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Factors affecting the fatigue strength of thin-plates in large structures

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Abstract

This paper studies the main factors affecting the fatigue strength assessment of thin plates in large structures. The first part of study includes the influence of initial distortions, joints' flexibility and surrounding structure on structural stress analysis of welded joint. The second part covers the influence of joint and its geometrical properties on fatigue strength modelling. The third part includes also the material elastic-plastic behaviour and the influence of crack propagation. The results show that if the structural analysis considers secondary bending properly, the local elastic fatigue damage parameters such as J-integral range can be used to model fatigue strength at 2-5 million load cycles. However, to explain the slope variation of the fatigue resistance curve, the consideration of material elastic-plastic behaviour and short crack growth is needed. The strain-based crack growth simulations indicate that longer short crack growth period is the reason for the higher slope value. The importance of short crack growth is dependent on the weld notch geometry and plate thickness.

Keywords

Fatigue strength; Fatigue crack initiation; Local approaches; Weld; Thin plate

1 Introduction

New lightweight solutions are required to improve the energy efficiency of vehicles such as ships. Weight reduction of large structures is possible by using thinner plates and high strength steel materials. Their efficient utilisation typically requires new structural topology, alternative manufacturing technology and robust design methods for structural durability [1], [2]. One of the key challenges in structural design of welded structures is fatigue due to its localized and cumulative nature [3]. This is especially true for thin plates due to their higher sensitivity for dimensional accuracy. While the choice of manufacturing technology and the achievable dimensional accuracy are affected by the size of the structure, the definition of thin plates is also dependent on the field of industry. For large structures such as ships, a plate thickness of less than 5 mm is considered thin in comparison to commonly used plate thicknesses [4], [5], while in car industry plate thicknesses are in the order of 1 mm [6]. Based on the selected plate thickness and structural topology, we can categorize the lightweight steel structures used in shipbuilding to classical stiffened panels with thin plates (3-4 mm) and steel sandwich panels with ultra-thin plates of 1-3 mm.

In large welded structures the manufacturing induced distortions cause additional challenges to structural analysis and fatigue strength assessment of thin plates. For example stiffened plate structures with thin plates are more sensitive to welding induced distortions and welding defects in comparison to thick plate alternatives [4], [5], [7], [8]. Relatively larger initial distortions in thin and slender structures cause geometrical non-linearity to structural response that must be taken into account when assessing local stresses. In closed sandwich panels slenderness of the plates forming the closed units is locally small, and thus the face and web plates are almost straight after panel production. In sandwich panels the core is prismatic and thus, it becomes complicated to connect one panel to another so that the full cross-section is connected. This means that there are geometrical discontinuities at the ends of the web plates, which act as possible crack initiation points. Thus from fatigue strength viewpoint prismatic joints that are inserted between two sandwich panels would be optimal [9]. However, in practice one-sided welding is preferred in production and this requires non-symmetrical panel-to-panel joints [10]. This non-symmetry causes local bending moments, which together with the discontinuous web plates are detrimental to the fatigue strength of the structure. Thus, it is reasonable to conclude that the structural response of a large thin-plated structure cannot be assessed by assuming flat plate geometries as is commonly done in idealised structural models.

Even though the structural analysis includes the geometrical non-linearity mentioned above, another challenge arises from assessing the actual fatigue strength of thin plates. The thinner plates are more susceptible to weld defects and distortion induced secondary bending than thick plates. Thus, the thin plates require the use local approaches in stress analysis, e.g. structural or notch stress approaches. Structural stress approach can capture the stress increase due to initial distortions. However, in thin plates the prevailing assumptions are pushed to their limits as the stress boundary condition at the neighbourhood of the weld notch tip can start to affect the stress state. The structural stress approach and notch stress approach have been shown to lead to good results in stiffened plate structures when the fatigue limit is concerned, but the slope of the fatigue resistance curve is seen to vary from the commonly used value [4]. Sonsino and several other researchers [11], [12], [13], [14], [15], [16], [17] have investigated fatigue strength of these thin-plate structures. Sonsino et al [12] reported that the slope of the fatigue resistance curve is five for thin plates and flexible joints. This differs from the commonly observed value of three for welded thick plates [18]. Furthermore, the scatter of experimental data is larger for thin plates in comparison to thick plates [12]. In steel sandwich panels, where the plate thickness is significantly smaller, neither the structural or notch stress approaches give reasonable results for fatigue strength, and an energy or J-integral based assessment method has to be used instead [19], [20], [21], [22]. However, it is seen that the slope of the fatigue resistance curve can be even higher than with structural and notch stress approaches. It has been stated that the increase of slope is related to the gradient of elastic stress at the notch tip [23], which is affected by the loading mode and traction-free boundary conditions around the notch. This issue requires further investigation as the assessment is based on local elastic stress and material plasticity effect was neglected. In addition, the holistic understanding of all affecting factors acting simultaneously is required in order to develop a robust approach for fatigue strength assessment of thin plates in large structures.

The objective of this paper is to investigate the factors affecting the fatigue strength of thin plates in large structures. The study covers different levels from the structural behaviour of large structures to crack growth in microscale. The paper consists of three main parts. Chapter 2 includes the scale transition from large structures to the welded joint, i.e. the influence of initial distortions, joints' flexibility and surrounding structure on structural stress analysis. Chapter 3 focuses on the influence of weld geometrical properties on fatigue strength modelling. To extend these studies and consider the weld geometry and plate thickness effect on fatigue resistance, Chapter 4 includes strain-based crack growth simulation. The studies presented in this paper utilise experimental and numerical investigations of two highly potential steel lightweight solutions for large structures. The investigated structures are a steel sandwich panel and a thin stiffened deck structure, which are manufactured with laser welding technologies. These structural topologies can result in significant weight reduction even without the utilisation of high strength steel.

2 Influence of geometrical non-linearity on response analysis

2.1 Scale transition between large structural assemblies and welded joint

When steel sandwich panels are used in large structures such as a passenger ship deck, the joining between the panels needs to be carried out. As the plates are thin and non-symmetrical joints are used, the sandwich panels undergo significant out-of-plane deformations when exposed to membrane loading. Therefore multi-level analysis is required to assess the loading at the fatigue critical locations [24], [25]; see Figure 1a. First, the stiffness of the joint needs to be defined using detailed FEA based on solid elements. Then, equivalent single layer (ESL) elements are used to assess for instance the global response of a passenger ship hull-girder with membrane (A-matrix in laminate theory), membrane-bending coupling (B-matrix) and bending stiffness (D-matrix) around the reference plane of the panel. Depending on the type of joint, panel geometry and selected reference plane, the nominal loading at the deck level can include only tensile or tensile and bending terms. As bending response is governed by the out-of-plane boundary conditions, the bending and membrane states are coupled by the B-matrix. This means that the nominal stress level associated with the membrane action of the deck might locally decrease between girders, while in at the location of girders it increases; see Figure 1b. Therefore, the stiffness of the joint and the bending effect due to joint non-symmetricity must be taken into account at all scales from joint to hull girder. The same principle applies to stiffened plate structures with high initial deformations. According to von Karman kinematics the bending and membrane responses are coupled. Thus, multilevel analysis is needed; see Figure 2. For thin decks with initial distortions the load redistribution takes place between plates, stiffeners and girders, as well as between different decks. However, the total load carried by each deck was almost the same for ideally straight decks and decks with initial distortions [25]. Consequently, the influence of geometrical nonlinearity on global analysis is small. Therefore, the sub-model loading for fatigue assessment can be defined from a simplified global model with geometrically linear analysis and ideally straight structure, assuming that the fatigue sub-model includes realistic initial distortions. Based on a sensitivity analysis the distortion shape must have less than 4 half waves in the stiffener direction or alternatively the distortion magnitude must be small (up to 2 mm) for the above mentioned simplification to be valid.

