RESEARCH PAPER

Influencing factors on fatigue strength of welded thin plates based on structural stress assessment

Heikki Remes · Wolfgang Fricke

Abstract New lightweight structures in shipbuilding aim at plate thicknesses below 5 mm in combination with welding processes characterised by low heat-input, i.e. laser and laser-hybrid welding. In the European research project BESST— "Breakthrough in European Ship and Ship Building Technologies", an extensive fatigue test programme was carried out for butt- and fillet-welded specimens, which were manufactured by conventional arc, laser and laser-hybrid welding processes. Plate thicknesses down to 3–4 mm were included. The test programme covered also the different production quality including various levels of misalignments. Utilising the extensive fatigue test results, the present paper aims to identify the factors that influence fatigue strength based on the structural stress approach. Secondary bending stresses due to misalignments are directly considered in the structural stress. Different methods of stress determination are applied, such as the through-thickness linearization, surface stress extrapolation, Haibach's approach and Xiao and Yamada's approach. Special attention is given to quality aspects such as undercuts. Based on the results, the suitability of the different structural stress approaches to the fatigue assessment of thin-plated joints in particular are discussed with special consideration of the various welding processes and quality aspects.

H. Remes (✉)
Department of Applied Mechanics, School of Engineering, Aalto University, Espoo, Finland
e-mail: heikki.remes@aalto.fi

W. Fricke
Hamburg University of Technology (TUHH), Hamburg, Germany

1 Introduction

To increase the energy efficiency of large steel structures such as ships, new lightweight solutions are needed. An interesting lightweight solution is to use thin, i.e. 3–4-mm-thick plates. For thin plates, the initial deformations are larger and the dimensional accuracy is stricter in comparison to thicker plates with the thickness of 6 mm or larger [1–4]. This causes special challenges for the fatigue strength assessment.

Fatigue strength assessment of welded structures is commonly carried out using the nominal, structural or notch stress approach [5, 6]. In the case of a large and complex structure, the application of nominal and notch stress approach is, however, limited since the definition of the nominal stress for the complex stress field is difficult or impossible and the notch stress approach requires very fine element mesh [7]. Therefore, the structural hot spot stress approach is the most widely applied for large welded structures; see e.g. [8, 9].

The structural stress is defined as a linearized stress, which neglects the nonlinear stress peak induced by the weld notch. In the case of the plate-to-plate connections, the structural stress can be obtained by linearizing the stress through the plate thickness as shown in Fig. 1a. Thus, the structural stress σ_S, composed of membrane stress σ_m and bending stress σ_b, can be calculated directly from the internal force F and moment M, or from a given stress distribution $\sigma(z)$ [6]:

$$\sigma_S = \sigma_m + \sigma_b = \frac{F}{A} + \frac{M}{W} = \frac{1}{t}\int_0^t \sigma(z)\mathrm{d}z$$

$$+ \frac{6}{t^2}\int_0^t \sigma(z)\cdot\left(t/2 - z\right)\mathrm{d}z, \qquad (1)$$

Fig. 1 Structural stress approaches applied in the present fatigue assessment of welded structures: **a** Linearization, **b** Haibach's approach [10], **c** Extrapolation [6, 8], and **d** Xiao and Yamada's approach [11]
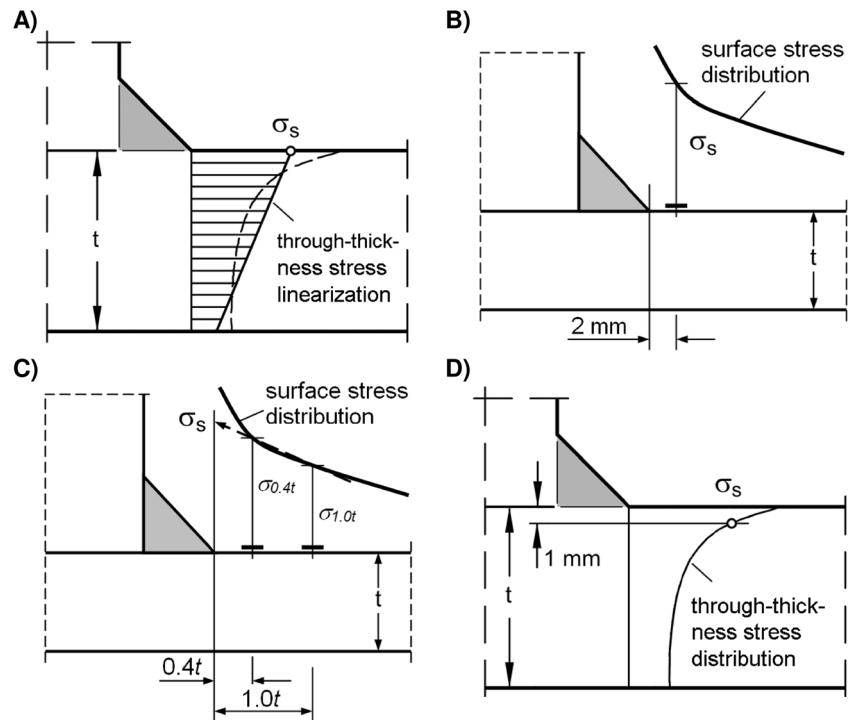
where A is the cross-sectional area, W the section modulus and t the plate thickness. Different approaches for structural stress assessment have been developed since 1968, when Haibach introduced the structural stress approach that utilises the plate surface strain at a small distance from the weld notch [10], Fig. 1b. Later, the surface stress extrapolation approach has been developed to exclude the local notch stress effect at the distance up to $0.4t$ from the weld toe, Fig. 1c. This approach is widely implemented in the fatigue design rules and guidelines [6, 8], typically using the locations $0.4t$ and $1.0t$ in front of the weld toe for stress extrapolation. More recently, Xiao and Yamada [11] introduced the approach based on the structural stress 1 mm below of the notch tip, Fig. 1d. This selection is

