by analyzing a quarter of the structure
- weld root is rounded with a keyhole shape
- quadratic displacement function
- linear-elastic analysis
- the mesh refinement at a weld root and weld toe

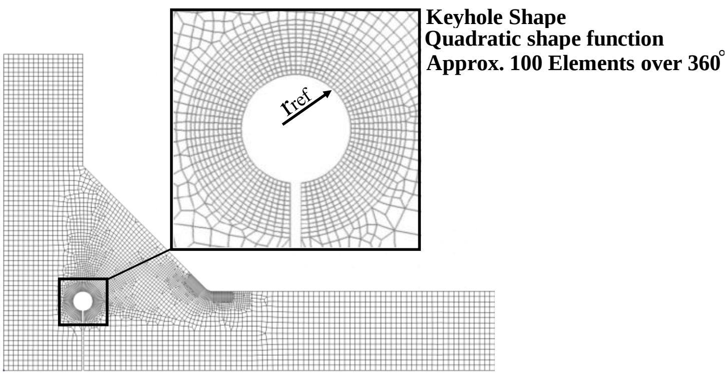

Fig. 5. Mesh applied for the notch stress analysis.

Based on the above technical recommendations, the 2D finite element models using the double-symmetry are applied, and only a quarter of the structure is analyzed to obtain the stress concentration factor (SCF) of LCFWJ. The fatigue effective K_f can be obtained from the SCF K_t using a fictitious notch radius of r_{ref} such that $K_f = K_t\,(r_{ref})$, on the assumption that there are no misalignments and also SCF due to bending loads, does not exist [5]. The extracted data points in the nominal stress system $\Delta\sigma_n$ can be converted into the notch stress system $\Delta\sigma_K$ using Eq. (3). The detailed of the procedure is available in [16], [18], [55].

$$\Delta\sigma_K = K_f.\Delta\sigma_n \quad (3)$$

The specimen geometry and corresponding finite element model, from the study of Frank [37], (N-type), is shown as an example of the procedure of obtaining fatigue notch factors K_f. A unit stress is applied to the specimen. Figure 6 illustrates stress result that can be translated as SCF K_t or fatigue notch factors K_f. Notch stresses are computed for each specimen, and compared with endurable stresses, provided as S–N curves in the IIW recommendation [18].

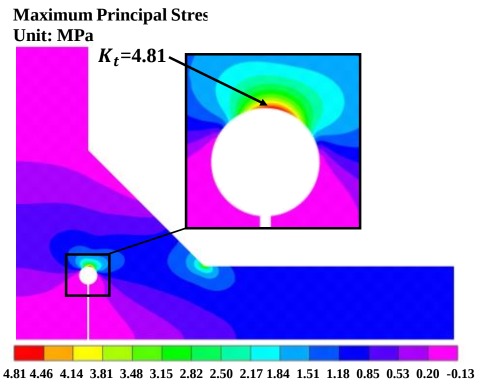

Fig. 6. N-specimen: By applying a nominal stress of 1 MPa, principal Stress distribution and notch stresses are obtained.

Using the above-described procedure, the assessment of the data points based on the notch stress approach applied reference radius of 1 mm, is shown in Fig. 7. For evaluating the fatigue data, FAT 225 for principal stresses provided in the IIW Recommendations, is utilized. Nonetheless, as reported by Sonsino [17], von Mises stresses with FAT 200 might be regarded for the evaluation of the notch stress approach with r_{ref} = 1 mm. The graph reveals the design S-N curve is not conservative at all. What is interesting about the data in this graph is that about 90% of the uncovered data points assign to those plate thicknesses are between 8 and 10 mm. Further analysis in this study indicates that in contrast to earlier findings, a smaller FAT class (FAT 168) characterized by K = 3, P_s = 97.7% and $R \leq 0.5$ might be suggested to obtain conservative results. Observed results from Figs. 3 and 7 show an 11% reduction in the scatter range has been achieved from the nominal stress concept ($1{:}\, T_\sigma = 1{:}\, 2.54$) to the notch stress approach ($1{:}\, T_\sigma = 1{:}\, 2.27$). Moreover, an S-N curve (FAT mean) calculated by P_s = 50%, $R \leq 0.5$ and K = 3 is driven in where a stress amplitude at $N = 2 \times 10^6$ cycles equals 290 MPa. At this point, it is worth mentioning that the negative inverse slope (K) of the curves obtained for FAT mean and the design curve equaled 3.08. But this study makes a simplification and employs K = 3.

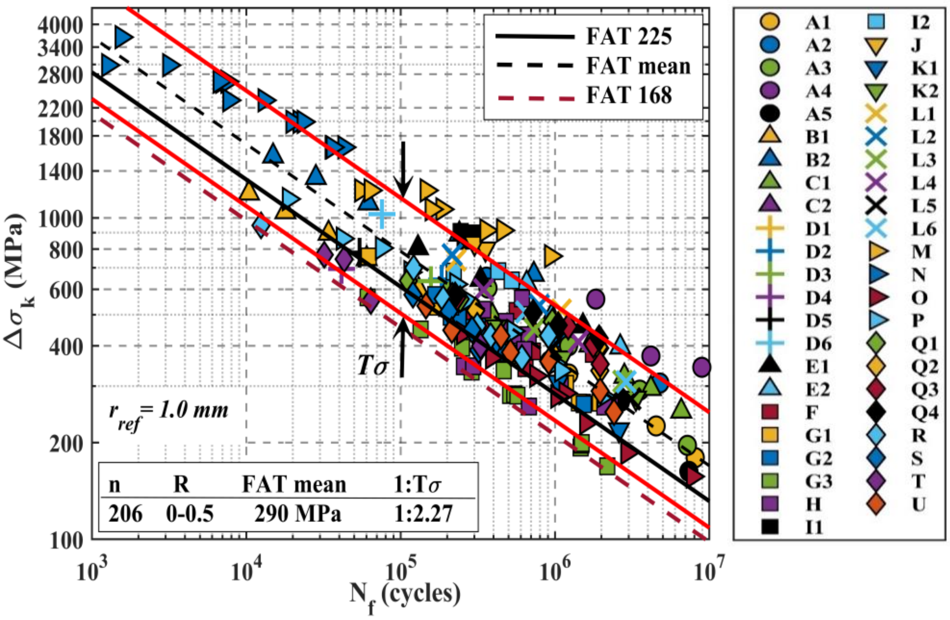

Fig. 7. The data points in the notch stress system with r_{ref} = 1.00 mm.