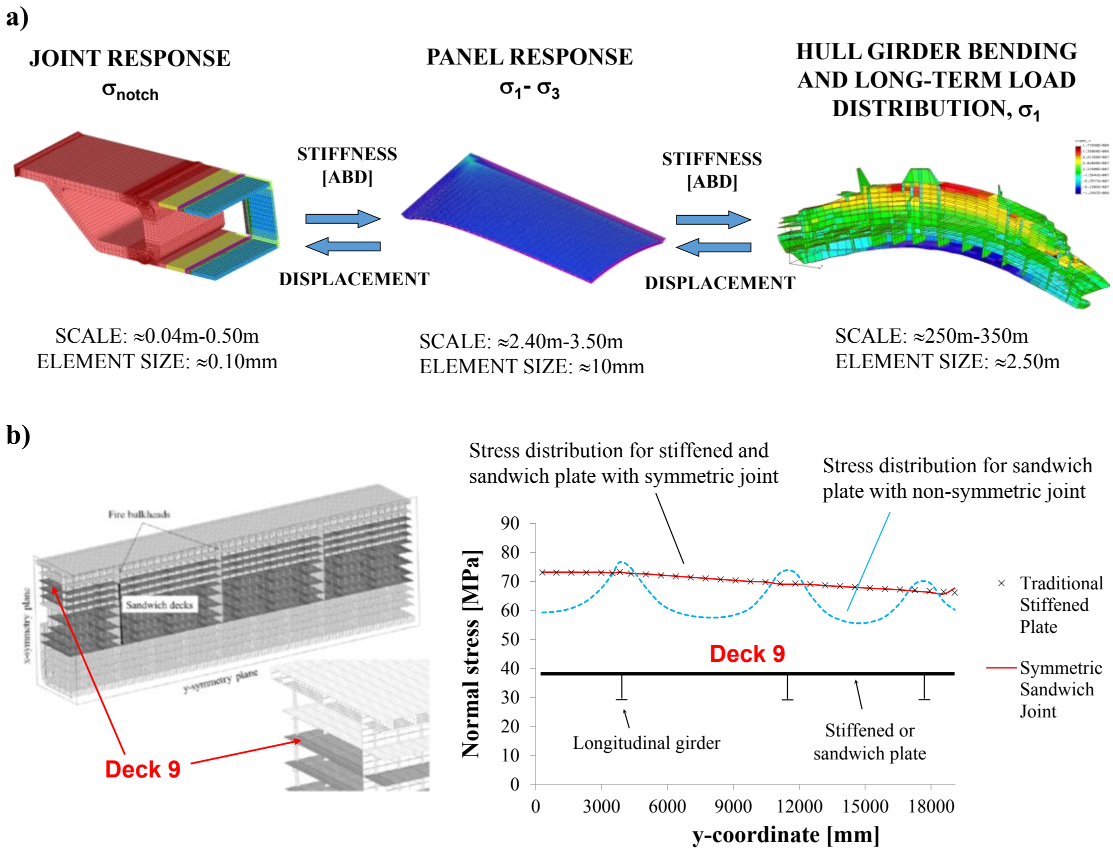


Figure 1: Multilevel analysis approach for the fatigue strength assessment of steel sandwich panel joints in a cruise ship structure (a) and resulting normal stress distribution (b). The given stress distributions correspond traditional and steel sandwich decks with equal cross-sectional area.

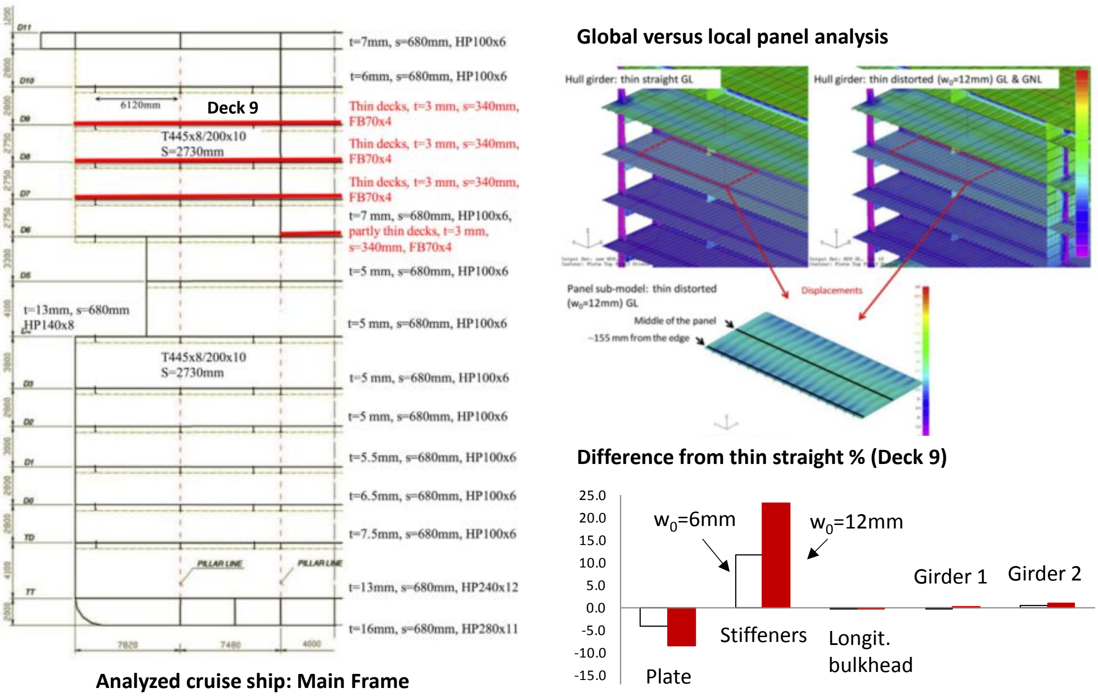


Figure 2: Influence on initial deformation (w_0) on structural behaviour of a thin-plate structure.