motivated by the assumption that the fatigue damage is governed by crack propagation at this depth. All these approaches are successfully applied for welded thick plates [12–14]. However, in the case of thin plates, the structural stress assessment has shown unexpectedly large scatter of fatigue strength and lower fatigue strength than that of thick plates [15, 16]. The reason for this difference is not yet known.

The objective of this paper is to investigate the different affecting factors on the structural stress assessment of welded thin plates. The influence of the welding method, joint type, secondary bending and weld shape are studied. It should be mentioned that secondary bending stresses due to misalignments are already included in the structural stress. The

Butt joint

Welding	Plate thickness of butt joint		
Method	3 mm	4 mm	6 mm
Arc (CV)	29 tests[T,R**]	23 tests[T,R]	-
Hybrid (HY)	30 tests[T,R]	15 tests[T,R]	10 tests[T]
Laser (LA)	10 tests[T]	10 tests[T]	-

T-joint

Welding	Plate thickness of T-joint*		
Method	3/5 mm	8/5 mm	8/7 mm
Arc (CV)	7 tests[T]	9 tests[T]	-
Hybrid (HY)	8 tests[T]	27 tests[T]	11 tests[T]
Laser (LA)	8 tests[T]	10 tests[T]	21 tests[T]

*) Thickness of the load-carrying plate / attached plate
**) Fatigue crack initiation form weld toe (T) and root (R) side
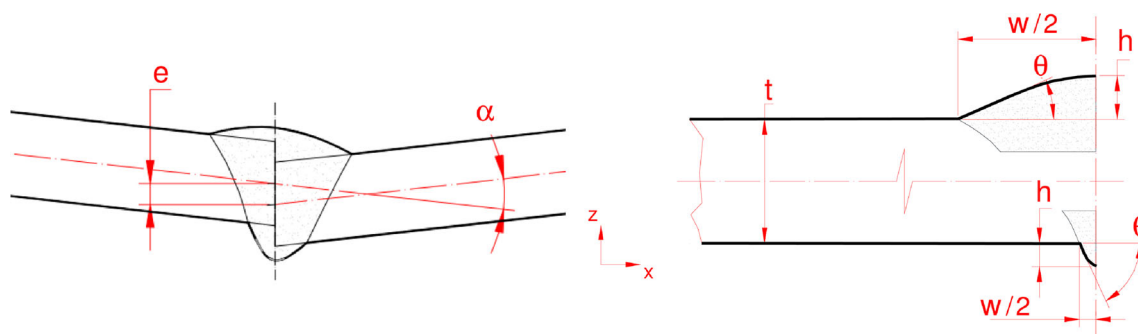
Fig. 2 Fatigue test programme

Fig. 3 Dimensions of the welded joints: α angular and e axial misalignments, t plate thickness, h weld height, w width, θ flank angle

obtained results are compared to thick plate results. In addition, the suitability of the applied structural stress approaches for welded thin plates is evaluated.

2 Methods

2.1 Experiments

The present investigation utilises the fatigue experiments of butt and T-joints welded by conventional arc (CV), laser-hybrid (HY) and pure laser (LA) welding [16]. The main focus is on the plate thicknesses of 3 and 4 mm as shown in Fig. 2. In addition, test series up to 8 mm plate thickness are included for comparison. The fatigue test programme analysed in the present study includes 128 butt- and 101 fillet-welded test specimens. The tested butt joints include both toe and root side crack initiation. In the case of fillet welded T-joints, the cracks initiated only from the weld toe side of the load-carrying plate. The yield strength of the specimen base plates varied between 293 and 466 MPa. More detailed information of the specimen manufacturing, base plate properties and experiments is given in [16].

