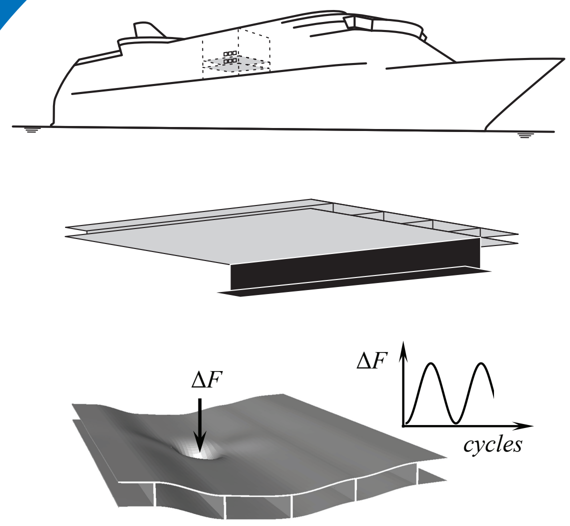
Department of Applied Mechanics

Fatigue strength assessment of laser stake welds in web-core steel sandwich panels

Darko Frank



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Fatigue strength assessment of laser stake welds in web-core steel sandwich panels

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Aalto University
School of Engineering
Department of Applied Mechanics
Marine Technology

Supervising professor
Prof. Jani Romanoff

Thesis advisor
Prof. Heikki Remes

Preliminary examiners
Prof. Feargal Brennan, Cranfield Uni., UK
Prof. Jonas W. Ringsberg, Chalmers Uni. of Tech., Sweden

Opponent
Prof. Emer. Preben T. Pedersen, Tech. Uni. of Denmark

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Abstract

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Abstract

Industries nowadays demand lightweight and space-saving solutions such as sandwich panels that offer high strength-to-weight ratios. In general, sandwich panels consist of homogeneous core material that carries a shear force and face plates that carry a bending moment. The web-core sandwich panel has an inhomogeneous core as it consists of unidirectional web plates that are periodically distributed and connected to the face plates by laser stake-welded T-joints. The joint has two crack-like notches on each side of the weld. When the panel bends, the out-of-plane shear deformation opposite to the web direction causes local bending of the joined plates in the vicinity of the weld. This leads to tension at one notch tip and compression at the other. The fatigue crack initiates at the tensile tip and propagates through the weld under cyclic loading until the plates are separated and the sandwich effect is lost.

The thesis investigates the fatigue resistance of laser stake-welded T-joints in the web-core panels under out-of-plane loading, i.e. lateral loading. The bending of the joined plates in panels can cause contact between the surfaces of the compressive notch. It is determined that the contact causes an increase of the stiffness of the T-joint in the case of significant face plate deflection since it results in a large rotation of the joint. The increase in the stiffness of the joint needs to be considered in the assessment of the global response of the panel, which defines the displacements that are imposed as the loads in the local strength assessment of the joint. If panel contains a low-stiffness filling material inside the voids, the contribution of the material increases the shear stiffness of the panel and reduces the deformation of the joint. Thus, under the same external loading, the filling prolongs the fatigue life of the panel.

The evaluation of the J-integral at the tips of the notches, modelled using statistically mean notch depth values, gave agreement on the fatigue strengths between all the series that were investigated at five million load cycles. The agreement is obtained regardless of plate thicknesses, the type of loading or whether the filling material is present. Good agreement with other steel joints is also demonstrated at five million load cycles. However, the slope of the fatigue resistance curve varies, depending mainly on the load type, i.e. tension or bending. The research determined that the slope depends on the distribution of the maximum principal stress in the vicinity of the notch tip. When the stress is characterized by a dimensionless gradient, evaluated in the stress direction, the slope-gradient relation appears linear. The gradient shows sensitivity towards the loading type and the plate thickness effect.

Keywords Fatigue Strength, Stress Analysis, Laser Weld, Stake Weld, Sandwich Panel, Web-Core

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Zagreb, 9 February, 2014.
Darko Frank

Contents

List of Abbreviations and Symbols

Alphabetic symbols

a	notch depth
b_f	breadth of specimen
C	material constant used in S-N curve
E	Young's modulus
e_{weld}	weld offset [mm]
$\bar{e}_{weld}$	average weld offset [mm]
e_1, e_2	strain energy parameters for modes I and II
F	force
h_g	height of root gap, i.e. distance between joint plates
h_w	web plate height
J	J-integral
K_i	stress intensity factor for fracture mode i
k_φ	rotational stiffness
l	length of specimen
M	moment
m	slope of the fatigue resistance curve
n	exponent of a stress function
N_f	number of cycles to failure
P_s	probability of survival
Q	shear force
r_{ref}	reference notch radius
s	spacing of web plates

T	scatter index
t_f	face plate thickness
t_w	web plate thickness
t_{weld}	weld thickness
$\bar{t}_{weld}$	average weld thickness
$\bar{W}$	average elastic strain energy density

Greek symbols

2α	notch opening angle
Γ	contour path surrounding crack tip
ΔJ	J-integral range
ΔJ^i	contribution of fracture mode i to J-integral range
ΔK_i	range of stress intensity factor for fracture mode i
ΔF	force range
$\Delta\bar{W}$	range of elastic strain energy density
θ_{MAX}	angle of the maximum principal stress
θ_{MTS}	initial crack propagation angle according to Maximum Tangential Stress criterion
θ_τ	angle of the plane where the maximum shear occurs
λ_1, λ_2	Williams' solution eigenvalues for fracture modes I and II
v	Poisson's ratio
ρ_f	fictitious notch radius
ρ	actual notch radius
ρ^*	substitute microstructural length
σ	normal stress
σ_{yield}	yield strength of material
σ_{UTS}	ultimate tensile strength of material
τ_{ij}	shear stress
χ	relative stress gradient
χ_{ij}^{θ}	dimensionless stress gradient

List of subscripts

1, 2,…, N	index
x, y, z	*x*-, *y*- and *z*-axes
xy, xz, yz	*xy*, *xz* and *yz* planes
I, II, III	fracture modes *I, II, III*

Abbreviations

2D	Two-dimensional
3D	Three-dimensional
FE	Finite Element
FEM	Finite Element Method
IIW	International Institute of Welding
NSIF	Notch Stress Intensity Factor
SED	Strain Energy Density
SIF	Stress Intensity Factor

List of Publications and Author's Contribution

This thesis consists of an introductory summary and the following four publications, which are referred to in the main text by their numerals prefixed by the letter "P".

1. Frank, Darko; Remes, Heikki; Romanoff, Jani; 2011. Fatigue assessment of laser stake-welded T-joints. International Journal of Fatigue, Vol. 33, pages 102-114. ISSN 0142-1123. DOI 10.1016/j.ijfatigue.2010.07.002. Corrigendum published in volume 33, issue 11, page 1504. DOI 10.1016/j.ijfatigue.2011.07.001.