2.2 Structural behaviour of welded joint in a panel

Similar to the joints between sandwich panels, the structural behaviour of a steel sandwich panel itself is highly affected by the geometrical properties of the stake-weld. Figure 3 shows the results from geometry and stiffness measurements for stake welds in thin plates [26]. The width of the stake weld is about 50% smaller than the web plate, and thus the rotation stiffness of the joint is not infinite, contrary to e.g. a fillet welded T-joint. The finite rotation stiffness means increased joint flexibility and this has a significant influence on the sandwich panel response and local stress at the weld notch in the case of out-of-plane loads. If the rotation stiffness is assumed to be infinite in FE analysis, about 30% error in the maximum deflection is observed between FEA and panel tests [26]. Panel response has been found to be dependent on plate aspect ratio (length and breadth ratio *L*/*B*) and joint stiffness [27]. In the range of L/B=0.3-3 the plate curvature is affected by the joint stiffness. This is seen as an increase of deflection, but also as the change of maximum nominal stress in the panel. Therefore, the 2-stage FE analysis is needed for fatigue strength assessment of a sandwich panel. This includes the panel analysis with finite weld rotation stiffness and local analysis of the joint with correct boundary conditions from the panel analysis. In local stress assessment of the joint the consideration of non-linearity due to contact effect is important only if rotation of the T-joint is very large in the high-cycle regime. The occurrence of contact is affected by load location and panel shear stiffness, as e.g. a filler material in the panel core reduces the rotation of the T-joint and increases the fatigue life [28].

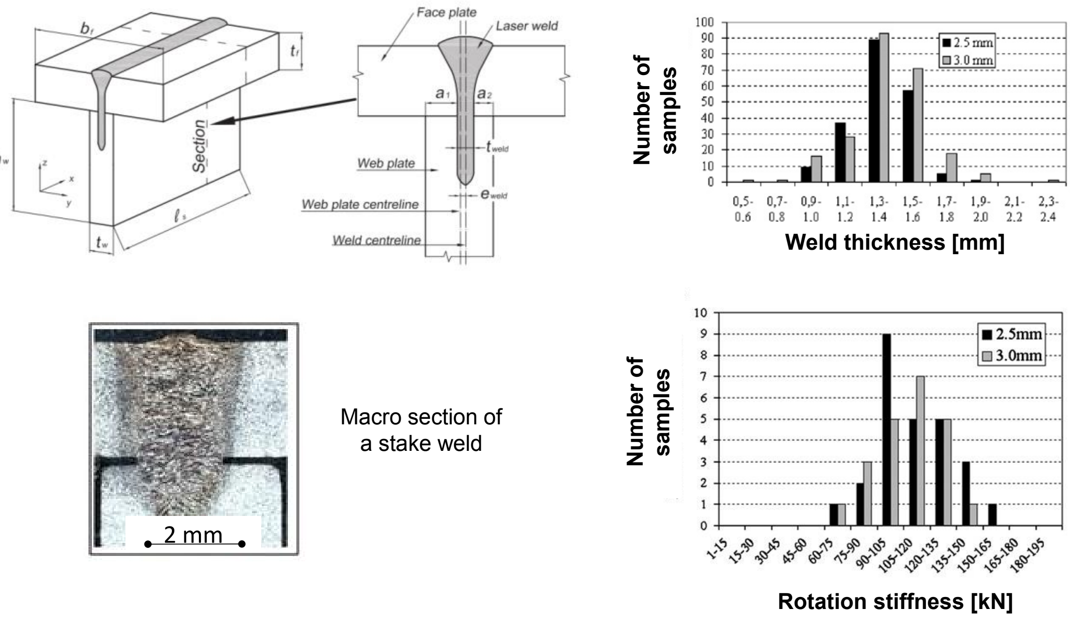


Figure 3: Macro section of stake-weld and main geometrical properties.

Weld flexibility does not need to be considered for the stiffened plate as the weld thickness and, thus, the stiffness of the weld is equal to the base plate. However, the initial distortions of the plate field need to be considered since they have an influence on structural behaviour [4], [29]. The welded thin plates have a curved deformation shape close to welded joint due to low bending stiffness of the plate itself. As shown in Figure 4 (left) the deformation shape and boundary condition defined by the surrounding structure have a significant influence on structural behaviour. Straightening under axial tensile loading is significant in welded plate specimens typically used in fatigue testing, and the relationship between structural stress and nominal stress is highly nonlinear. Geometrical nonlinearity is significantly smaller in plates with curvature in two directions [29]. For stiffened plate structures, the geometrical non-linearity depends on the shape and magnitude of initial distortion. Although non-linearity is not always significant in panel level, the shape of distortions has an important effect on the magnitude and shape of structural stress distribution at the weld seam; see Figure 4 (right). The location of the fatigue critical area can change depending on the shape and magnitude of distortions. For stiffened plate, the results show that the shape of distortion can be even more important than the amount of distortion. To take this into consideration a geometrically nonlinear analysis with the actual deformation shape is necessary in order to calculate the structural response i.e. strains and stresses accurately; see Figure 5 [30]. However, the relationship between structural and notch stress is always constant regardless of straightening [4].

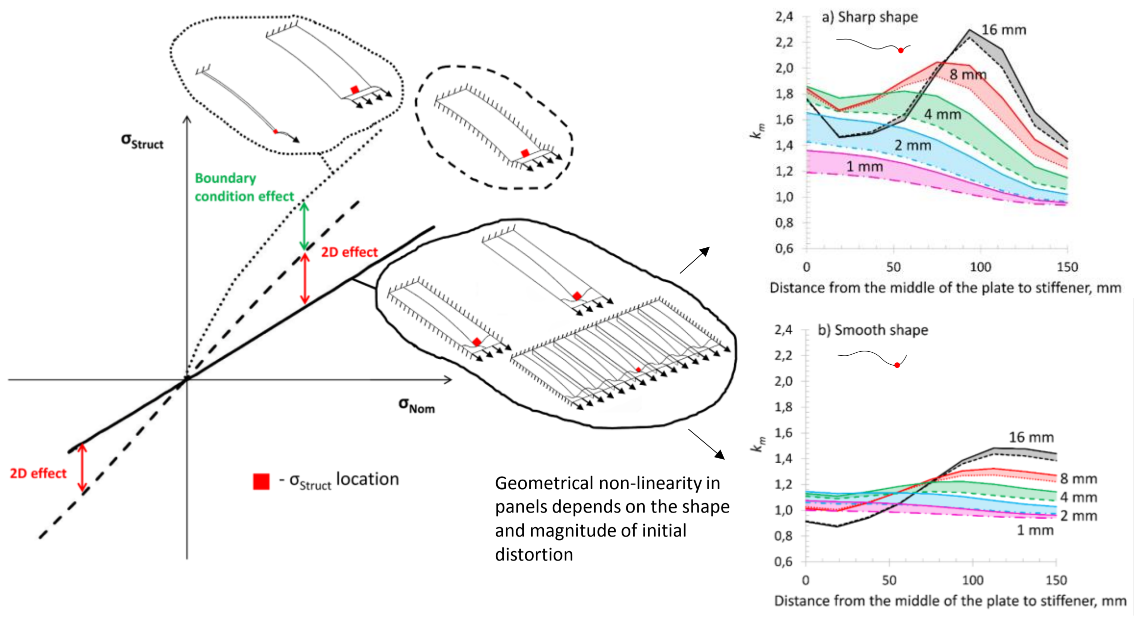


Figure 4: Influence of surrounding structure and initial distortion shape on the response (Structural stress σ_{struct} and stress magnification factor k_m) of thin plate structure.