The fatigue test specimens were cut from welded plates, and the fatigue tests of the specimens were carried out with load ratio $R=0$, 0.25 and 0.5. The specimens were clamped to test grips with rotating clamping device, which avoids secondary bending moments during the specimen clamping [2]. Before fatigue testing, the shape of the base plates, misalignments and weld dimensions were recorded based on geometry measurements and macro-sections of the welded joint, see Fig. 3.

2.2 Numerical analyses

Numerical analyses consisted of the structural stress analysis of all test specimens. In the analysis, the deformed shape of the plates and misalignments were used for each different specimen, while constant mean values of the weld dimensions were used for all specimens within each series. Based on the measured shape of the specimens and weld geometry, 2D section models were created for finite element analysis. The element size is approximately 0.1 mm at the weld notch and 1 mm elsewhere. As shown in Fig. 4, the numerical analysis utilised two types of geometry models: a simplified and a realistic model. The simplified model follows the common modelling principles using an idealised weld profile without the undercut and weld notch rounding. In the case of realistic geometry model, the mean value of the measured undercut and weld notch rounding was included. The realistic model is primarily used in the following analyses while the simplified model was applied for comparison. It should be noted that the structural stress is not the same for the simplified and realistic model, as in one case stress is linearized below the weld notch
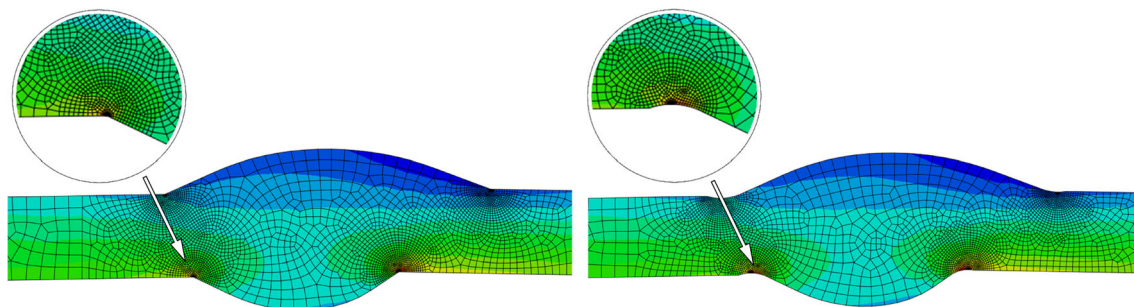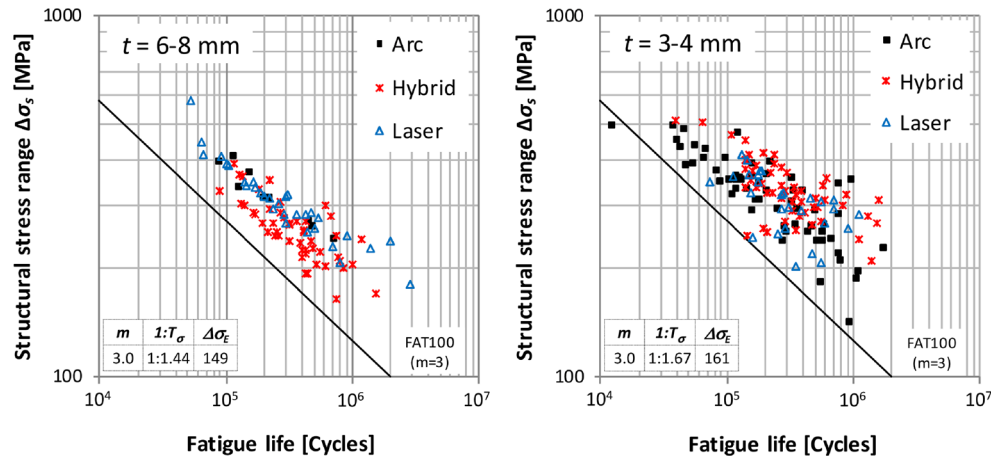

Fig. 4 Examples of the FE model for a conventionally arc-welded 3-mm-thick specimen with an axial misalignment of 0.2 mm and angular misalignment of 1.6°: simplified (*left*) and realistic model including weld undercuts (*right*)

and in the other below the undercut. The latter one results in higher stresses. The structural stress for each test specimen was evaluated at the fatigue crack initiation location observed in the fracture surface analysis. Specimens with visible weld defects or base material failure were excluded from the analysis. Due to the type of the joints, i.e. the plate-to-plate connections, the stress through-thickness linearization approach is applied as a primary approach in the subsequent fatigue analysis. Haibach's approach, surface stress extrapolation and Xiao and Yamada's approach were applied for comparison.