The author measured the geometry of the specimens, performed the calculations, devised the conclusions and wrote the manuscript. Remes assisted with data preparation for the statistical analysis and provided valuable comments on the manuscript. Romanoff contributed to the manuscript with valuable comments.

2. Frank, Darko; Remes, Heikki; Romanoff, Jani. 2013. *J*-integral-based approach to fatigue assessment of laser stake-welded T-joints. International Journal of Fatigue, Vol. 47, pages 340-350. ISSN 0142-1123. DOI 10.1016/j.ijfatigue.2012.09.019.

The author measured the geometry of the specimens, carried out the fatigue tests, performed the calculations, derived the conclusions and wrote the manuscript. Remes assisted with the statistical analysis and provided valuable comments on the manuscript. Romanoff contributed to the manuscript with valuable comments.

3. Frank, Darko; Romanoff, Jani; Remes, Heikki. 2013. Fatigue strength assessment of laser stake-welded web-core steel sandwich panels. Fatigue & Fracture of Engineering Materials & Structures, Vol. 36, pages 724-737. ISSN 1460-2695. DOI 10.1111/ffe.12038.

The author performed the calculations, devised the conclusions and wrote the manuscript. Romanoff conducted the experiments and provided valuable comments on the manuscript. Remes contributed to the manuscript with valuable comments.

4. Frank Darko; Remes, Heikki; Romanoff, Jani. 2013. On the slope of the fatigue resistance curve for laser stake-welded T-joints. Fatigue & Fracture of Engineering Materials & Structures, Vol. 36, pages 1336-1351. ISSN 1460-2695. DOI 10.1111/ffe.12105.

The author formulated the hypothesis of a dimensionless gradient, performed the analysis, drew the conclusions and wrote the manuscript. Remes contributed to the manuscript with valuable comments. Romanoff conducted the experiments and provided valuable comments on the manuscript.

General Features

The laser-welded web-core steel sandwich panel is a set of steel plates assembled by utilizing a stake-welded T-joint. The joint connects a vertical core plate called the web plate to the horizontal face plates that are located far from the mid-plane of the cross-section of the panel. The so-called *sandwich effect* is made possible by the coupled response of the connected web and face plates. The breadthwise penetration of the laser beam determines the thickness of the weld, which is less than half of the thickness of the web plate. Consequently, the joint has two crack-like notches on each side of the weld. This makes the joint considerably less stiff than an equivalent fillet-welded T-joint. In the bending response of the panel the stiffness of the joint needs to be accurately accounted for. The stiffness is usually assumed to be constant with respect to the increase in the load at small load levels. The web plates are positioned at distances 10-100 times larger than the thickness of the plate. This leaves voids in the panel, which make the core inhomogeneous. Usually, when a sandwich panel bends its homogeneous core carries the shear force, whereas the face plates carry the global bending moment. In web-core sandwich panels, besides the bending moment, the face plates carry a significant portion of the shear force in the plane orthogonal to the web plate. In empty panels this portion of the shear force is carried solely by the face plates. This causes the secondary bending of the web and face plates, which manifests itself in tension stress at one notch tip and compression at the other. The fatigue crack initiates as a consequence of the dominant tension stress range at the tip of the critically loaded panel joint. After the initiation, the crack propagates through the weld until the face and web plates are separated by the fracture of the weld material. The separation is considered as a failure of the panel since it causes a local loss of the *sandwich effect*.

Original Features

This thesis utilizes local approaches in the assessment of over 70 experiments in which stake-welded T-joints deform in the plane orthogonal to the weld line. Joints with face plate thicknesses in the range from 2.5 to 16 mm are considered. The aim of the thesis is to acquire knowledge about the fatigue resistance of the joint that can be utilized for panels subjected to lateral loads. This thesis presents the following original features:

1. Systematic comparison of local stress and energy-based approaches for thick joints under tensile loading is conducted to determine their applicability to this type of joint. It is shown that the *J*-integral-based approach is suitable [P1];

2. Under tensile loading of the web plate, it is shown that the stress state at the notch tips depends on the thickness of the face plate. Consequently, in the case of thin face plates the shear and notch-parallel normal stresses become equally important as the normal stress component in the load direction [P2];

3. It is demonstrated that when the fatigue load is positioned on top of the face plate between two web plates, contact occurs in a high-cycle regime. This causes an increase of the stiffness of the joint. The increase needs to be considered in the assessment of the response of the sandwich panel [P4]. However, when the load is positioned on top of the web plate, the constant stiffness of the joint is sufficient for the assessment in a high-cycle fatigue regime [P3];

4. It is shown that adding the filling material into the panel voids increases the shear stiffness of the panel and reduces the bending moment in the critical joint, which manifests itself in prolonged fatigue life [P3];

5. Assuming that the weld has statistically mean geometry, and applying the *J*-integral approach, it is demonstrated that the fatigue strength of the joint at five million load cycles is similar, regardless of the loading condition imposed and the plate thicknesses. The fatigue strength at five million cycles also agrees with that of other steel joints [P1]-[P4];

6. The dimensionless stress gradient is formulated to characterize the stress distribution in close proximity to a notch tip. It is demonstrated for a high-cycle regime that the slope value of the fatigue resistance curve is related to the dimensionless gradient of the maximum principal stress evaluated in the stress direction [P4].

1. Introduction

1.1 Motivation and Objective

Industries such as civil engineering and, especially, transport are seeking lightweight and space-saving structural solutions such as sandwich panels. These panels consist of face plates separated by a low-density core. This permits high strength- and stiffness-to-weight ratios. In general, the core carries the shear force, while the face plates carry the bending moment. The face plates and core can be made of various materials, such as metals, polymers and composites connected to one another by adhesives, mechanical joints, friction or welding. The core can be a single part made of homogeneous material or it can consist of various unidirectional shapes that are periodically distributed across the length or breadth of a panel. Since steel and welding are commonly used in large ships, this thesis focuses on laser-welded steel sandwich panels with a unidirectional core; see Figure 1.

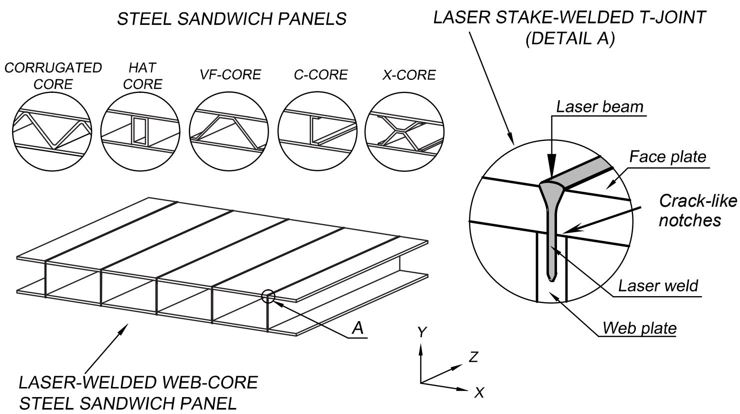

Figure 1. Sandwich panels and the definition of a laser stake-welded T-joint.