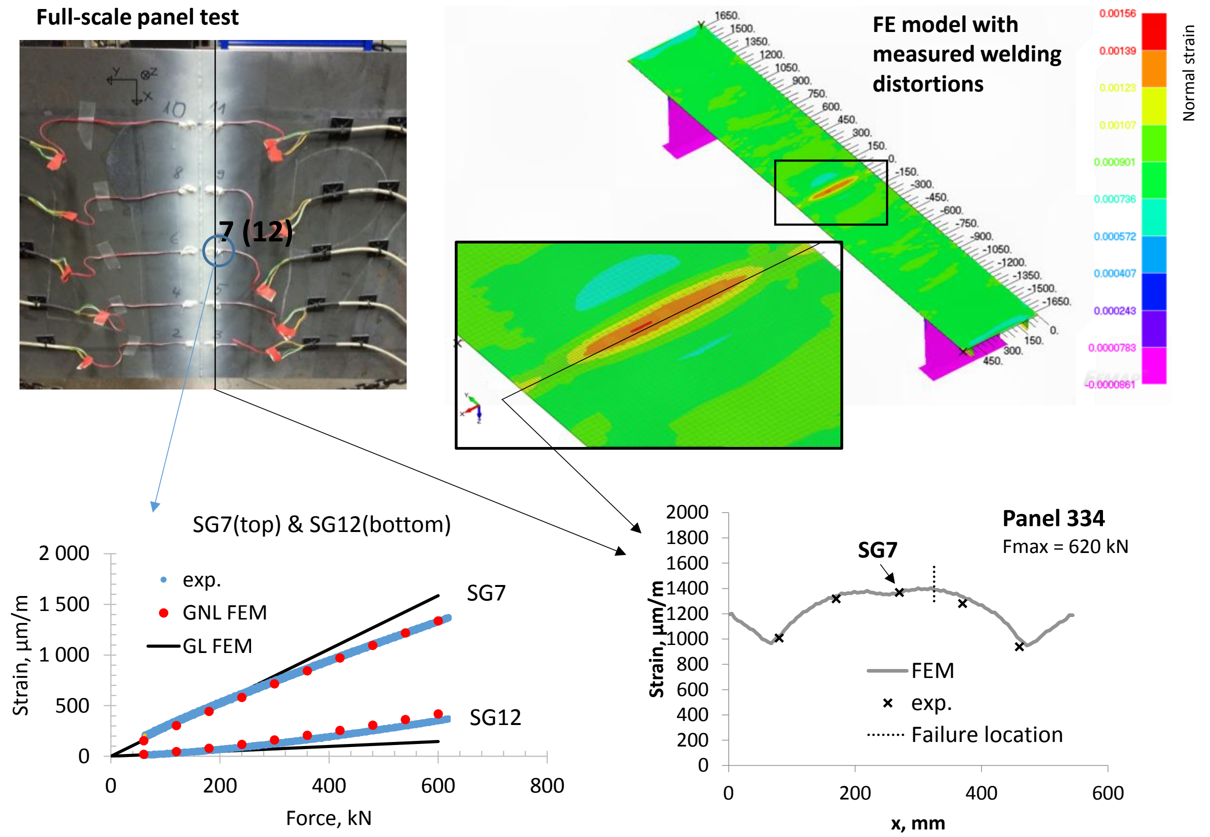


Figure 5: Comparison of normal strain from FE analysis and experiments of full-scale specimen of thin ship deck structure.

3 Influence of weld geometry on the fatigue strength analysis

3.1 Fatigue strength of laser stake-welds

In addition to proper structural analysis, the local fatigue strength assessment is also very important for thin plates. Fatigue strength is influenced by the joint type and weld geometry. For laser-stake welded joints the weld width defines structural stress at the weld. In addition, weld eccentricity can cause secondary bending. Using local approach, such as J-integral approach, different weld geometries can be properly modelled [20], [21], [22]. Figure 6 shows measured fatigue strength values for a stake weld in terms of applied load and range of J-integral. Using J-integral approach the scatter of test results is reduced and fatigue strength at 2 million load cycles is similar and independent of thickness and loading effects as shown in Figure 6b. In addition, the experiments show that the slope of the fatigue resistance curve is similar for both thin and thick plate. The slope is almost the same for applied load and J-integral approaches. For stake weld under bending, the fatigue strength at 2 million load cycles is similar to that of axial loading, but the slope is different; bending increases the slope value as shown in Figure 6b. The analysis shows that this slope variation is related to the local stress gradient

[23]. This physical property is highly affected by plate thickness and joint rotation stiffness. These findings and conclusions are the same for several other local approaches such as effective notch stress approach and strain energy density SED approach [22]. However, the energy based approaches such as J-integral show smaller scatter band [20], [21].

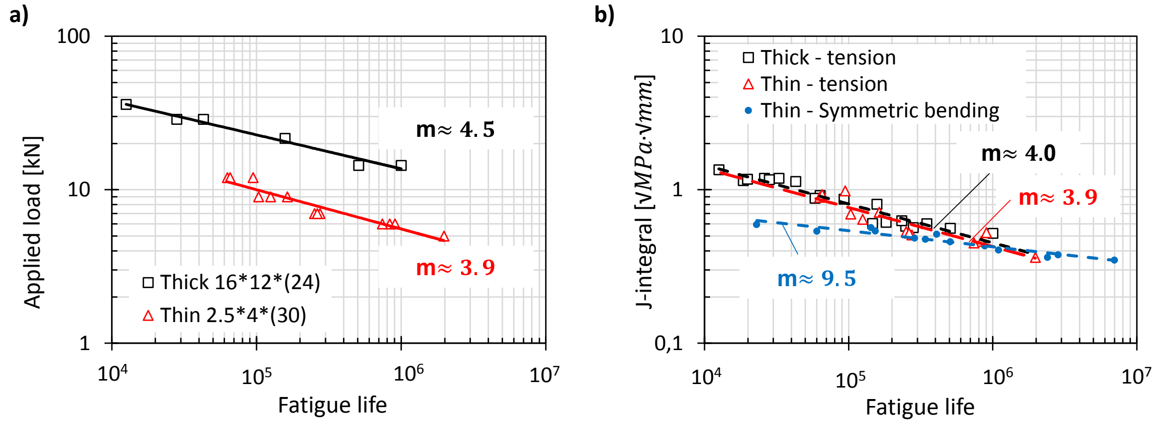


Figure 6: Fatigue strength comparison for skate-welded joint: F-N curve for thick and thin plate under axial loading (left), J-integral based fatigue resistance curve i.e. ΔJ-N curve for tension and bending loading (right).