3 Results

3.1 Influence of welding method and joint type

The fatigue life of the test specimens is presented as a function of the structural stress in Figs. 5 and 6. In these figures, the results are categorised based on the welding method and joint type. As shown in Fig. 5, the welding method does not have a

significant influence on the fatigue strength of the thin plates. In the case of thick plates, the fatigue strength of the hybrid welded joints is slightly lower than that of arc- and laser-welded joints. However, all test results, excluding one test point, are above the reference S-N curve FAT100 [6] with the slope value of $m=3$.

The influence of joint type on fatigue strength is shown in Fig. 6. In the case of thick plates, fatigue strength of the butt joints is higher than that of T-joints. For thin plates, the difference in fatigue strength between the butt and T-joints is very small, but the scatter band of the test results for the butt joints is significantly wider than that of the T-joints.

3.2 Influence of misalignments and weld geometry

The influence of misalignments was studied based on the stress magnification factor k_m, giving the stress increase of the nominal stress due to secondary bending caused by misalignments. As shown in Fig. 7, fatigue strength in terms of structural stress is found to be somewhat independent of the bending effect which is expected as secondary bending stresses are already considered by the structural stress evaluation.

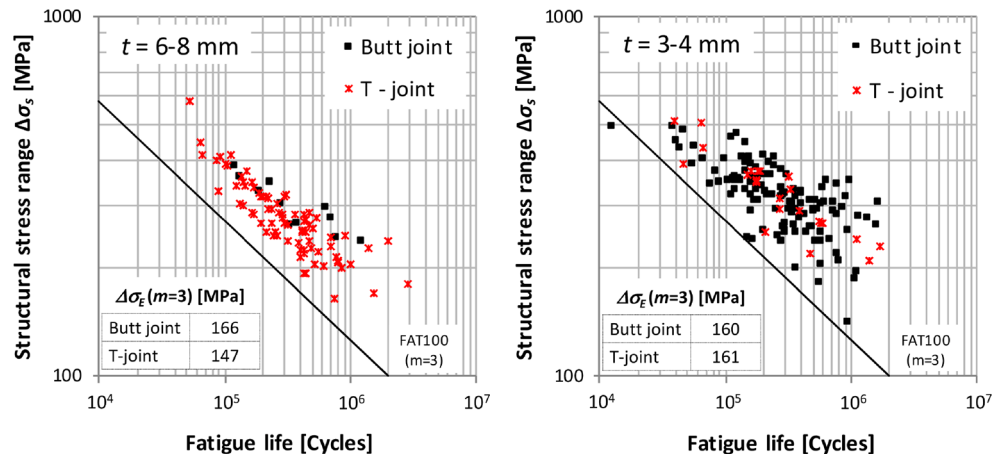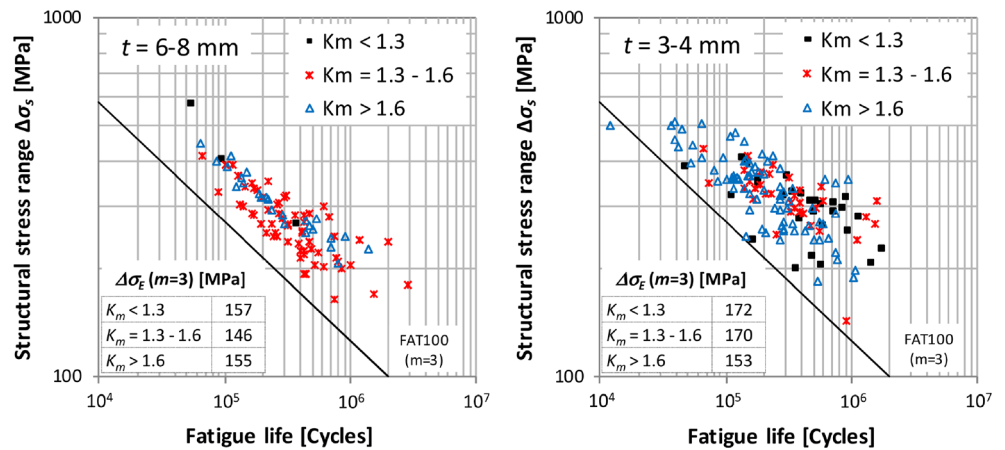**Fig. 6** Influence of joint type on fatigue strength of thick and thin plates

The influence of the weld shape is illustrated in Fig. 8, where the fatigue strengths are categorised by the flank angle θ at the fatigue critical weld notch. In the case of thick plates, the fatigue strength is reduced with the increasing flank angle. This relation is not clearly observed for thin plates, where the test results are randomly distributed in relation to the flank angle.