4.1. Applicability of notch stress system using reference radius of 1.00 mm

Since the geometrical parameters such as plate thickness and weld thickness are explicitly taken into account through modeling in the notch stress approach, the macro effects on fatigue strength can be reflected, in the other words, SCF reflects the influence of the geometrical parameters on fatigue strength. This interpretation contrasts with the nominal stress method in which the cumulative effects of the parameters on the fatigue strength are presented.

4.1.1. Influence of plate thickness

In the present section, the effects of geometrical parameters, such as the plate thickness, weld penetration depth, and weld throat thickness, on weld root fatigue strength are examined in detail. Figure 8 provides a comparison between the results of the nominal and notch stress systems evaluating the thickness effect on fatigue strength. The data points with penetration depth equal to 0 are used to ensure comparability. There is proof of the existence of the thickness effect in the notch stress method, as shown in Fig. 8 (b), so that fatigue strength goes up along with the plate thickness, which might be related to the increased SCF of the thicker plate.

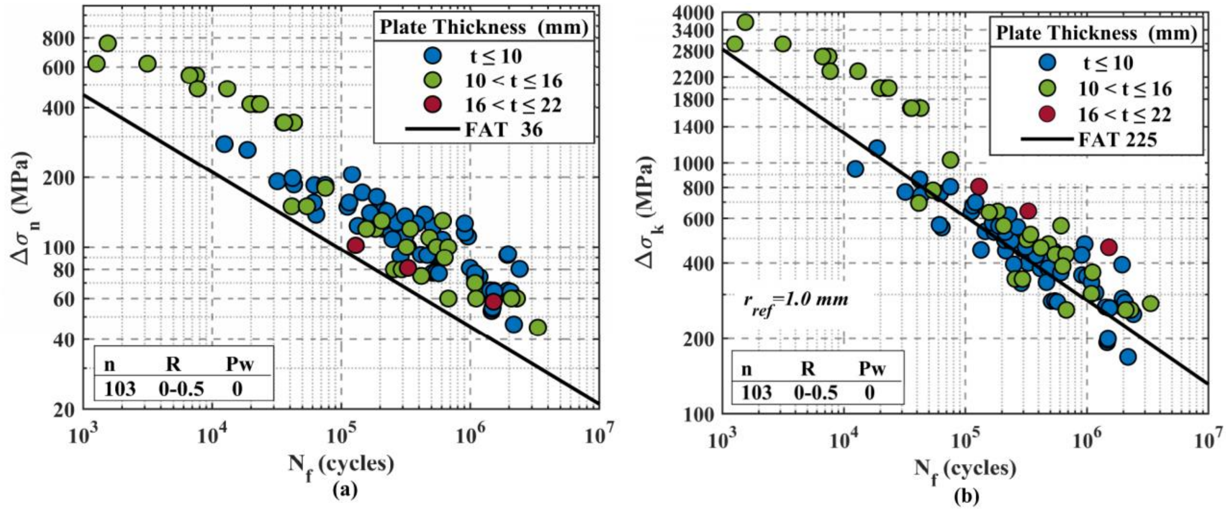

Fig. 8. Comparison between nominal stress (a) and notch stress systems (b) considering thickness.

4.1.2. Influence of weld throat thickness

To determine the difference between nominal and notch stress methods to examine the weld throat thickness effect on fatigue strength, data points based on weld throat thickness (a), which are normalized by main plate thickness (a/t), are classified, see Fig. 9. As the correlation between weld throat thickness and fatigue strength is shown in Fig. 9, growth in weld throat thickness gives lower fatigue strength in the notch stress approach (Fig. 9 (b)). This is in agreement with the sensitivity study performed in [56] which proves higher FAT classes for load carrying joints with lower nominal weld throat thickness. On the other hand, because there does not exist a clear trend in the data points converted to the nominal stress approach, it is difficult to put an accurate interpretation on the results in Fig. 9 (a).

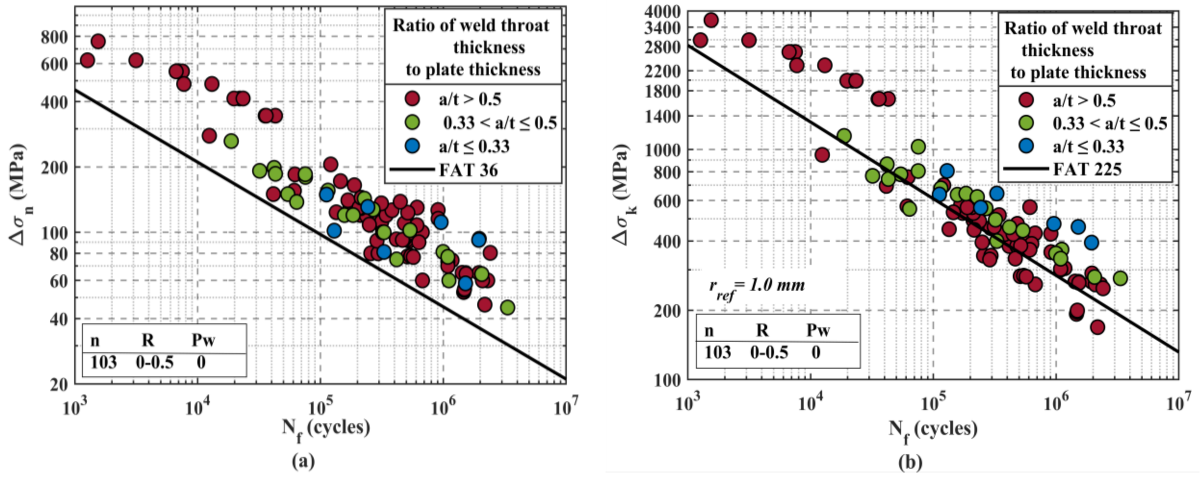

Fig. 9. The influence of weld throat thickness on fatigue strength in nominal stress (a) and notch stress systems (b).

4.1.3. Influence of penetration depth

The relationship between weld penetration depth and fatigue strength is shown in Fig. 10 (a) and (b) obtained from nominal and notch stress methods, respectively. The trends in both approaches indicate fatigue strength decrease through a reduction in weld penetration. However, the notch stress method with the proposed FAT 225 leads to more non-conservative estimations especially for low penetrations. This stems from the fact that these joints showing higher initial crack sizes in fracture mechanics point of view, simultaneously causing higher notch stresses due to the decrease in the ligament size.