3.2 Fatigue strength of laser-hybrid welded butt joints

In thin plate structures the butt joint becomes fatigue critical due to initial distortions of the plate field [31]. In addition, laser-hybrid welding results in significantly different weld geometry compared to conventional welding processes, such as sub-merged arc welding [32], [33], [34]. The small weld bead and smooth weld toe transition geometry observed for laser-hybrid welded butt joints are beneficial for fatigue strength. However, for thin plates, the narrow laser-produced root side weld may result in a sharp weld notch geometry, especially when plate edges have axial misalignment [35], [8]; see Figure 7a. In addition, possible undercuts can be deep in relation to the plate thickness. Such geometrical features cause high stress gradients at the notch and reduce the fatigue strength significantly [33], [35], [8]. The consideration of these geometrical defects is a challenge for welded thin plates. As studied in Ref [35] the stress gradient effect can be taken into account in the fatigue strength assessment by utilizing local approaches such as the effective notch stress approach; see Figure 7b. However, due to small weld dimensions, the peak stress is limited to a small material volume close to surface. Thus, the traditional effective notch stress approach relying on a stress averaging length of ρ*=0.4 mm almost completely neglects the influence of the stress gradient. The accurate consideration of the stress gradient requires a significantly smaller stress averaging length in the range of ρ*=0.05…0.10 mm; see Figure 7c. Such small stress averaging length was also proposed for structural steel (σ_y≈400-550 MPa) by Neuber in the original study for effective notch stress concept [36].

In order to understand the combined effect of structural behaviour and fatigue strength of a welded joint, the fatigue behaviour of a 4-mm thick laser-hybrid welded structure was also studied using small- and full-scale specimens. The experiments included accurate optical geometry measurements of the specimens and constant amplitude fatigue testing under axial loading [31]. Figure 8 shows the fatigue test results in terms of structural hot spot stress. The results revealed that when initial distortion shape and geometrical nonlinearity are properly considered, the small- and full-scale specimens have equal fatigue strength with small scatter and the same S-N curve slope close to m=5. In addition, the results clearly show that the measured fatigue strength is considerably higher for good quality welds than the current structural stress design curve FAT100 [18]. The measured mean fatigue strength at 2 million load cycles is about 240 MPa for both full- and small-scale specimens. These experiments are reported in more detailed in Ref [31].

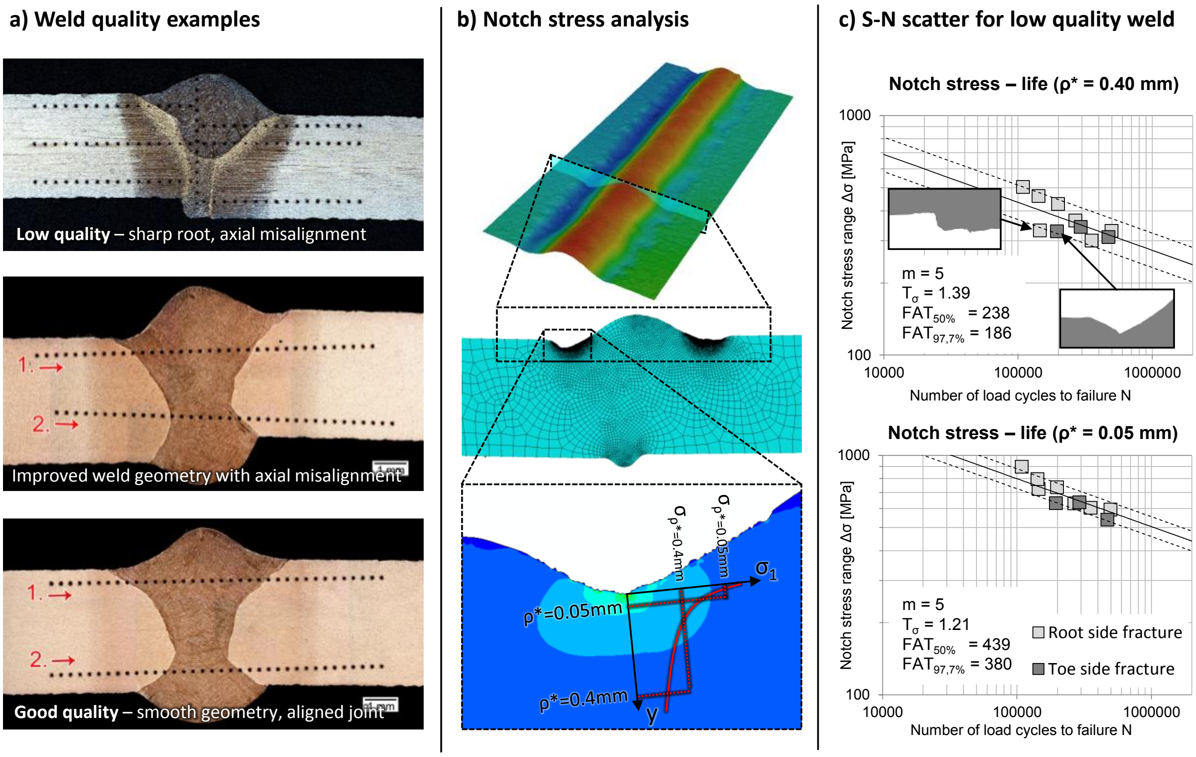


Figure 7: Weld notch effect on fatigue strength of laser-hybrid welded joint in thin plate.

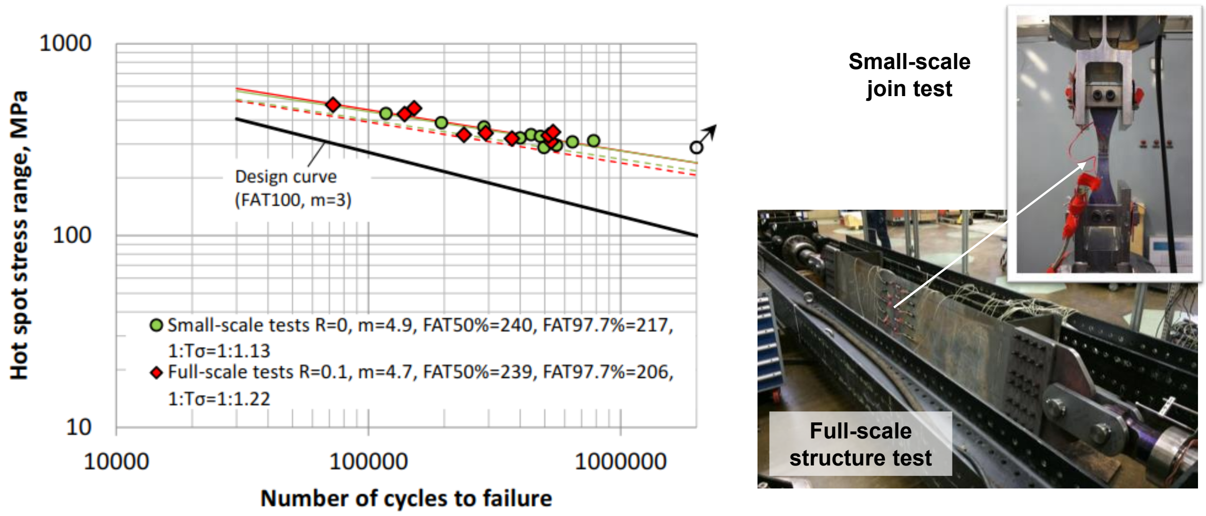


Figure 8: Fatigue strength of a laser-hybrid welded butt joint in thin plate structure. The results correspond to small-scale joint tests and full-scale structure tests.