3.3 Influence of undercuts at the weld toes

Figures 9 and 10 present the influence of the undercut depth and notch sharpness, i.e. D/R ratio, on the fatigue strength. The undercut depth does not show clear correspondence to the fatigue strength, but the notch sharpness shows better correspondence to the fatigue strength. This is more visible in the case of thick plates. The reason for this difference was studied more thoroughly using three butt joint series with a plate thickness of 3 and 6 mm. For these test series, the individual undercut at the critical weld notch and axial misalignment values were measured and the test results are categorised according to these values, instead of the mean geometries of the series. As shown in the right part of Fig. 11, the scatter and low fatigue strength values are mainly related to higher

undercut values. Two test points with low fatigue strength for a narrow hybrid weld ($D<0.05$ mm) are related to a sharp notch introduced by axial misalignment; see the left part of Fig. 11. This statistical variation in weld notch geometry between individual specimens is not considered in Figs. 9 and 10, where the mean weld notch geometry of each series is utilised for all specimens.

The influence of the undercut on the structural stress is presented in Fig. 12, where the mean value of the undercut depth for each series is applied. Particularly for thin plates, the undercut reduces the effective cross-section and increases the structural stress. The difference in the structural stress between realistic models including the undercut and simplified models without the undercut varies between 2 and 31 %. The highest differences are observed for the cases with the largest undercut depth. For thick plates, the difference between realistic and simplified models is less than 10 %.

3.4 Influence of structural stress evaluation

Differences between stress linearization and other approaches are presented in Fig. 13. Surface stress
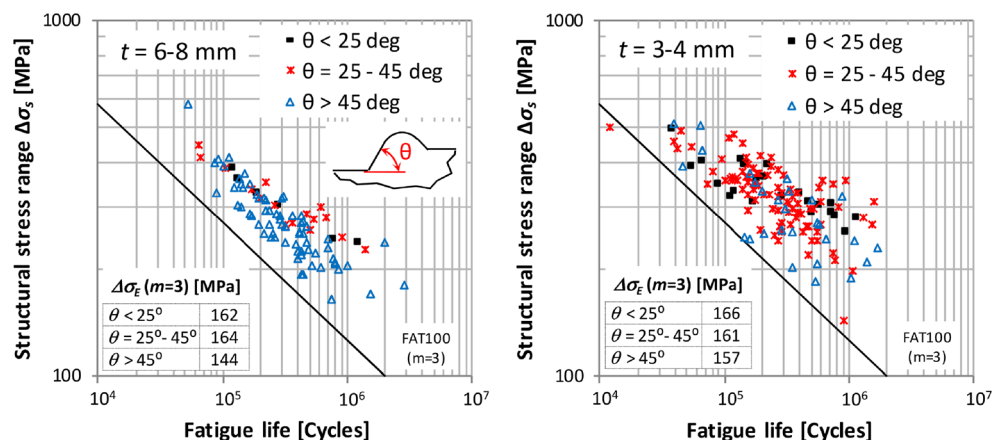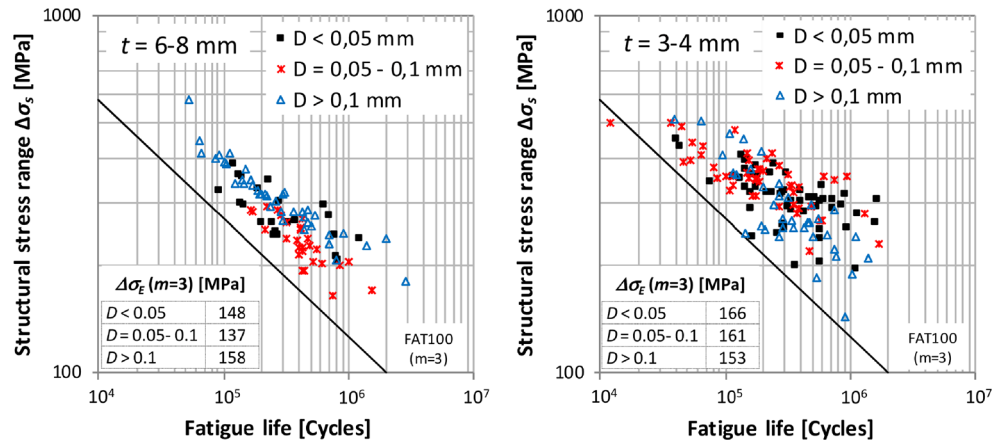
Fig. 9 Influence of undercut depth D on fatigue strength of thick and thin plates