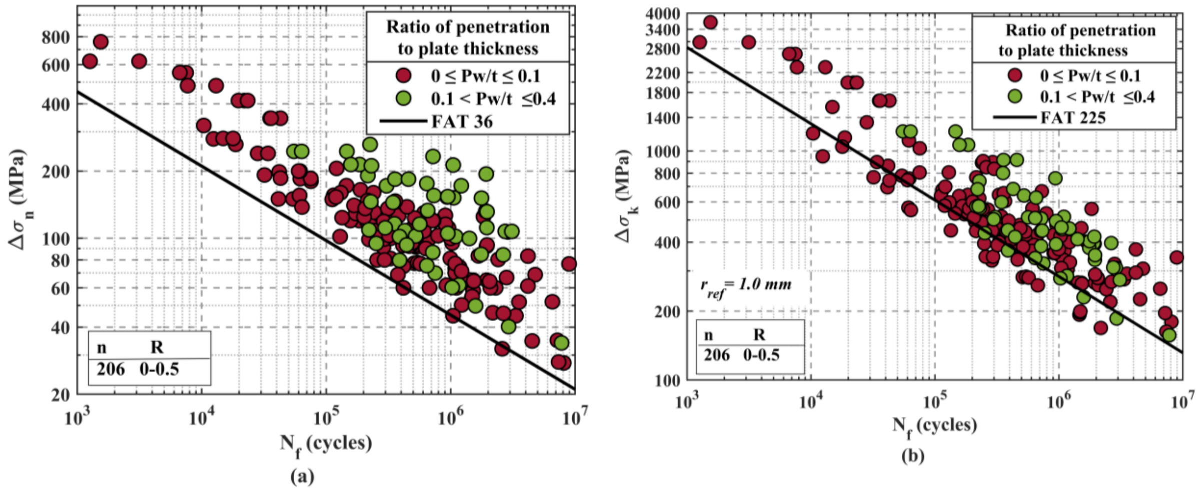

Fig. 10. The effect of weld penetration on fatigue strength in nominal stress (a) and notch stress approaches (b).

4.1.4. Influence of material strength

This section contributes to examine the yield strength effect of base material on weld root fatigue strength. Applied data points, chosen for this observation, have the same plate thickness (t = 10 mm), and the zero-penetration depth to eliminate the plate thickness and weld penetration effects and thus ensure the comparability of the results. Figure 11 compares the results obtained from nominal and notch stress approaches. As shown in Fig. 11 (a) and (b), there is a clear trend of decreasing fatigue strength while yield strength increases. What stands out in Fig. 11 (b), related to the notch stress system, is the sensitivity to the changes in yield strength ≥ 600 MPa, which creates a gap separating its data points from other categories. Surprisingly, data points with yield strength ≥ 600 MPa are not covered by FAT 225 in the notch stress method, see Fig. 11 (b). Expectedly, the higher notch sensitivity of materials with higher material yield and ultimate strength leads to decreasing fatigue strength for high- and ultra-high-strength steels [57]. However, it should be noted that a limited number of test results were found for LCFWJs made of high- and ultra-high-strength steels, and further verification should be conducted. Moreover, further studies that address the notch sensitivity in accordance with the material strength should be undertaken.

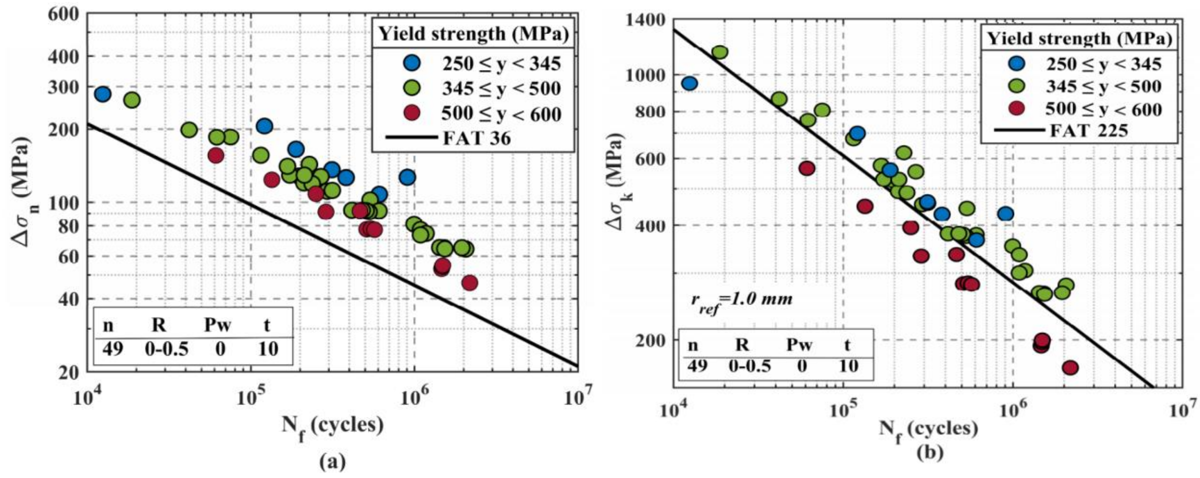

Fig. 11. The examination of yield strength material on weld root fatigue strength in nominal (a) and notch stress systems (b).

4.2. Reference radius of 0.3 mm

Due to the clear nonconservative estimations of current FAT class (FAT 225) utilizing r_{ref} = 1 mm, it is of importance to check the condition with other proposed FAT classes for different radii. The first systematic study of the reference radius of 0.3 mm was reported by Sonsino et al. [28] for evaluating a thickness range of $5\ mm \leq t \leq 10\ mm$. The design S–N curve for principal stresses with FAT 320, corresponding to FAT 280 for the von Mises stresses provided to apply with the reference radius of 0.3 mm for both root and toe failure, see Fig. 12. Sonsino et al. [28] recommended using shallower slope (K = 5) when the utilized radius is r_{ref} = 0.3 mm.