The inhomogeneous core is a typical feature of sandwich panels composed of steel only. Steel sandwich panels are closed structures welded from inside or outside utilizing a laser weld [1-4]. In thin-walled sandwich panels, the material is positioned far from the neutral axis of the cross-section what makes them bending-efficient. Consequently their strength-to-weight ratio is higher than that of conventional one-sided stiffened panel structures where the material is close to the neutral axis. Sandwich panels also occupy less space because of their smaller stiffener heights. Besides these benefits, the usage of these panels can also reduce production time and costs [4-7]. In sandwich panels, the uniaxial and periodic core allows the material to be positioned in the direction of the primary loads [8-11]. Such a core also allows the integration of low-strength insulation material and different wiring and piping systems into the panels, enabling additional space savings [4, 12]. In addition, many research efforts have confirmed that sandwich panels have good impact and blast resistance properties [2, 13-18]. Filling the voids improves the shear stiffness of the panel [19], the critical buckling stress [20-22] and the collapse load [23]. It has also been shown that if the panels are filled with low-density in situ PUR foam, the secondary bending stresses in the connected plates and in the welds decrease significantly [24] and this allows further weight savings. As a result of the advantages of steel sandwich panels, they were already considered for the superstructures of ships some time ago [25-28]; see Figure 2.

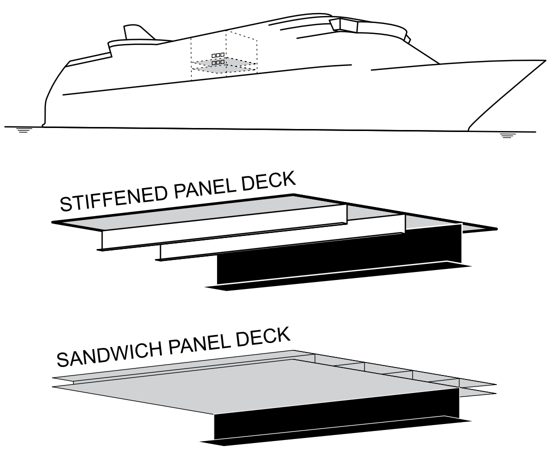

Figure 2. View of stiffened and sandwich panel decks.

The web-core sandwich panel has perhaps the simplest core topology of all steel sandwich panels. This panel type is unique because it is assembled utilizing a laser stake-welded T-joint instead of a lap joint as in the case of the other panel types shown in Figure 1. The design and production aspects of web-core panels in the shipbuilding industry have been explored by many authors [5, 26, 32-35] and in civil engineering [36-38]. Kujala et al. [25] and Metschkow [26] consider the fatigue life when panels are used for primary structural members such as decks and bulkheads, which need to withstand the normal and shear stresses caused by the bending of the hull girder. Although the estimated fatigue life of the panels within these studies exceeds the service life of the ship, the analysis is limited only to the primary response of the hull girder, meaning the membrane forces in the plane of the sandwich panel as a result of wave loads. However, sandwich panels also need to withstand lateral loads, i.e. the secondary and tertiary out-of-plane loads such as uniform deck pressure and local patch loads. The objective of this thesis is to identify and validate a method for fatigue strength assessment of web-core panels under lateral loads. The intention is to provide a basic approach that can later be extended for different load ratios and to account for combined in- and out-of-plane loading.

1.2 State of the Art

1.2.1 Experimental Investigations of Panels and Joints

Fatigue tests of laser stake-welded T-joints were reported by Socha et al. [39] and some years later by Boronski and Szala [40, 41]. Fatigue experiments conducted on web-core sandwich panels under lateral fatigue loads were performed by the Sandwich Consortium [42] and later by Kozak [43, 44]. Kozak's experiments were performed on web-core panels with face plate thicknesses of 2.5 and 3 mm, which is the minimum allowable for marine applications [45]. The common observation is that the panels fail by a fatigue crack propagating through the weld. According to Kozak [44], the failure in the weld is caused by local bending of the plates in the vicinity of the weld, as shown in Figure 3. As a result, one notch is in a tensile stress state, whereas the other is in a compressive state. This failure mode also occurs if the panel voids contain in situ low-strength PUR foam [42].

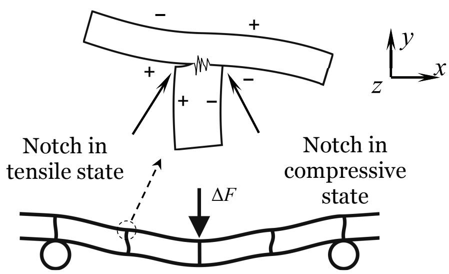

Figure 3. Weld failure resulting from the bending of the joint. Tension and compression in the plates are distinguished by + and – signs, respectively.

Kozak [44] reported a large scatter of results if the nominal stress approach to fatigue assessment is applied to stake welds. Consequently, he emphasized that the nominal stress approach is not suitable for the bending case as there are too many unknown factors for a large scatter. In addition, the full field strain measurements and fatigue experiments on laser stake welds conducted by Boronski and Szala [40, 41] indicated that the contact between the free surfaces of the compressive notch might have an influence on the deformation of the joint and fatigue strength. The Sandwich

Consortium [42] additionally reported that the fatigue resistance curve, based on the force range, varies under different loading conditions and with the use of different filling materials. The slope value is found to be larger than that which is commonly observed for other steel joints, but possible reasons for the slope difference were not given. Thus, it remains unclear what is the fatigue strength of a laser stake-welded T-joint and a sandwich panel having many joints. However, it was learned that the measured strains at the critical joint do not change until final stage of the total fatigue life in high-cycle regime. The change is noticed in a few percent of the total fatigue life prior to the weld failure. This indicates that the investigations based on the initial, i.e. the intact geometry could be sufficient to describe the total fatigue life.

The studies [39-44] did not consider scatter of results caused by residual stresses because the scatter for panels was very small [42]. It is known for laser welds that the tension residual stress on the interface between heat-affected and fusion zones can reach up to 600 MPa, i.e. close to the yield limit [46]. However, it can be assumed that residual stresses do not affect fatigue properties of laser welds with sharp crack-like notches [47]. The reason is because even under a low-level loading a small-scale plasticity develops at sharp notch tips and the plastic strain relieves the residual stresses in a small number of cycles [47].