4 Influence of weld shape and thickness on fatigue resistance

4.1 Strain-based crack growth simulations

The influence of weld notch shape on macro crack initiation time and fatigue life is studied with the recently developed strain-based crack growth approach [37], [38], [39]. In this approach the fatigue crack initiation and growth are modelled as a repeated crack initiation processes within a volume related to the material microstructure as shown in Figure 9. The volume is called the damage zone, where the micro cracks nucleate and coalesce, and finally cause macro crack growth. In the first crack growth step (n=1), the initial geometry is described by the weld notch dimensions, without an artificial initial crack to include the short crack growth period. After the failure of the initial damage zone, the crack is propagated with similar steps until the final fracture is reached. The size of the damage zone, i.e. the material characteristic length, is defined from grain size statistics [38], [40], [41], assuming that the damage process follows the weakest link scenario. According to the Hall-Petch relationship [42], [43] low strength is related to large grain size and thus, the material characteristic length is considered to correlate with the grain size at a probability level of 99% [38], [39], [40]. Based on the fatigue-effective stress and strain within the damage zone, the fatigue damage parameter P_{SWT} [44] and the corresponding number of load cycles N_{in} for the growth step n is calculated. The load cycles N_{in} are obtained using the Coffin-Manson formula [45], [46] and the hardness-based estimation of fatigue strength coefficients [47]. The total fatigue life N_f is the sum of the load cycles covering all the growth steps. Based on the number of load cycles N_{in} at the growth step n, the crack growth rate CGR can be calculated at a certain crack length from:

$$CGR_n = \frac{N_{in}}{a_0} \; . \qquad (1)$$

The crack growth rate CGR is always related to a certain crack length a, and thus it enables a comparison between the present results and the fracture mechanical approach using stress intensity factors K_I.

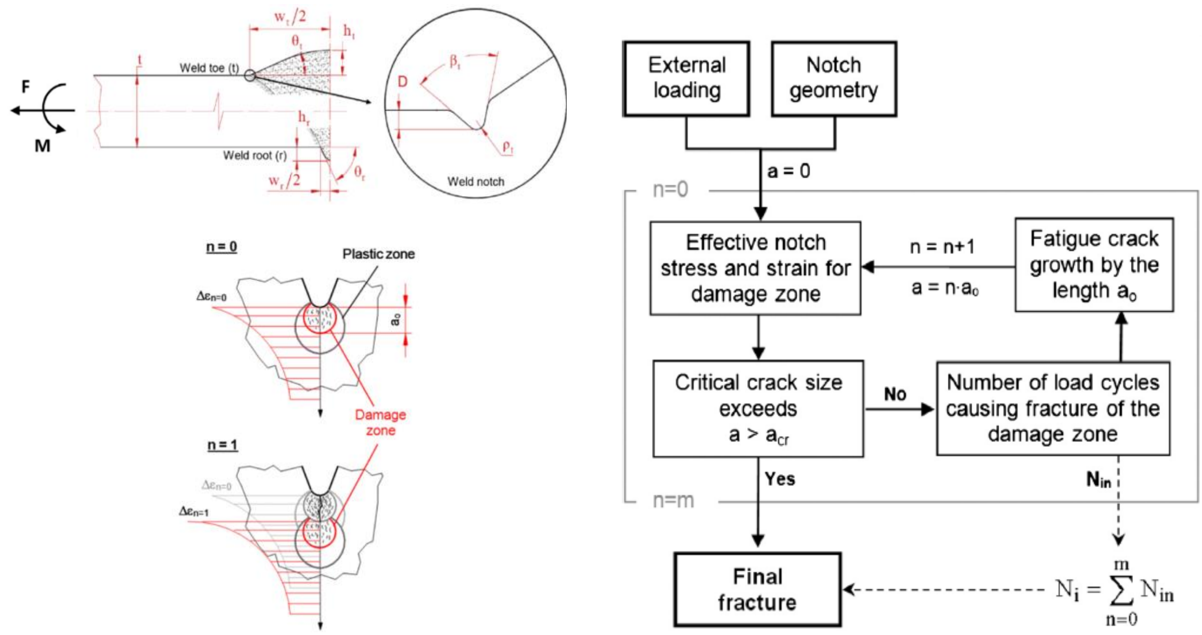
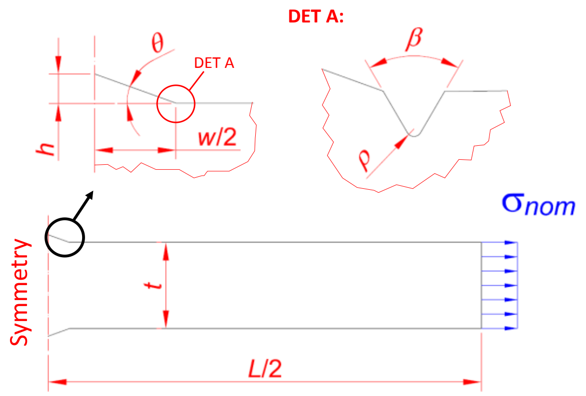


Figure 9: Flow chart of the strain-based approach to fatigue crack growth modelling.

The numerical analysis consider three different weld shapes: a high-performance weld (Case 1), a high-performance weld with a moderate weld bead (Case 2), and the current standard weld with undercut depth of 0.1 mm (Case 3); see Figure 10. The plate thickness is 3 mm. For comparison, the plate thickness of 12 mm was also studied. For 12 mm thickness, the weld shape is kept the same, but the weld size is scaled according to the thickness ratio. The three weld shape cases were defined based on the weld geometry measurements for laser and laser-hybrid welds [37]. The non-linear material behaviour was described using the isotropic hardening rule, von Mises yield criterion, and separate stress-strain curves for monotonic and cyclic loading. A fatigue crack is assumed to grow in the direction perpendicular to the maximum principal stress. Since the direction of the maximum principal stress can vary according to the weld geometry, the crack growth direction is calculated for each growth step n.



Dimensions	Case 1	Case 2	Case 3
Plate thickness *t* [mm]	3	3	3
Height *h* [mm]	0.07	0.27	1.3
Width *w* [mm]	1.5	1.5	1.5
Flank angle θ [degree]	5	20	60
Undercut depth *d* [mm]	0	0	0.1
Notch angle β [degree]	-	-	60
Notch tip radius ρ [mm]	-	-	0.02

Figure 10: Weld geometry cases considered in the analysis.

4.2 Macro crack initiation and slope of fatigue resistance curve

Fatigue life estimations for the total fatigue life are compared in Figure 11. The estimated curves are compared to the structural stress approach design curve FAT100 [18] and the fatigue test data for high quality welds shown in Chapter 3.2 [31]. The estimated S-N curve for the weld with a 0.1 mm deep, sharp undercut (Case 3) is similar to the structural stress design curve with slope value m=3. However, for smoother weld geometries (Case 1 and 2) the estimated S-N curves are significantly higher and have a larger slope value, being more similar to the test data. The differences in slope are related to the macro crack initiation period.