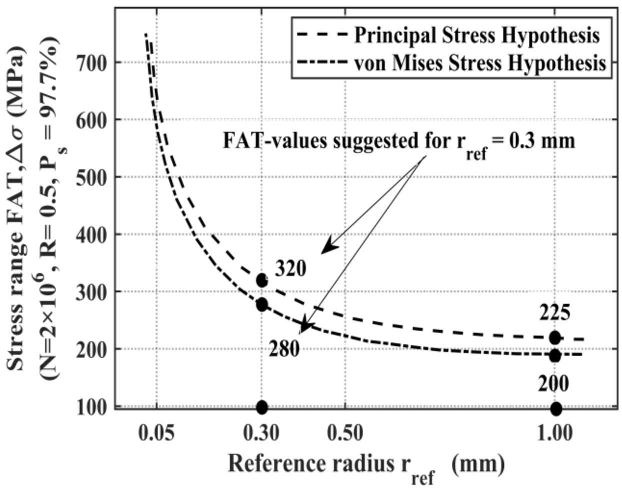

Fig. 12. Recommended FAT values for steel applying for r_{ref}=0.3 mm [28].

In the following diagram (Fig. 13), the data points assessment of LCFWJ, failing from the root with a thickness range of $5\,mm \leq t \leq 10\,mm$ shows the recommended S-N curve is conservative for $N < 10^6$. However, the S-N curve underestimate the weld root fatigue strength at high load levels. The scatter range diminishes and equals to 1:1.83. Nevertheless, the number of data points, applied in this approach is less than the previous one. On the other side, a statistical analysis of the data points is carried out and indicated that a lower FAT class (FAT 255) with K = 3 can be considered to cover all data points which leads to conservative results at low and high load levels with the same scatter rang obtained by FAT 320 coupled K = 5. It should be noted that the statistical analysis of the data indicates the negative inverse slope of the design curve (FAT 255) is 3.1, but for making a simplification, K = 3 is used. This proposal also keeps the consistency of the curve slope with FAT 255 proposed for $r_{ref\,=}$ 1 mm.

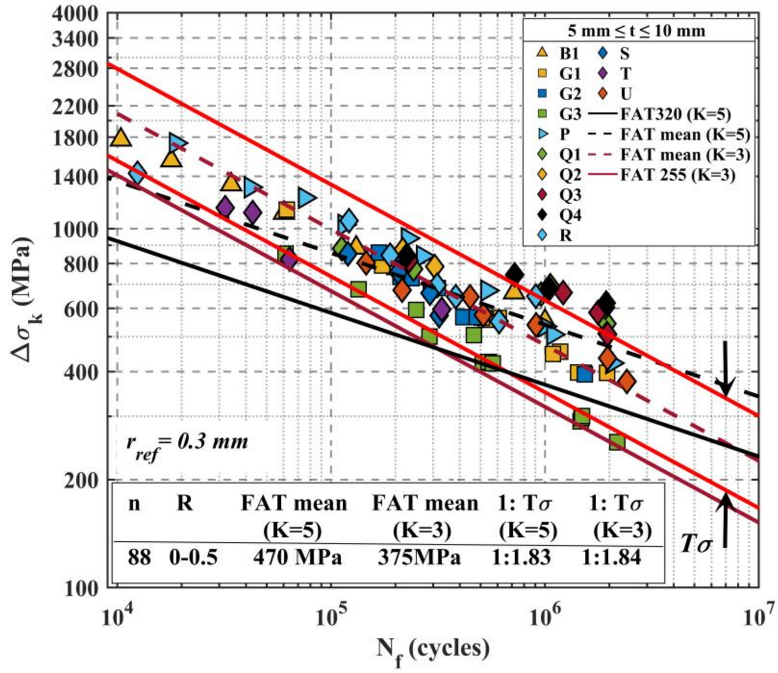

Fig. 13. The data points extracted from thickness between 5 mm ≤ t ≤ 10, in the notch stress system with r_{ref} = 0.3 mm.

To have a general view of applying r_{ref} = 0.3 mm for evaluating the root failure in LCFWJs, Fig. 14 presents the results achieved from the evaluation of LCFWJ, considering all thickness range of 5 mm ≤ t ≤ 28 mm. From the graph, it can be observed that FAT 240 coupled K = 3 might be covered all data points. However, compared with the data obtained from r_{ref} = 1.0 mm in Fig.7, the scatter range increases from 1:2.27 to 1: 2.34.