1.2.2 Mechanics of Web-Core Sandwich Panels

Fatigue strength assessment is challenged by the mechanical behaviour of the sandwich panel, the T-joint, and their interaction. In web-core sandwich panels the face plates carry the shear force in the plane orthogonal to the web direction. This consequently causes the secondary bending of the face and web plates [48], which in turn causes high local stress gradients. This causes difficulties with the definition of the nominal stress. Depending on the load distribution over the upper face plate, the laser stake-welded joint can experience a mixture of normal and shear stresses simultaneously [49]. Romanoff et al. [50] demonstrated that the panel bending response depends on the rotational stiffness of the joint; see Figure 3. The stiffness of a laser stake-welded T-joint is considerably reduced in comparison to the equivalent fillet-welded T-joint since the weld thickness of the stake-welded T-joint is less than the thickness of the plates it connects. It is known that the stiffness of the joint increases as a result of the contact between the free surfaces of the compressive notch and that this can significantly affect the stresses in the weld [50]. Therefore, the fatigue assessment of the joint in web-core panels is challenging since the response of the panel depends on the stiffness of the joint, which is influenced by the contact effect. Moreover, the joint within the panel is exposed to the mixture of stresses that are possibly influenced by the contact effect. Achieving an accurate panel bending response is a prerequisite for the local assessment of the joint. In practical applications lateral loads are most commonly approximated by uniform pressure across the whole surface of the panel or by patch loading concentrated over a small area of the panel; see Figure 4. Romanoff et al. [49, 51] performed detailed stress investigations in the plates of web-core panels subjected to uniform pressure and patch loading. These investigations showed that the deformation of the critical joint is mainly two-dimensional (2D) in the plane orthogonal to the weld line; see Figure 4. Considering these facts, it seems more convenient to use a local approach to the assessment of the fatigue strength rather than the nominal stress approach, since the combined influence of contact, stiffness and mixed stresses can be considered accurately in the local analysis.

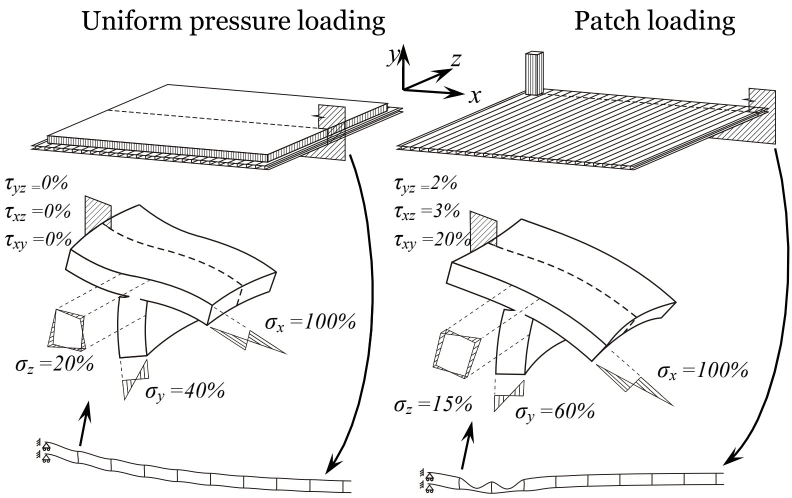

Figure 4. Stresses in web-core sandwich panels with dimensions 3 x 3 m; core height of 40 mm, web plate spacing 120 mm; web plate thickness 4 mm; face plate thickness 2.5mm; uniform pressure of 1 ton over the whole surface or 500 kg over the patch size 200 x 200 mm.

1.2.3 Local Approaches to Fatigue Assessment

The transport industry requires panels that can withstand a large number of load cycles. In general, the requirement exceeds 100,000 cycles and thus the high-cycle fatigue regime is of primary interest. In this regime material yielding is confined to the small area surrounding the notch tip and this condition is referred to as the small-scale yielding. The average grain size in a heat-affected zone of laser welds is around 5 μm [52], whereas it seems to be about 1 μm in a fusion zone [53]. In addition to fine granular structure, Boronski [54] and Jutila [55] showed that laser welds have high yield strength of about 800 MPa, ultimate strength of about 1100 MPa and a very small plastic elongation. Considering these facts, the linear-elastic material assumption in the fatigue strength assessment seems justified. Several local concepts are recommended for the assessment of welded joints under a small-scale yielding condition. These approaches can be stress- or energy-based. The most commonly used is the notch stress concept with a reference radius of 1 mm [56]. This approach is based on the averaging of stress using a fictitiously enlarged notch tip radius. According to the micro-support theory of Neuber [57], the actual notch tip radius is enlarged by the product of the stress multiaxiality factor and the substitute micro-structural length. Radaj used a multiaxiality factor of 2.5 for the plane strain conditions and a micro-structural length of 0.4 mm for low-strength cast steel in the welded zone. When the actual tip radius is assumed to be zero, the fictitious radius becomes equal to 1 mm. The approach is utilized in Finite Element (FE) analysis, where the material is removed from the model within the radial distance of 1 mm from the notch tip, i.e. around the so-called reference radius. According to the International Institute of Welding (IIW), the approach is suitable for joints with plate thicknesses of 5 mm and above [58] because the removal of the material might have a weakening effect on thinner plates [56]. This is important for laser stake-welded T-joints since even in thick-plate joints the weld thickness is less than 5 mm. Therefore, the stiffness of the joint, which needs to be accurately accounted for, might be influenced by the removal of the material. The weakening effect can be avoided by using the notch stress approach with a small reference radius of 0.05 mm [58, 59]. This approach is used for thin-plate joints, for example by Zhang et al. [60], Eibl et al. [61] and Sonsino et al. [62, 63]. Regardless of the radius size, the aim of both notch stress concepts is to define the fatigue strength at two million cycles [56, 64]. However, these methods have not been applied thoroughly to laser stake-welded T-joints and thus investigation is needed.

In laser stake-welded T-joints there are two sharp crack-like notches [50]. Dealing with the sharp notches in welded joints, Lazzarin and Tovo [65] showed that the total fatigue life can be estimated on the basis of the initial unmodified geometry when the Notch Stress Intensity Factor (NSIF) is used as the fatigue strength parameter. Since then the approach has been successfully applied to different welded joints [66]. During the last decade another approach based on the intact notch geometry has been extensively researched. The fatigue strength parameter in this approach is the Strain Energy Density (SED) averaged over a control volume surrounding the notch tip [67]. The concept is based on the hypothesis that the energy concentration caused by the notch is constant, regardless of whether the material is linear-elastic or elastic-plastic. Under the small-scale yielding conditions the hypothesis results in constancy of the average strain energy density (SED) contained in a control volume, which in that case is larger than the yield zone [68]. The approach has been validated for different notch geometries, plate thicknesses and loading conditions [69, 70], but excluding the laser stake-welded T-joints.

Besides SED averaged over a control volume, fatigue strength can be expressed by the strain energy release rate. The strain energy release rate available for crack growth is the difference between the work of external forces and the change in the internal energy of the body [71]. The fundamentals of fracture mechanics state that the crack in a body extends by an increment when the available strain energy release rate becomes larger than the amount of energy required to create the increment [72]. Rice [73] devised the analytical expression, called the *J*-integral, that evaluates the strain energy release rate over a contour path surrounding the notch tip. The expression is useful for cracks and notches with parallel free surfaces, i.e. zero notch opening angles. This is the case in laser stake-welded T-joints. The *J*-integral can be evaluated for linear-elastic or elastic-plastic materials. Therefore, when the *J*-integral is evaluated under the linear-elastic hypothesis it is identical to Irwin's energy release rate. There are also alternate formulations of the *J*-integral proposed for sharp V-shaped notches where the angle of the notch opening is different from zero [74, 75]. Both of these studies suggest that the *J*-integral can be used as the fatigue strength parameter, but this needs to be validated in the case of laser stake-welded T-joints.