extrapolation, Haibach's approach and Xiao and Yamada's approach lead to acceptable fatigue strength assessment with the scatter range index T_σ smaller than 1:1.5 in the case of thick plates. Extrapolation and Haibach approaches are in general well-suited to thin plates. However, some differences up to 40 % were observed. This is shown as slightly higher scatter range index T_σ and as smaller fatigue strength in comparison to the linearization approach. The cases with a high difference are related to specimens where undercuts and high angular misalignments, i.e. secondary bending stress, exist. In particular, the surface stress extrapolation and Haibach's approach have problems with undercuts. Xiao and Yamada's approach is not able to give reasonable prediction for thin plates and it is sensitive to bending stresses. This approach underestimates the structural stress when the k_m value is high and plate thickness is small in comparison to the 1 mm reference distance. Figure 14 illustrates the difference in structural stress between the stress linearization and Xiao and Yamada's approach as a function of the magnification factor k_m for secondary bending. In Fig. 14, the k_m factor is normalised by the ratio of section modulus on plate surface and at 1 mm below the surface. The

maximum difference is 36 % for thick plates and 193 % for thin plates.

4 Discussion

The extensive evaluation of the fatigue test results of butt and T-joints allows an insight into the applicability of the different structural stress approaches for welded thin plates. The evaluation also reveals different influencing factors, which are discussed in detail in the following:

4.1 Geometry

The effects of misalignment are treated in the structural stress approach on the loading side, i.e. the additional secondary bending stresses are already considered in the structural stress. Consequently, the evaluated fatigue strength in terms of structural stress is independent of the bending effect as shown in Fig. 7.

The plate thickness was not observed to influence the fatigue strength as shown in Fig. 6, however, the scatter range of fatigue life is higher for thin specimens. In addition,

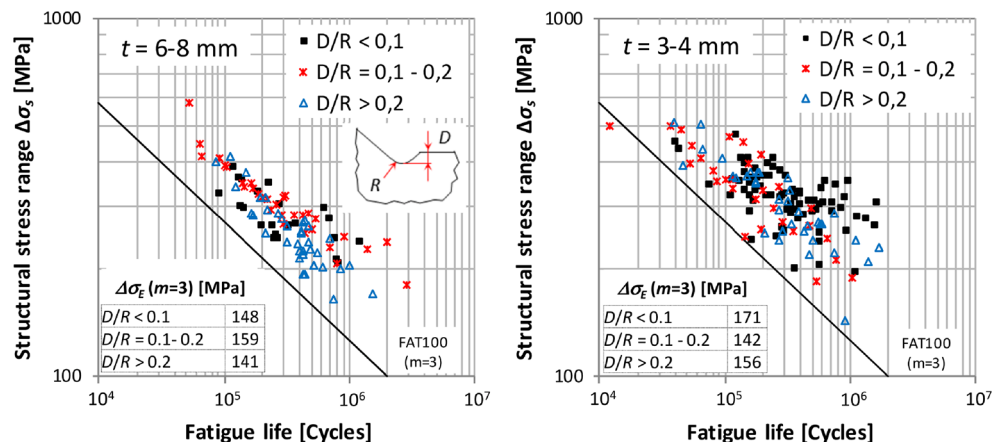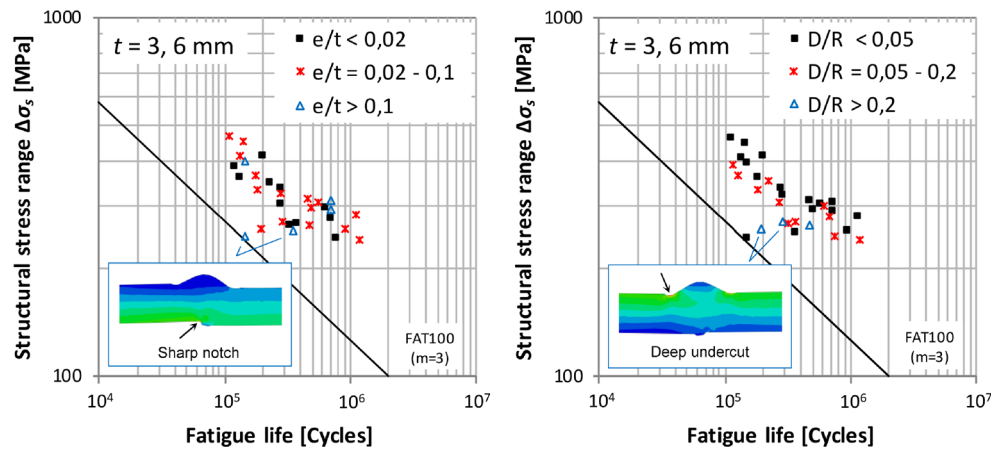**Fig. 10** Influence of weld notch sharpness on fatigue strength

Fig. 11 Influence of axial misalignment resulting in sharp notches and undercut depth on the fatigue strength of laser and laser-hybrid welded butt joints with a plate thickness of 3 and 6 mm

a slope exponent m>3 can hardly be seen since the scatter band is widened in the high-cycle domain. For thin-plated joints, the high scatter is mainly caused by the effects of the local geometry, in particular undercuts. Although the structural stress in the present analysis is based on the net section below the undercut, the undercut depth and particularly notch sharpness determine the fatigue life in the scatter band. In addition, other factors such as high axial misalignment creating a sharp notch at the root side of butt joints move data points to the lower boundary of the scatter band.