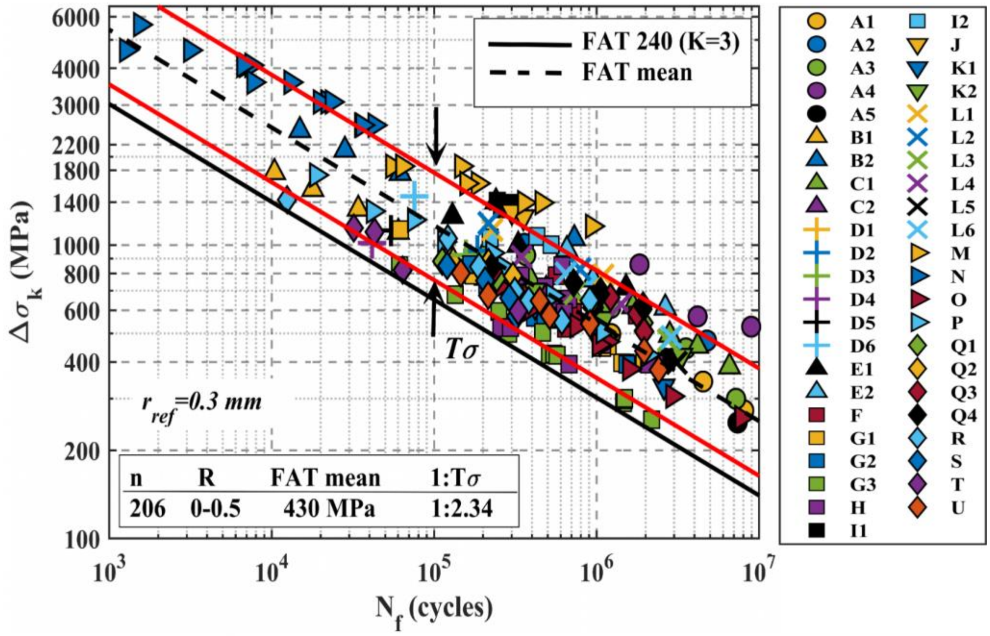

Fig. 14. The data points in the notch stress system with r_{ref} = 0.3 mm

4.3. Reference radius of 0.5 mm

To fill the gap between r_{ref} = 0.3 mm and r_{ref} = 1 mm, the reference radius of 0.5 mm is tested in this study. The results obtained from the assessment of LCFWJ based on r_{ref} = 0.5 mm are shown in Fig. 15. Given the graph, it is apparent that FAT 240 considering principal stresses with K = 3.6 is conservative for all thicknesses except for few points which belong to 10-mm plat thickness. However, compared to FAT 225 with K = 3 implemented for r_{ref} = 1 mm, it has a 5% increase in the scatter range. In addition, FAT mean (Ps = 50%, $R \leq 0.5$) is included in Fig. 15. Moreover, the graph below illustrates FAT 220 extracted from statistical analysis considering K = 3 to achieve uniformity among the slopes of the S-N curves and decrease the scatter range 1: T_{σ} from 1:2.37 to 1:2.30 proposed for the evaluating the fatigue strength of LCFWJ, failing from the root considering all thickness range of 5 mm $\leq t \leq$ 28 mm. Figure 15 is also provided for comparison with the results of Fig. 14, which is related to reference radius of 0.3 mm. Statistical analysis of Fig. 15 shows a slight reduction in scatter value compared with Fig. 14 from 1:2.34 to 1:2.30.

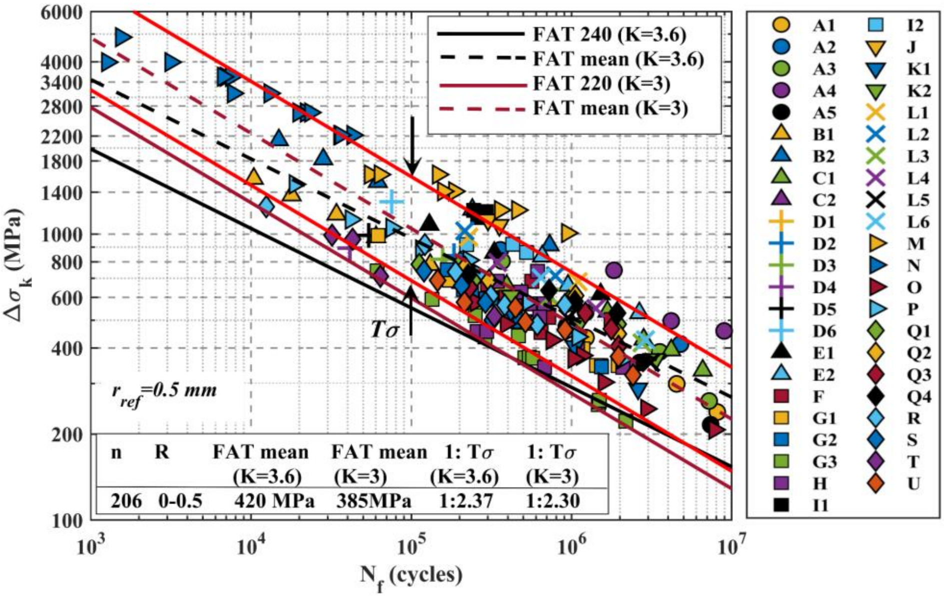

Fig. 15. The data points in the notch stress system with r_{ref} = 0.5 mm.

To assess the performance of the notch stress method using r_{ref} = 0.5 mm on a thickness range of $5\,mm \leq t \leq 10\,mm$, Fig 16 is provided in which the scatter band obtained from the statistical analysis considering FAT 210 with K = 3 is shown. Data from this graph can be compared with the data in Fig. 13, which shows the scatter value declined by around 6.5%. Furthermore, the design curve (FAT 250, with K = 3.8) gives a fairly conservative estimate for plate thickness between 8 and 10 mm for $N < 10^6$. According to these data, K = 3.8 used for FAT 250 may reduce to 3 (resulting in FAT 220) to maintain the consistency with the curve slopes coupled FAT classes provided in the IIW recommendation and to cover all data points. The results of Fig. 15 indicate that there has been a decrease in the scatter range from 1: 2.37 to 1:2.30 when K reduces from 3.6 to 3, whereas the reduction of K from 3.8 to 3, in Fig. 16, shows a 5 % increase in scatter value.

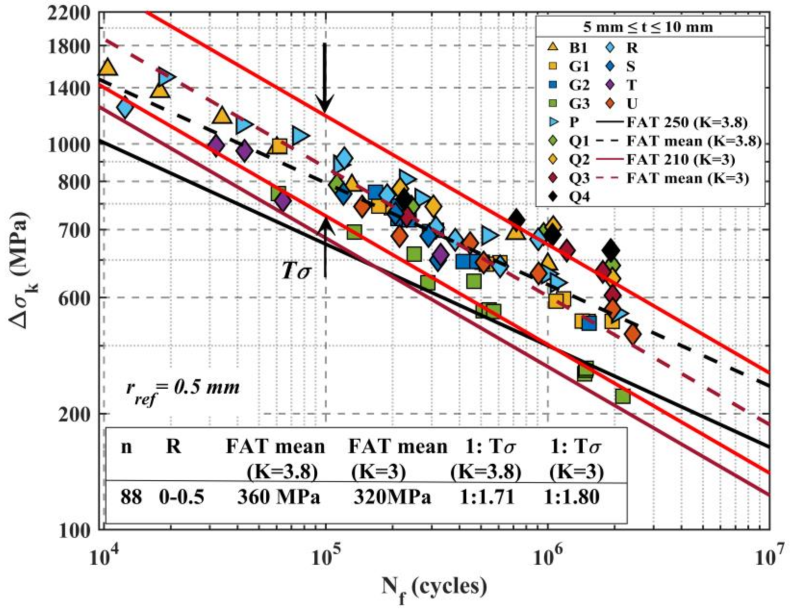

Fig. 16. The data points extracted from thickness between 5 mm $\leq t \leq$ 10, in the notch stress system with r_{ref} = 0.5 mm.

4.4. Overview of the reference radii investigated

In Fig.17, there are the reference S-N curves with K = 3 driven for assessment of LCFWJ using different radii for thickness range between 6 mm and 28 mm considering the location of failure (root side). The literature [17], [28], focusing on the notch stress concept, has revealed that various parameters, such as loading mode (bending, axial, torsion), stress ratio, thickness, stiffness (flexibility) and stress concentration, are involved determining the slope of the S-N line, yet a complexity arises in the evaluation of the interaction of these parameters. As described in previous sections, the impact of thicknesses can be clarified for the reference radii defined. In order to evaluate the effect of changing reference radii, separate S-N curves have been implemented, including the IIW-design lines and the S-N curves gained from Ps = 50% and 97.7 % for FAT mean and the design curve, respectively.