1.2.4 The Slope of the Fatigue Resistance Curve

The experimental results indicate that the slope of the fatigue resistance curve varies for stake welds in sandwich panels. In general, the fatigue resistance curve for welded joints is commonly defined in a high-cycle regime as:

$$N_f(\Delta S)^m = C, \quad (1)$$

where S represents a fatigue strength parameter that can be expressed by force, stress or energy. The parameter m is the slope of the fatigue resistance curve, C is the material constant and N_f represents the number of load cycles to final fracture. According to different recommendations, the slope value is 3 for thick steel joints ($t > 5$ mm) under the influence of tension stresses, whereas in the case of torsion loading the slope is 5 [64, 76]. Lazzarin and Berto [77] suggested an explanation of the different slopes by showing that the SED concentration in the highly stressed volume surrounding the notch tip is higher in the case of torsional than tensile loading. Sonsino et al. [62, 63] observed that the slope for thin plates ($t < 5$ mm) differs from that for the thick ones. It was found that in the case of a tensile load the slope changes from 3 to 5, while in the case of torsion it changes from 5 to 7. Berto and Lazzarin [70], dealing with multiaxial fatigue in combined tensile and torsional loading, reported that in- and out-of-phase loading cause different slopes. However, it is unknown how the combined stresses at the notch tip impact on the slope [70]. In the case of web-core sandwich panels, values for the slopes from 3 to over 10 are observed, depending on the face plate thickness, loading condition and type of filling material [42]. These facts indicate that various effects influence the slope of the sandwich panel, but these have not yet been systematically investigated.

1.3 Scope of the Work

The present work investigates the fatigue strength of laser stake-welds in web-core steel sandwich panels. The panel fails as a result of local separation of the face and web plates caused by the fracture of the stake weld. Consequently, the *sandwich effect* and load-carrying capacity are locally lost. The conservative assumption used here is that the joint that fails first defines the fatigue life of the panel. The research applies local approaches aiming to determine a total fatigue life of the joint based on the initial geometry and stiffness of the joint. In order to study different panel bending responses separately from plate thickness and contact effects, the investigation is divided into the four stages schematically presented in Figure 5.

[P1] Thick joints under tensile loading and without contact effect. (t > 5 mm)	[P2] Thin joints under tensile loading and without contact effect. (t < 5 mm)	[P3] Thin panels under symmetrical bending including possible contact effect. (t < 5 mm)	[P4] Thin panels loaded between the webs including contact effect. (t < 5 mm)

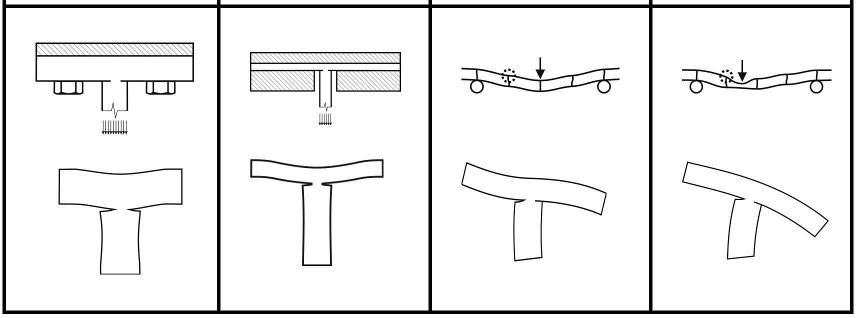

Figure 5. Loading and boundary conditions in different stages of the research.

The research stages are:

1. The first stage investigates the joints with plate thicknesses in a range in which local stress-based fatigue assessment approaches are known to be valid for other steel joints than laser stake welds. The loading condition is tensile and the contact effect is not present. [P1]

The investigation considers the joints with plate thicknesses above 5 mm subjected to tensile loading on the web plate. The test setup prevents contact between the plates. This loading condition is theoretical since it does not occur in the sandwich panel bending response. However, this stage enables the fatigue strength of laser stake-welded T-joints to be compared to that of other types of welded joints. It also enables different local approaches to be compared.

2. The second stage investigates welded joints with thin plates corresponding to the minimum requirements of classification societies. The loading condition is tensile so as not to cause contact. [P2]

The second stage is the intermediate step between thick joints under tensile loading and the bending of thin panel joints that involves contact. The investigation considers the joints with plate thicknesses below 5 mm, where the notch stress approach with a 1-mm reference radius is not applicable. The tensile loading allows the comparison of the fatigue strengths of thick and thin specimens without the influence of the contact.

3. The third stage investigates the joint under bending when the face plate deflection is moderate between the web plates. The possible influence of the contact is considered. The response of the joint corresponds to the critical joint in the panel under uniform pressure loading. [P3]

The investigation considers the panel specimens with plate thicknesses below 5 mm subjected to symmetrical bending as shown in Figure 5. The test setup allows the secondary bending of the plates and the realistic influence of the contact effect. The span between the supports is small, with the aim being to maximize the local shear-induced secondary bending of the T-joints; see Figure 5. Such a situation simulates the T-joint behaviour close to the edges of sandwich panels under a uniform pressure load. Two-stage FE analysis is employed. The panel bending response is assessed with a shell element model using rotational springs to simulate the stiffness of the joint. The displacements from the panel analysis are mapped to the local model, which computes the stress in the T-joint and around the notch tips. This stage also investigates the influence of the low-stiffness filling material on the panel response and its fatigue strength.

4. The final stage investigates the panel joints in the case of significant deflection of the face plate between the web plates. This loading condition corresponds to the critical joint of the sandwich structure subjected to patch loading. [P4]

The investigation considers experiments similar to those in the third stage, but with the load shifted to a position between two web plates; see Figure 5. The test setup causes the thin face plate to bend significantly between the webs, causing contact and a possible influence on the slope of the fatigue resistance curve.