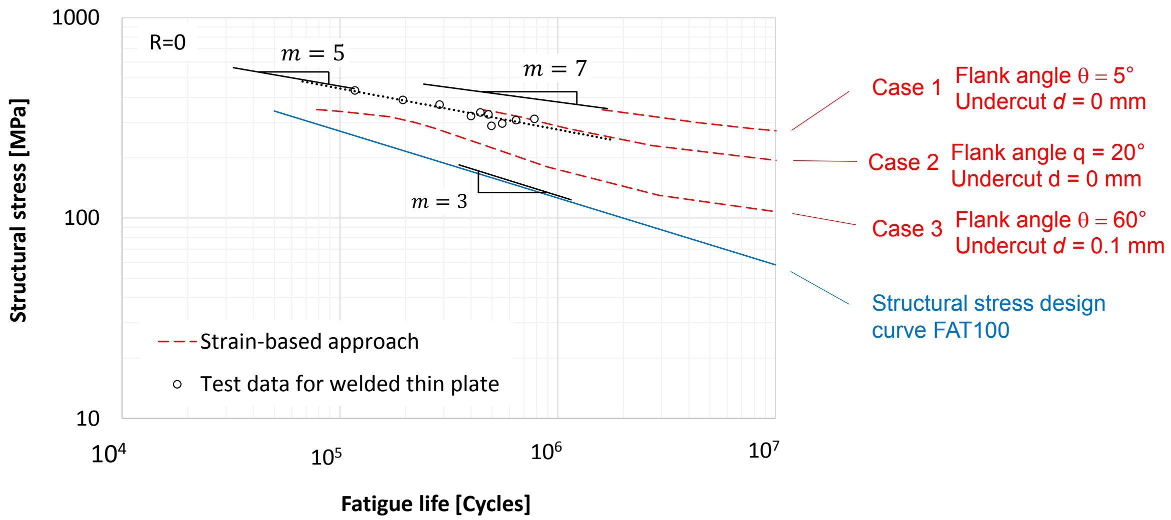


Figure 11: Fatigue strength prediction for different weld notch qualities: Case 1) a smooth weld, Case 2) a normal weld without undercut, Case 3) a weld with 0.1 mm undercut.

In order to understand the influence of macro crack initiation on fatigue strength, the crack growth rate and fatigue life accumulation is studied further. Figure 12a shows the portion of fatigue cycles accumulated in different crack length ranges. The portion of crack growth life of the total fatigue life N_f is calculated for the selected crack length ranges, e.g. 0-0.1mm and 0.1mm-0.2mm. The results show that in Case 1 (a smooth weld) and Case 2 (normal weld without undercut) the most of the fatigue life is spent in the crack length range 0-0.1mm. This is very similar for both thin (t=3mm) and thick (t=12mm) plates. In Case 3 (weld with 0.1 mm undercut), the proportions the of total fatigue life N_f is more constant between different crack length ranges illustrating the bigger importance of macro crack propagation, especially for thick plates. For thin plates with undercut the short crack period (a=0.1-0.2mm) still remains more important than other long crack periods. The reason for this difference in crack initiation and propagation is studied by plotting the fatigue crack growth rate CGR (Eq. 1) as a function of stress intensity factor ΔK_I; see Figure 12b. In this study, effective crack length ($a_{ef}=d+a+a_o$) is used to cover also initial stage with a crack length of 0 mm. As shown in Figure 12b, the crack growth rate curve is similar for all different cases, but the weld notch shape and plate thickness define the starting point of the CGR curve. For thick plate and weld with undercut (t=12mm, Case 3), the crack growth starts in the Paris regime (B) and continues as tearing related crack growth (C). The same undercut case in thin plate includes more of the short crack growth period (A) and thus the slope of CGR curve also changes. Obviously, for smooth weld geometries (Case 1 and 2), the short crack growth period (A) dominates for both thick and thin plates. In these cases, the linear elastic fracture mechanics with a selected threshold value, e.g. ΔK_{th} = 5.4 MPa·√m or ΔK_{th} = 2 MPa·√m (IIW) [18], seems to make a significant simplification as it does not cover the majority of the short crack growth period; see Period (A) in Figure 12b.

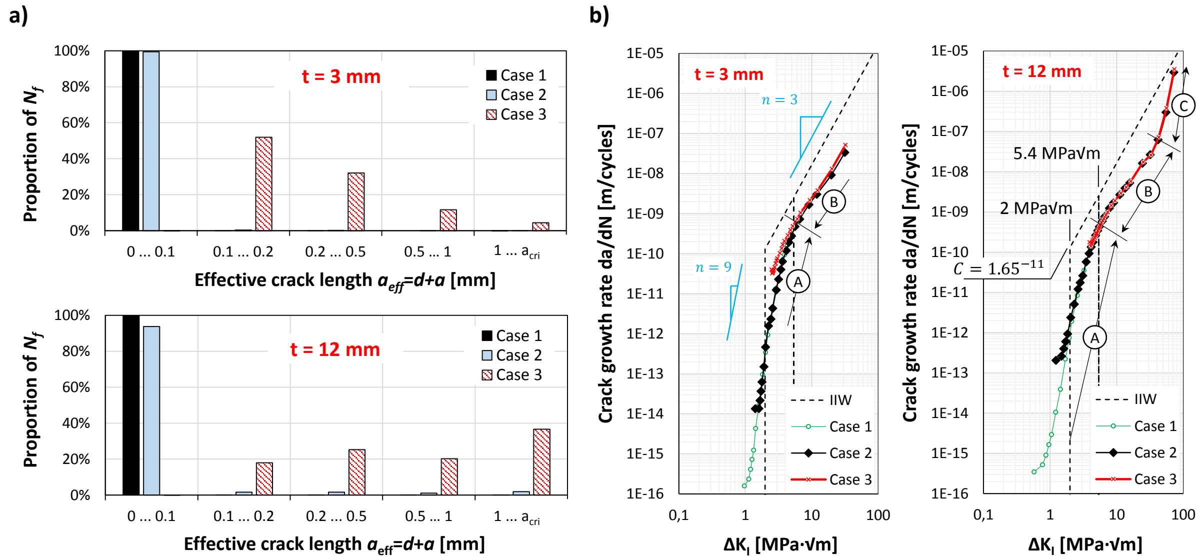


Figure 12: Fatigue crack growth comparison between thin plate (t = 3mm) and thick plate (t=12mm) for nominal stress range of 130 MPa: a) The crack growth time between different crack length, b) the crack growth rate. The figure b includes also the design values recommended by IIW [18].