It is apparent from Fig. 8 (b) that for the root failure of LCFWJs with a thickness range of $t \leq 10\ mm$, FAT 225 provided in IIW recommendation is nonconservative. FAT 168 with K = 3, thus, is proposed to obtain conservative results in the notch stress approach.

From the conservative results in Fig 13, it can be seen that FAT 255 with K = 3 might be considered to evaluate the fatigue strength of LCFWJ failing from the root to prevent from underestimating the fatigue strength at high load level in spite of the fact that FAT 320 with K = 5 is originally proposed by Sonsino et al. [28], for a reference radius of 0.3 mm to assess the fatigue strength of the welded joins with thin plate thickness ($5\ mm \leq t \leq 10\ mm$).

Another reported S-N curve is related to r_{ref} = 0.5 mm proposed for assessing the fatigue strength considering a thickness range between 6 mm and 28 mm. However, the scatter value obtained from FAT 220 coupled with r_{ref} = 0.5 compared with FAT 168 is about 2% higher.

Investigation in the notch stress method using r_{ref} = 0.5 mm also shows in contrast to earlier findings achieved from the notch stress method with r_{ref} = 0.3 mm, r_{ref} = 0.5 mm coupled with FAT 210 and K = 3 (Fig.16), might be employed to evaluate the weld root fatigue strength of LCFWJs with plate thickness between 5 mm to 10 mm leading to a lower scatter range ($1{:}\,T_\sigma$=1:1.80) compared with other provided reference radii, and indicates reasonable estimates.

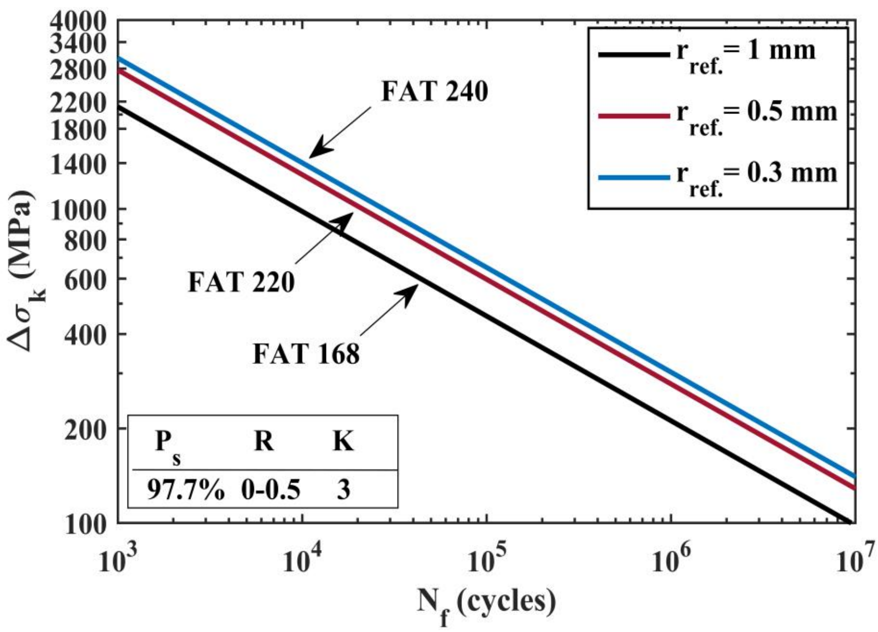

Fig. 17. References S-N lines extracted for the notch stress method for thickness range between 6 mm and 28 mm.

The results, as mentioned in section 4.4, indicate that although the negative inverse slope (K) of the curves employed in the previous recommendations is varying between 3 and 5, those of the FAT classes recommended in the current study are kept equal to 3 without sacrificing the accuracy in fatigue life estimation, maintaining the consistency with the IIW recommendations.

5. Conclusion

In this investigation, the main goal was to assess the fatigue strength of LCFWJs, failing from the weld root using notch stress approach with different radii and compare with the nominal stress approach results. The second aim of this study was to investigate the effects of plate thickness, weld penetration depth, weld throat thickness, and yield strength on the fatigue strength of LCFWJs. To summarize the key findings, the following conclusions can be drawn:

- The analysis of the data confirmed that, although the root failure in LCFWJs can be conservatively evaluated by FAT 36 recommended by IIW, by the use of the notch stress method with r_{ref} = 1 mm, the scatter range can be decreased by 10% and reliably estimate the weld root fatigue strength of LCFWJs employing FAT 168 with K = 3.
- When the whole range of thickness is considered (5 mm ≤ t ≤ 28 mm), either of r_{ref} = 0.3 mm with FAT 240 or r_{ref} = 0.5 mm with FAT 220 are applicable in fatigue analysis of LCFWJ.
- The results of this research demonstrate that to the weld root fatigue strength of LCFWJs considering the thickness range of $5\,mm \leq t \leq 10\,mm$, the notch stress method (FAT 210) with r_{ref} = 0.5 mm might be utilized, which brings lower scatter compared with the FAT 255 and r_{ref} = 0.3 mm. But the use of the latter is justified too, due to the slight scatter difference.

Acknowledgements

This work was supported by Business Finland in the Intelligent Steel Applications (ISA) project (Grant ID: 7386/31/2018).

References

[1] K. J. Kirkhope, R. Bell, L. Caron, R. I. Basu, and K.-T. Ma, “Weld detail fatigue life improvement techniques. Part 1: review,” *Mar. Struct.*, vol. 12, no. 6, pp. 447–474, Jul. 1999.

[2] S. J. Maddox, “Hot-Spot Stress Design Curves For Fatigue Assessment of Welded Structures,” *Int. J. Offshore Polar Eng.*, vol. 12, no. 02, p. 8, 2002.

[3] S. KAINUMA and T. MORI, “A fatigue strength evaluation method for load-carrying fillet welded cruciform joints,” *Int. J. Fatigue*, vol. 28, no. 8, pp. 864–872, Aug. 2006.

[4] D. Radaj, “Review of fatigue strength assessment of nonwelded and welded structures based on local parameters,” *Int. J. Fatigue*, vol. 18, no. 3, pp. 153–170, 1996.

[5] D. Radaj, C. M. Sonsino, and W. Fricke, *Fatigue assessment of welded joints by local approaches*. Woodhead Publishing Limited, 2006.