1.4 Limitations

The ship classification society Det Norske Veritas [45] demands that the thickness of face plates should be at least 2.5 mm for steel sandwich panels. However, the laser stake welding of web-core sandwich panels is extremely difficult if the web plate has a thickness below 4 mm. Because of that, this study is limited to specimens with a face plate thickness above 2.5 mm and a web plate thickness above 4 mm. As indicated by previous experiments, for these thicknesses the secondary bending causes fatigue damage in the weld. The study is limited to the conditions where the longitudinal bending of the web plate is negligible. This limitation is valid at the locations where the curvature of the panel in the web plate direction is close to zero, i.e. at the mid-span of long panels. This makes 2D investigation possible using the plane strain assumption. Linear-elastic material is used since the investigation aims to explain the fatigue resistance in a high-cycle regime in which the plasticity of the material is confined to a small region surrounding the notch tip that has a negligible size with respect to the joint. Besides the panels made exclusively of steel, panels filled with low-density in situ PUR foam are also considered. This is because the insulation material in practical applications mostly has low-strength and low-stiffness properties similar to those of PUR foam. The fatigue tests in question are conducted under constant amplitude loading and with a load ratio $R = 0$. This limitation enables focusing to the parameters that affect the fatigue strength. Crack initiation and propagation phases are not distinguished and analysed because the aim is to determine a total fatigue life based on the intact geometry of the joint. Effects of residual stresses are not considered because of the existence of sharp crack-like notches.

2. Fatigue Strength Assessment of Panel Joints

2.1 Response Analysis

The local approaches require that the panel bending response is accurately calculated. The calculated response is used as the input for the local response assessment of the T-joint. In this specific case, contact between the surfaces of the compressive notch can occur. In general this means that the stiffness of the joint can vary as a function of the loading. Since the width of the weld is significantly smaller than the dimensions of the panel, the solid element modelling of the sandwich panel including the T-joint and the contact becomes extremely expensive in terms of computational efforts [51]. Therefore, shell element modelling is preferred in the assessment of the panel response. The rotational springs with a non-constant stiffness are utilized to model the relation between the moment and the rotation of the T-joint. The stiffness for these calculations is taken from the experiments on stake-welded T-joints [50]. This approach is successfully validated with the panel experiments in [P3] and [P4]. The panel response defines the boundary displacement for the local model of the fatigue-critical joint. As shown in Figure 6, the behaviour of the joint is affected by the loading position and mechanical properties of the panel.

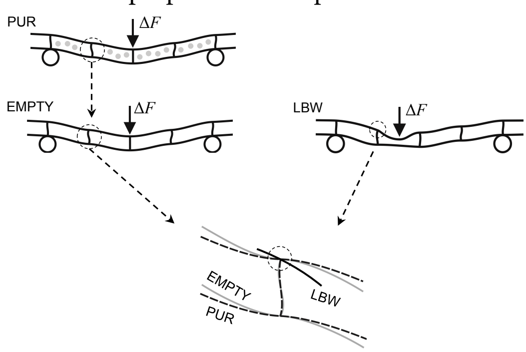

Figure 6. Comparison of panel loading conditions and the response of the critical joint. LBW – load between the web plates. PUR – panel filled with PUR foam. EMPTY – panel without filling.

When the loading is between the webs (LBW, in Figure 6), large local deflections occur in the loaded face plate. This causes contact between the web and face plate at the load level corresponding to the high-cycle fatigue regime [P4]. In the case when the loading is on top of the web plate (EMPTY, in Figure 6) the contact is not present for the considered fatigue load range [P3]. This means that the constant stiffness assumption [49] is valid in the latter case. However, in the former case the increasing stiffness of the joint needs to be included in the modelling of the response of the sandwich panel. It is also presented in [P3] that because of the low-density filling material (PUR, in Figure 6), the shear stiffness of the panel increases and the resulting moment in the joint decreases significantly. This resembles the work of Kolsters and Zenkert [19] and also Romanoff et al. [24], who reached the same conclusion regarding the influence of the filling material on the response of the panel and the joint. However, this thesis extends the state-of-the-art for the panel assessment in the case when the assumed constant stiffness of the joint no longer achieves the accurate response.

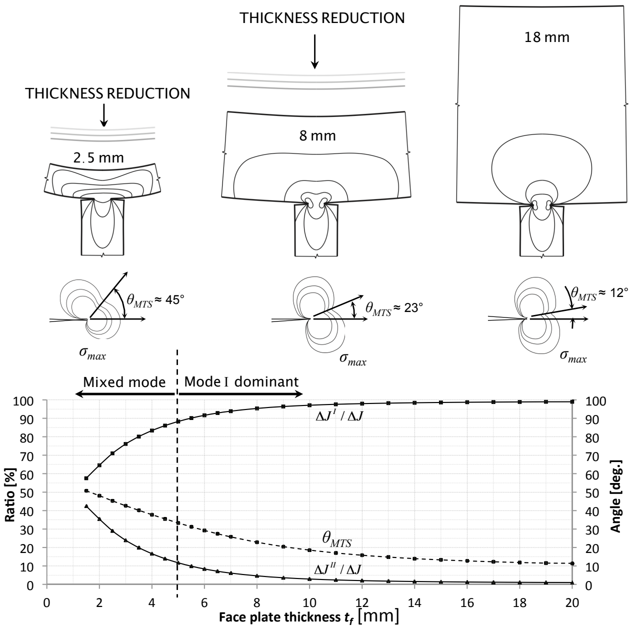

Figure 7. Stress distribution in plates and around the tips with the diagram of mode I and II contributions to the J-integral. The assumed angle of the crack growth direction, θ_{MTS}, is orthogonal to the maximum principal stress direction.

The response of the critical joint is the basis for the fatigue strength assessment by local approaches. The response is greatly affected by the loading condition. [P2] investigates how the thickness of the face plate affects the response of the joint under tension loading. The comparison of thin joints (t < 5 mm) from [P2] and thick ones (t > 5 mm) from [P1] was made under the same tensile loading in the web plate that prevents contact between the plates. [P2] demonstrates that at a constant load level a decrease in the thickness of the face plate has a significant impact on the stress distribution in the face plate and the stress state at the notch tips.

Because of this, the direction of the maximum principal stress, σ_{max}, changes considerably; see Figure 7. Specifically, when the face plate is 2.5 mm thick, the in-plane shear becomes almost equally significant as the normal stress components. This can be presented using the *J*-integral as shown in Figure 7, where $\Delta J^i = (1 - \nu^2)\, \Delta K_i^2 / E$ are the contributions of the modes and *i* stands for I or II, respectively. It is worth noting that the tensile specimens and test setup from [P2] are very similar to the ones used by Jutila [55]. The maximum level of fatigue loading in [P2] is less than half of the load level at which plastic deformation could be identified by the sophisticated imaging system in [55]. Therefore, it is the fact that yielding is highly localized at the notch tips under the load levels considered in this study. Additional comparison shows that the maximum fatigue loading in [P2] is about 30% of the joint's ultimate strength load from [55] what is common for fatigue tests.

The bending of the joint plates in a laterally loaded panel causes the surfaces of the compressive notch to gradually come into contact as the load level increases; see Figure 8. Consequently, the newly formed contact surface increases, and participates in carrying the compressive stress. This thesis clarifies the previous assumptions by Boronski and Szala [41] and Romanoff et al. [50] that the contact effect is important, but only in the case of significant rotation of the T-joint in a high-cycle regime. The contact redistributes the stresses in the weld to a larger area than the actual weld; see Figure 8. This is in agreement with the findings of Romanoff et al. [50].