5 Discussion

At present, fatigue strength assessment of large and complex welded structures is commonly made using structural stress approaches [18]. The structural analysis typically utilizes idealised geometry, which does not include initial deformations. Additional bending due to initial deformations is considered separately by multiplying the obtained stress with the stress magnification factor based on beam-theory. In addition, the common assumption is that the influence of geometrical non-linearity can be neglected. As shown in Chapter 2, this common approach is not suitable for thin plates in large structures since the geometrical non-linearity plays a significant role due to initial deformations and flexibility of the joints. Thus, proper consideration of scale transition from large structures to panel level and finally the welded joint using a multilevel analysis approach is especially important. Main factors affecting structural analysis depend on the structural topology. For a steel sandwich structure the web-plate spacing and thus slenderness ratio is low. Therefore, the influence of initial deformation is very small or insignificant. However, in this case the accurate modelling of bending stiffness for the narrow joint is crucial since the weld width is smaller than the nominal web plate thickness. This has a significant influence on global structural behaviour and the load carrying mechanism. This also affects the local deformation of a fatigue critical joint and the fatigue effective stress at the weld notch. In the case of a stiffened thin plate the bending stiffness of the joint is equal to plate itself, but the slenderness ratio is also significantly higher due to larger stiffener spacing. In this case, the welding induced distortions are significant and they have a non-linear effect on structural behaviour. These findings are in agreement with the previous studies [12] stating that the joint and structural flexibility has an influence on the structural behaviour and thus also on the fatigue resistance. At present the limited modelling accuracy for flexibility and geometrical non-linearity can partly explain the large scatter of fatigue strength for thin plates observed in the previous studies; see e.g. [12]. The other important reason for large scatter in fatigue strength is fatigue strength modelling without the proper consideration of weld shape effect; see Chapter 3. Fatigue strength of laser-stake welded joints and laser-hybrid welded butt joints are sensitive to local geometrical variation. If the actual geometry of the laser stake-weld is included, the fatigue strength can be predicted more accurately. The fatigue strength of laser-stake welds in terms of J-integral and SED [48], [49] is very similar to what is observed for arc welded thick plates [50], [51]. Similarly, in the case of butt joints in thin plates, geometry modelling of the weld shape should be accurate in order to consider the influence of the stress gradient. A small stress averaging length is required in the effective notch stress approach to accurately consider the influence of the stress gradient, as shown in Figure 7. These finding are in agreement with the previous results of Neuber [36]. The present paper shows that if the influence of weld shape, initial distortions, joints' flexibility and surrounding structure are properly considered, fatigue strength at 2-5 million load cycles i.e. at the endurance limit can be accurately modelled. Furthermore, the results indicate that the plate thickness, stiffness and structural flexibility have no influence on the slope value of fatigue resistance curve (see e.g. Figure 6) as assumed earlier based on the experimental results [12].

The measured slope values for laser-stake welds are approximately 4 or higher and they are independent of the plate thickness; see Figure 6. This is an unexpected result, as it could be assumed that crack propagation should dominate due to crack-like defects and thus the slope should be three; see e.g. [1]. The possible reason for this can be the fact that in macroscopic scale the notch radius of a stake weld is large in comparison to grain size. Typically, laser welds have a fine-grained microstructure [38]. Due to this, the laser stake-weld might include a significant short-crack growth period before the stress field ahead of the weld notch tip corresponds to that of a long crack. This hypothesis, which requires further analysis, is supported by the numerical simulation of butt joints; the stress and short crack growth period is highly affected by geometrical variation as shown in Chapter 4.2. In the case of high-quality welds, the slope of the fatigue resistance curve is increased as observed in earlier experimental investigations [33], [52], [53]. The numerical simulation presented in this paper explain the slope difference. During crack growth the notch stress and crack tip plasticity increase significantly after transitioning from short crack growth to macro crack growth and as a result the slope of CGR changes [34]. For thin plates without weld defects the development of the crack until the size of a macro crack (0.1 mm) dominates, resulting in a higher slope of the fatigue resistance curve compared to a weld with defect(s). This importance of short crack growth period indicates that new advanced approaches are required for thin plates and high-quality welds in order to model both crack initiation and propagation as shown in Table 1. This conclusion is in line with a state of the art review [54]. The authors state that the consideration of macro crack initiation time is the main challenge for the present fatigue strength approaches. The strain-based crack growth approach used in this study can be utilized for numerical simulation of SN curves for different welded joints and quality levels, but it is too time consuming for fatigue design purposes.

Table 1: Factors affecting fatigue strength assessment of thin plates in large structures

Fatigue strength assessment method	Factors affecting the fatigue behaviour Scale transition	Weld shape effect	Material effect
Structural stress approach	Geometrical non-linearity and initial distortions	Joint type*	no
Local stress-based approach	Initial distortions and joint flexibility	Joint type and weld geometry	no
Strain-based crack growth analysis	Initial distortions and joint flexibility	Joint type and weld geometry in microscale	Influence of short crack growth

*) Structural stress approach can consider difference of load and non-load carrying joints

6 Conclusions

This paper studied different factors affecting the fatigue strength assessment of thin plates in large structures. The study covered three parts of analysis: 1) the scale transition in structural analysis from large structures to the welded joint, 2) the influence of joint geometrical properties on fatigue strength modelling, and 3) the influence of material elastic-plastic behaviour and short crack propagation on total fatigue life. Based on the obtained results, the following conclusions can be drawn:

- The bending stiffness of stake welds has a significant effect on the structural behaviour of steel sandwich panels. Its consideration in structural analysis is important in order to estimate the local behaviour of fatigue critical joints. This affects the accuracy of fatigue strength estimation (e.g. at 2 million load cycles), but it does not have an influence on the slope of the fatigue resistance curve.
- In thin plate structures, the low bending stiffness of the plate itself results in a curved shape for the welded joints. The consideration of shape and amount of initial deformation is required for reliable structural stress analysis. In addition, geometrical non-linearity i.e. straightening of initial deformation as a function of load level is needed in order to increase the accuracy of fatigue strength estimation. However, this structural flexibility does not influence the slope of the fatigue resistance curve.
- In the case of stake welds with crack-like defects, fatigue strength can be properly estimated using local energy-based approaches. Despite of the crack-like defects, the slope of the fatigue resistance curve was surprisingly 4 or higher for both thick and thin plates.

- In the case of butt joints in thin plates, the geometrical shape of the weld notch has a significant influence on fatigue strength. The proper consideration of high stress gradients requires a significantly smaller stress averaging length than commonly used in fatigue assessment methods such as the effective notch stress approach. This can explain the large scatter of the test results, but not the slope of fatigue resistance curve.
- To model the slope of the fatigue resistance curve, the consideration of material elastic-plastic behaviour and short crack growth is needed. The strain-based crack growth simulations indicate that longer period of short crack growth is the reason for the higher slope value. The importance of short crack growth is dependent on the weld notch geometry and plate thickness.

The present study was focused on the fatigue behaviour of large thin-plated structures. The study included two different advanced structural solutions manufactured with laser welding technology. To extend the current knowledge, high strength steels with yield strength of 690 MPa and other joint types such as fillet welds should be considered in the future. In high quality thin plate structures, the influence of short crack growth on fatigue behaviour should be further investigated. This is also needed to explain the unexpected slope values for stake welds and to develop a solid fatigue design basis. Fatigue design approaches should be able to consider both initiation and crack propagation periods. In addition, new simplified design approaches are required for structural stress analysis of thin-plate structures to consider the influence of initial deformation already in the design phase.

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