[6] D. Radaj, *Design and Analysis of Fatigue Resistant Welded Structures*. Woodhead Publishing Limited, 1990.

[7] W. Fricke and H. Paetzoldt, “Fatigue strength assessment of scallops—an example for the application of nominal and local stress approaches,” *Mar. Struct.*, vol. 8, no. 4, pp. 423–447, 1995.

[8] C. E. N. Eurocode, “9: Design of aluminium structures-Part 1-3: Structures susceptible to fatigue,” 1999.

[9] A. Nussbaumer, L. Borges, and L. Davaine, *Fatigue design of steel and composite structures: Eurocode 3: Design of steel structures, part 1-9 fatigue; Eurocode 4: Design of composite steel and concrete structures*. John Wiley & Sons, 2012.

[10] A. Ahola, T. Björk, and Z. Barsoum, “Fatigue strength capacity of load-carrying fillet welds on ultra-high-strength steel plates subjected to out-of-plane bending,” *Eng. Struct.*, vol. 196, p. 109282, 2019.

[11] W. Fricke, “Weld root fatigue assessment of fillet-welded structures based on structural stresses,” in *International Conference on Offshore Mechanics and Arctic Engineering*, 2006, vol. 47489, pp. 505–512.

[12] J. D. Sørensen, J. Tychsen, J. U. Andersen, and R. D. Brandstrup, “Fatigue analysis of load-carrying fillet welds,” 2006.

[13] J. Baumgartner, H. C. Yıldırım, and Z. Barsoum, “Fatigue strength assessment of TIG-dressed welded steel joints by local approaches,” *Int. J. Fatigue*, vol. 126, pp. 72–78, Sep. 2019.

[14] J. Baumgartner, H. Schmidt, E. Ince, T. Melz, and K. Dilger, “Fatigue assessment of welded joints using stress averaging and critical distance approaches,” *Weld. World*, vol. 59, no. 5, pp. 731–742, Sep. 2015.

[15] Ö. Karakaş, G. Zhang, and C. M. Sonsino, “Critical distance approach for the fatigue strength assessment of magnesium welded joints in contrast to Neuber’s effective stress method,” *Int. J. Fatigue*, vol. 112, pp. 21–35, Jul. 2018.

[16] W. Fricke, *IIW recommendations for the fatigue assessment of welded structures by notch stress analysis*. Woodhead Publishing Limited, 2012.

[17] C. M. Sonsino, “A Consideration of Allowable Equivalent Stresses for Fatigue Design of Welded Joints According to the Notch Stress Concept with the Reference Radii rref = 1.00 and 0.05 mm,” *Weld. World*, vol. 53, no. 3–4, pp. R64–R75, Mar. 2009.

[18] A. F. Hobbacher, *Recommendations for Fatigue Design of Welded Joints and*

Components. Cham: Springer International Publishing, 2016.

[19] C. MORGENSTERN, C. SONSINO, A. HOBBACHER, and F. SORBO, "Fatigue design of aluminium welded joints by the local stress concept with the fictitious notch radius of rf=1mm," *Int. J. Fatigue*, vol. 28, no. 8, pp. 881–890, Aug. 2006.

[20] H. Neuber, "Über die Berücksichtigung der Spannungskonzentration bei Festigkeitsberechnungen [About the consideration of the stress concentration in strength assessments]," *Konstruktion*, vol. 20, no. 7, pp. 245–251, 1968.

[21] Ö. Karakaş, "Application of Neuber's effective stress method for the evaluation of the fatigue behaviour of magnesium welds," *Int. J. Fatigue*, vol. 101, pp. 115–126, Aug. 2017.

[22] M. M. Pedersen, O. Ø. Mouritsen, M. R. Hansen, J. G. Andersen, and J. Wenderby, "Re-analysis of fatigue data for welded joints using the notch stress approach," *Int. J. Fatigue*, vol. 32, no. 10, pp. 1620–1626, Oct. 2010.

[23] T. Bruder, K. Störzel, J. Baumgartner, and H. Hanselka, "Evaluation of nominal and local stress based approaches for the fatigue assessment of seam welds," *Int. J. Fatigue*, vol. 34, no. 1, pp. 86–102, Jan. 2012.

[24] B. Kranz and C. M. Sonsino, "Verification of FAT Values for the Application of the Notch Stress Concept with the Reference Radii R ref= 1.00 and 0.05 mm," *Weld. World*, vol. 54, no. 7–8, pp. R218–R224, 2010.

[25] O. KARAKAS, C. MORGENSTERN, and C. SONSINO, "Fatigue design of welded joints from the wrought magnesium alloy AZ31 by the local stress concept with the fictitious notch radii of rf=1.0 and 0.05mm," *Int. J. Fatigue*, vol. 30, no. 12, pp. 2210–2219, Dec. 2008.

[26] C. M. Sonsino, H. Hanselka, Ö. Karakas, A. Gülsöz, M. Vogt, and K. Dilger, "Fatigue Design Values for Welded Joints of the Wrought Magnesium Alloy AZ31 (ISO-MgAI3Zn1) According to the Nominal, Structural and Notch Stress Concepts in Comparison to Welded Steel and Aluminium Connections," *Weld. World*, vol. 52, no. 5–6, pp. 79–94, May 2008.

[27] Ö. Karakas, "Consideration of mean-stress effects on fatigue life of welded magnesium joints by the application of the Smith–Watson–Topper and reference radius concepts," *Int. J. Fatigue*, vol. 49, pp. 1–17, Apr. 2013.

[28] C. M. Sonsino, T. Bruder, and J. Baumgartner, "S-N Lines for Welded Thin Joints — Suggested Slopes and FAT Values for Applying the Notch Stress Concept with Various Reference Radii," *Weld. World*, vol. 54, no. 11–12, pp. R375–R392, Nov. 2010.

[29] J. Baumgartner, "Review and considerations on the fatigue assessment of welded joints using reference radii," *Int. J. Fatigue*, vol. 101, pp. 459–468, Aug. 2017.

[30] Ö. Karakaş, J. Baumgartner, and L. Susmel, "On the use of a fictitious notch radius equal to 0.3 mm to design against fatigue welded joints made of wrought magnesium alloy AZ31," *Int. J. Fatigue*, vol. 139, p. 105747, Oct. 2020.

[31] A. Ahola, T. Skriko, and T. Björk, "Experimental investigation on the fatigue strength assessment of welded joints made of S1100 ultra-high-strength steel in as-welded and post-weld treated condition," in *Advances in Engineering Materials, Structures and Systems: Innovations, Mechanics and Applications*, CRC Press, 2019, pp. 1254–1259.