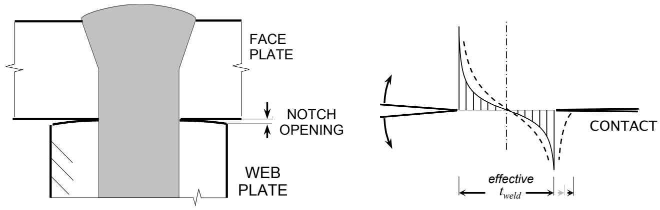

Figure 8. Geometry of the laser stake-welded T-joint and the influence of the contact effect on the stress distribution

Regardless of the contact or loading, the stress distribution at the notch tips is singular. Thus, in order to characterize the stress distribution, the dimensionless stress gradient is introduced in [P4]. The gradient is used in addition to the *J*-integral to explain the fatigue strength and the slope of the fatigue resistance curve. The research considers only theoretical elastic stresses from which perspective a granular material structure doesn't exist. However, some comparison between FE sizes and approximate grain size of 1 μm in fusion zone is worth mentioning. The contour path over which the *J*-integral is evaluated was about five grains away from the tip (5 μm). The closest FE node for the calculation of the dimensionless gradient was about two grains from the tip (2 μm). In addition, the smallest elements used to extract any stresses within the study were about 1.5 μm, meaning always larger than the grain.

2.2 Fatigue Strength Assessment by Local Approaches

The local FE assessment of the joint requires consideration of the weld geometry, in which the notch depths are not constant along the weld line. Thus, in [P1] and [P2] the weld geometry is considered by measuring the notch depths at multiple cross-sections of each specimen. The critical tip under tensile loading is the one with the greater depth, which is more stressed. In the bending case, it is the tensile one. Figure 9 presents the synthesis using the *J*-integral calculated at the critical notch tip of each specimen from [P1]-[P4] on the basis of the mean geometry of the weld; the given probability of survival is P_S = 50%. The results show that the fatigue strength at 5 million load cycles is very similar for all series, demonstrating that the mean geometry of the weld is adequate for the fatigue strength assessment of this joint without considering residual stresses. It can be assumed that the residual stresses differed between series because the used power output of the laser beam varied. For example, power output used for FWE series was 40 kW, for FWA-C series it was 25 kW and all other thin series were welded with the laser that has the maximum output of 12 kW. This observation supports the conclusions made by Sonsino [47] for laser-welded lap joints.

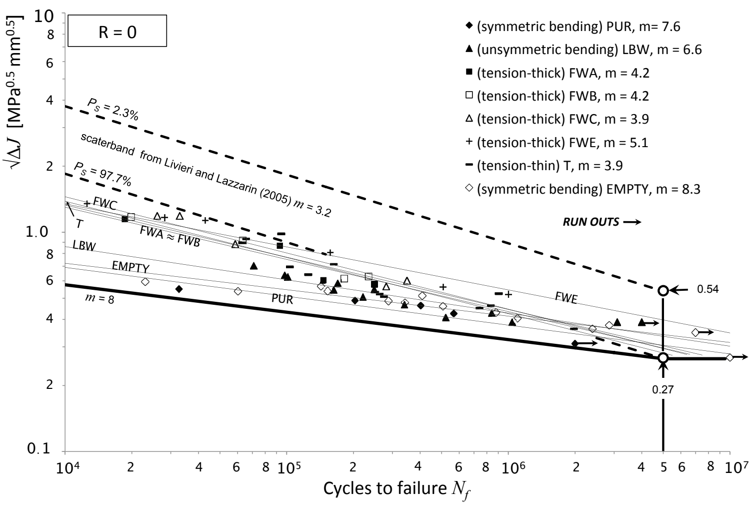

Figure 9. Results obtained using the *J*-integral approach in [P1]-[P4]

The difference between the fatigue strengths of the thin (T) and the thick series (FWA-FWE) under tensile loading cannot be distinguished at five million cycles, even though a major contribution of mode II is present in the thin joints (t < 5 mm) in [P2]. This agreement of fatigue strengths between the thick and thin joints is in line with the work of Sonsino [59] and Sonsino et al. [62], who propose the same fatigue strength for different thick and thin joints at two million load cycles using an 0.05-mm rounding approach. A similar finding can also be observed on the basis of the previous work done by Berto and Lazzarin [69] using the average SED approach. Remes and Fricke [78] indicated the same for butt welds using the structural-stress approach, whereas Fricke et al. [79] used the nominal stress approach. A similar finding was presented using a 1-mm rounding approach by Lillemäe et al. [80]. In addition, the diagram in Figure 9 shows agreement between all the tensile and panel series at five million load cycles, indicating that there is no difference in the fatigue strengths under tensile and bending loads. The comparison between laser stake-welded T-joints and other steel joints in the same diagram reveals that the 97.7% probability of survival (P_S = 97.7%) according to Livieri and Lazzarin [66] is conservative for all series at five million load cycles; see Figure 9. From these results it is obvious that the J-integral is useful for the local fatigue assessment of laser stake-welded T-joints with crack-like notches. This brings forth the potential of the strain energy release rate as the strength parameter in the fatigue assessment of sharp crack-like notches, in addition to the sharp V-notches investigated by Lazzarin et al. [74] and Livieri and Tovo [75]. Furthermore, the mean J-integral value at two million cycles for all series in this thesis corresponds to mode I SIF value of 170 MPa $mm^{0.5}$ that is commonly applied threshold value for crack propagation in welds [64].

The comparison of the J-integral to other local approaches is investigated in [P1]. The thick tensile specimens are considered also to include the fictitious rounding concept r_{ref} = 1 mm. The results of r_{ref} = 1 using the maximum principal stress as the criterion show that the P_s = 97.7% curve for laser stake-welded T-joints estimates the fatigue strength at two million cycles to be 15% less than that from Radaj et al. [56]. When compared to the recommended design curve [64, 59] the reduction is 12%, but 10% higher than the curve recommended by Pedersen et al. [81]. This indicates that the the r_{ref} = 1 mm concept is applicable for thick laser stake-welded T-joints, but is not sufficient for the assessment of joints with plate thicknesses below 5 mm since the artificial keyhole model affects the stiffness of the joint. The substitute r_{ref} = 0.05 concept, normally intended for thin plates, is also applied to thick joints in [P1]. However, in this case the fatigue strength (P_s = 97.7%) of laser stake-welded T-joints is 30% higher than that of the other steel joints from Sonsino et al. [62] and Sonsino [59]. Better agreement was observed for the J-integral approach, where the fatigue strength (P_s = 97.7%) at five million cycles for laser stake-welded T-joints was 3% less than for other steel joints, according to Livieri and Lazzarin [66]. Good agreement was observed for the average SED, where the P_S = 50% value for laser stake-welded T-joints at two million cycles is 16% less than that for other steel joints, according to Berto and Lazzarin [69]. This shows the benefit of the energy-based approaches in the fatigue assessment of laser stake-welded T-joints.