4.2 Structural stress assessment

Four approaches of structural stress determination have been applied. The through-thickness stress linearization and Haibach's approach yield the narrowest scatter bands of the fatigue test results, see Fig. 13. The results of the surface stress extrapolation are slightly more scattered, whereas Xiao and Yamada's approach is shown not to be suitable for thin-plated joints because the 1 mm stress is located close to the neutral axis. This results in nonconservative fatigue lives in comparison to

the proposed design S-N curve especially in the case of pronounced secondary bending.

The results of the evaluation indicate that the effect of undercuts particularly for thin-plated joints should be considered. This can be done in the through-thickness linearization by choosing the net section below the undercut. This is, however, problematic in Haibach's approach or in the surface stress extrapolation. Modelling the undercut may decrease the structural stress and lead to unreasonable results.

4.3 Design S-N curve

The existing design S-N curves, e.g. FAT 100 according to [6, 7], are suitable for the fatigue assessment of thin-plated joints particularly if the stress linearization through the net section below undercuts is applied. When using Haibach's approach or the surface stress extrapolation to determine the structural stress, almost all fatigue test results are still above the design S-N curve.

The evaluation has shown that weld quality plays an important part. Sharp undercuts and root notches due to axial

Fig. 12 Influence of geometry modelling on the fatigue strength assessment
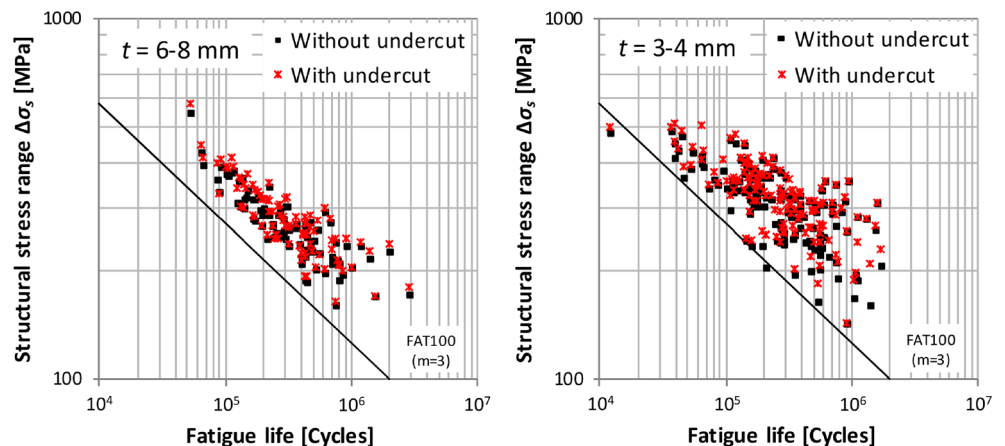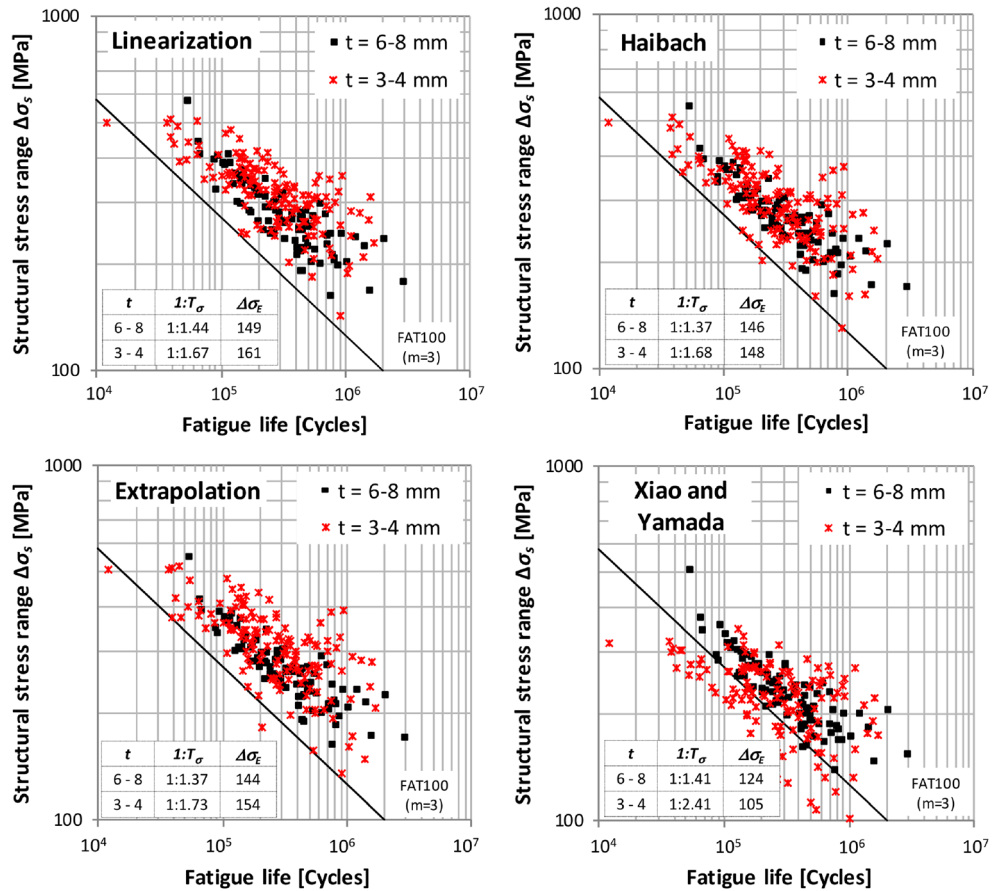
Fig. 13 Fatigue life as a function of the structural stress range for different approaches