[32] M. Braun, A.-S. Milaković, F. Renken, W. Fricke, and S. Ehlers, "Application of local approaches to the assessment of fatigue test results obtained for welded joints at sub-zero temperatures," *Int. J. Fatigue*, p. 105672, 2020.

[33] W. Sundermeyer, W. Fricke, and H. Paetzold, “Investigation of weld root fatigue of single-sided welded T-joints,” *Anal. Des. Mar. Struct. V*, vol. 309, 2015.

[34] L. Zong, G. Shi, Y.-Q. Wang, J.-B. Yan, and Y. Ding, “Investigation on fatigue behaviour of load-carrying fillet welded joints based on mix-mode crack propagation analysis,” *Arch. Civ. Mech. Eng.*, vol. 17, no. 3, pp. 677–686, May 2017.

[35] N. F. D. Sheet, “No. 18: Data sheets on fatigue properties for load-carrying cruciform welded joints of SM50B rolled steel for welded structure (Effect of specimen size),” *Natl. Res. Inst. Met.*, 1980.

[36] S. Vishnuvardhan, G. Raghava, M. Saravanan, and P. Gandhi, “Fatigue Life Evaluation of Fillet Welded Cruciform Joints with Load-Carrying Welds,” *Trans. Indian Inst. Met.*, vol. 69, no. 2, pp. 585–589, 2016.

[37] K. H. Frank, “The fatigue strength of fillet welded connections,” Lehigh University, 1971.

[38] S. Kainuma and I.-T. Kim, “Fatigue strength evaluation of load-carrying cruciform fillet-welded joints made with mild steel plates of different thickness,” *Int. J. Fatigue*, vol. 27, no. 7, pp. 810–816, 2005.

[39] P. J. Singh, D. R. G. Achar, B. Guha, and H. Nordberg, “Fatigue life prediction of gas tungsten arc welded AISI 304L cruciform joints with different LOP sizes,” *Int. J. Fatigue*, vol. 25, no. 1, pp. 1–7, 2003.

[40] I. YAMAGUCHI, Y. TERADA, and A. NITTA, “On the Fatigue Strength of Steels for Ship Structure,” *Sel. Pap. from J. Soc. Nav. Archit. Japan*, vol. 1, pp. 19–35, 1968.

[41] S. Kainuma and T. Mori, “A study on fatigue crack initiation point of load-carrying fillet welded cruciform joints,” *Int. J. Fatigue*, vol. 30, no. 9, pp. 1669–1677, 2008.

[42] W. Song, X. Liu, and S. M. J. Razavi, “Fatigue assessment of steel load-carrying cruciform welded joints by means of local approaches,” *Fatigue Fract. Eng. Mater. Struct.*, vol. 41, no. 12, pp. 2598–2613, 2018.

[43] K. Anami, H. Yokota, and R. Takao, “Evaluation of Fatigue Strength of Load-Carrying Cruciform Welded Joint under Combination of Axial Loading and Out-of-Plane Bending,” *Int. J. Steel Struct.*, vol. 8, no. 3, pp. 183–188, 2008.

[44] T. Hanji, K. Tateishi, M. Shimizu, D. Uchida, K. Asano, and R. Kimura, “Fatigue strength of cruciform joints and longitudinal joints with laser-arc hybrid welding,” *Weld. World*, vol. 63, no. 5, pp. 1379–1390, 2019.

[45] M. Braun, R. Scheffer, W. Fricke, and S. Ehlers, “Fatigue strength of fillet-welded joints at subzero temperatures,” *Fatigue Fract. Eng. Mater. Struct.*, vol. 43, no. 2, pp. 403–416, 2020.

[46] T. Hanji, C. Miki, and K. Saiprasertkit, “Low-and high-cycle fatigue behaviour of load-carrying cruciform joints containing incomplete penetration and strength mismatch,” *Weld. World*, vol. 56, no. 5–6, pp. 133–146, 2012.

[47] T. Mori, D. Uchida, T. Fukuoka, and M. Myoken, “Assessment of fatigue strength of cruciform welded joints failing from weld roots under out-of-plane bending,” *Doboku Gakkai Ronbunshuu A/JSCE J. Struct. Earthq. Eng.*, vol. 66, no. 3, pp. 568–575, 2010.

[48] K. Saiprasertkit, T. Hanji, and C. Miki, “Fatigue strength assessment of load-carrying cruciform joints with material mismatching in low-and high-cycle fatigue regions based on the effective notch concept,” *Int. J. Fatigue*, vol. 40, pp. 120–128, 2012.

[49] H. Jakubczak and G. Glinka, “Fatigue analysis of manufacturing defects in weldments,” *Int. J. Fatigue*, vol. 8, no. 2, pp. 51–57, 1986.

[50] B. S. EN, “1-9: 2005, Eurocode 3: Design of steel structures----Part 1-9: Fatigue,” *Br. Stand. Inst.*, 2005.

[51] G. L. DNV, “DNVGL-RP-C203: Fatigue Design of Offshore Steel Structures, no,” *DNVGL-RPC203*, 2016.

[52] B. Standard, “Guide to fatigue design and assessment of steel products,” *BS*, vol. 7608, p. 2014, 2014.

[53] H. P. Lieurade, I. Huther, and F. Lefebvre, “Effect of Weld Quality and Postweld Improvement Techniques on the Fatigue Resistance of Extra High Strength Steels,” *Weld. World*, vol. 52, no. 7–8, pp. 106–115, Jul. 2008.

[54] W. Fricke, “IIW guideline for the assessment of weld root fatigue,” *Weld. World*, vol. 57, no. 6, pp. 753–791, Nov. 2013.

[55] T. Mori and M. Myoken, “Applicability of effective notch stress conception to fatigue strength evaluation for cruciform welded joints failing from weld root,” *J. Japan Soc. Civ. Eng. Ser. A*, vol. 64, no. 1, pp. 188–195, 2009.

[56] B. Jonsson, G. Dobmann, A. F. Hobbacher, M. Kassner, and G. Marquis, *IIW Guidelines on Weld Quality in Relationship to Fatigue Strength*. Cham: Springer International Publishing, 2016.

[57] N. E. Dowling, *Mechanical behavior of materials: engineering methods for deformation, fracture, and fatigue*. Pearson, 2012.