misalignment decrease the fatigue life of several thin-plated specimens. On the other hand, welds with higher quality show increased fatigue strength together with a shallower slope of the S-N curve.

5 Conclusions

This paper aimed to provide a better understanding of the relation between the influencing factors and fatigue strength of welded
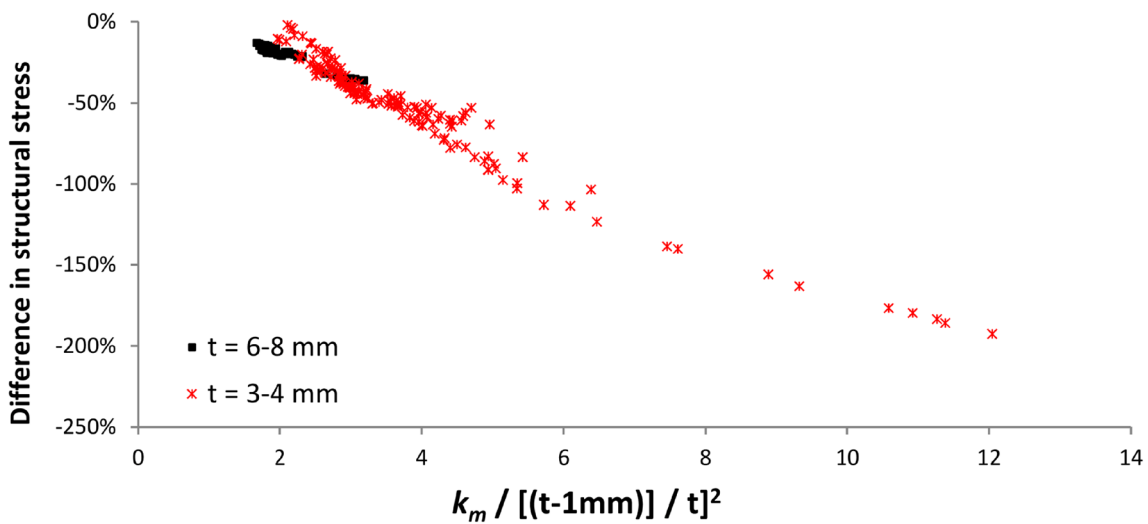

Fig. 14 Difference in structural stress range between stress linearization and Xiao and Yamada's approach depending on the magnification factor k_m for secondary bending

thin plates. On the basis of the experimental and numerical investigations, the following conclusions can be drawn:

- No beneficial plate thickness effect was observed in butt and T-joints between 3–4 and 6–8-mm-thick plates.
- Weld quality and particularly undercuts affect thin-plated joints more than thick-plated ones, resulting in larger scatter especially in the high-cycle domain.
- The structural stress approach, in particular the through-thickness linearization, is well-suited for fatigue strength assessment of thin-plated joints.
- The effect of undercuts should be included by determining the structural stress in the net section.
- The 1-mm stress approach by Xiao and Yamada should not be applied to thin-plated joints because the stress location is close to the neutral axis, thus not capturing the secondary bending effect.
- Quality aspects such as misalignments and undercuts play a major part and therefore improved quality may result in higher S-N curves and slope exponents.

The present study was limited to the structural stress analysis, and thus the influence of weld notch shape was not explicitly considered. Therefore, further investigations are planned to focus on the influence of the weld notch shape using the local approaches such as the notch stress approach. Furthermore, the influence of residual stress on fatigue strength is left for future work.

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