Even though the fatigue strengths of all the series are in agreement, the slope of the fatigue resistance curves varies. It is shown in [P4] that the slope in the case of joint bending is higher than in the case of tension; see Figure 10. The results indicate that the reduction in the face plate thickness reduces the slope value slightly. The results contradict the findings from Sonsino et al. [62, 63], which state that the slope value increases for welded joints as the plate thickness decreases. For laser stake-welded T-joints with a narrow weld, the loading condition, especially bending, has a stronger influence on the slope than the plate thickness effect. The detailed analysis of the stress distribution at the notch tip in [P4] reveals that the maximum principal stress has a significant influence on the slope value; see Figure 10.

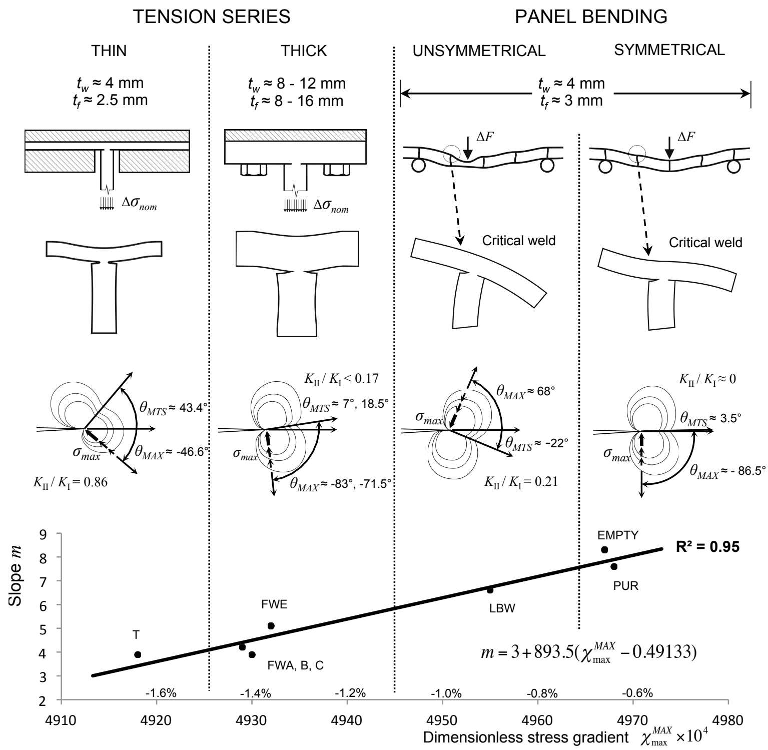

Figure 10. The relation between the dimensionless stress gradient and the slope m.

The slope of laser stake-welded T-joints is shown to depend on the distribution of the maximum principal stress, which is here characterized by the dimensionless gradient evaluated in the stress direction, χ_{max}^{MAX}. The gradient exhibits sensitivity towards the thickness of the plate and the loading condition. The maximum principal stress direction is approximately orthogonal to the direction of the crack path observed in the experiments in [P2]. The stress direction is related to the maximum yield direction, according to Sih's theory, which assumes that the yielding occurs along the course where the maximum strain energy density develops [82, 83]. This indicates why the dimensionless gradient of the theoretical elastic stress is able to relatively quantify the effects of the small-scale yielding at the notch tip.

3. Conclusions

This thesis investigated the high-cycle fatigue resistance of laser stake welds in web-core steel sandwich panels subjected to lateral loads. The thesis considers the case where the local loss of the *sandwich effect* occurs as a result of the separation of the plates caused by the fatigue failure in the weld zone of the critically loaded panel joint. The focus of the thesis is on thin plate panels in which the plate thicknesses are above 2.5 mm. The plate thickness effect is investigated by a comparison of thick and thin stake-welded joints under tension loading in order to eliminate the influence of the contact between the plates. The panel loading conditions that were considered caused responses and stress states of the critical joints that are similar to those when panels are subjected to uniform pressure or patch loading. Under lateral loads, the joined plates are prone to the secondary bending caused by the low shear stiffness of the panel in the plane opposite to the web plate direction. This causes the tension stress range at one of the notches of the joint and compression at the other. In this case, the fatigue crack initiates at the tip of the tensile notch and its propagation leads to the failure of the weld and the local loss of the *sandwich effect*. The efforts of this thesis were focused on identifying the local approach to the fatigue strength assessment that can consider joint deformation, the local stress field at the notch tip and the contact at the compressive notch.

The *J*-integral is shown to be useful parameter for prediction of total fatigue life based on the intact notch geometry and assuming the elastic continuum. Statistically mean geometry of the weld proved to be sufficient for the fatigue strength assessment of panel joints and tensile specimens. When the fatigue strengths of all investigated series are compared, the agreement is found at five million cycles where the agreement with other steel joints is also achieved. The compared fatigue strengths agree regardless of different plate thicknesses, steels, loading conditions and whether the contact occurs or not. The contact effect is present only in the case of a significant face plate deflection and then, the resulting increase of the joint's stiffness must be included in the assessment of the panel response. The increasing stiffness is necessary for obtaining accurate global displacements of the panel that need to be imposed as boundary conditions in the local FE assessment of the joint. It is also shown that the filling material partially increases the shear stiffness of the panel and reduces the secondary bending of the plates what results in a smaller bending moment in the critical joint. This prolongs the fatigue life of the panel or, in other words, influences the fatigue strength based on the force range. However, filling doesn't influence the fatigue strength based on the *J*-integral range as the parameter. The slope of the fatigue resistance curve for laser stake-welded T-joints mainly varies according to the loading condition imposed on the joint. These conditions cause different elastic stress distributions in the close vicinity of the notch tip. The distribution of the maximum principal stress in the direction of the stress significantly influences the slope value because this direction is associated with extension of the plastic zone. When the stress distribution is characterized by the dimensionless gradient, the linearly approximated relation between the slope and the gradient is useful for slope prediction of laterally loaded panels in a high-cycle regime.

The thesis considered laser stake-welded T-joints with plate thicknesses in the range from 2.5 to 16 mm. However, future work could consider joints made of plates with different thicknesses. The work focused on loading conditions in which fatigue failure is caused by two-dimensional deformation in the plane orthogonal to the weld line and thus, the assessment was based on the plane strain hypothesis. However, the *J*-integral is not limited to the plane strain analysis and thus, the work could be extended to loading conditions causing considerable mode III at the notch tips, e.g. panel bending in the web plate direction. The future investigation should also consider other load ratios than R = 0 because load ratio influences the fatigue strength. Before web-core panels are used as load-carrying structures, durability under variable amplitude loading needs to be considered because variable amplitude is the feature of service loads. This is important because different amplitude sequences cause different fatigue lives. Furthermore, panels are subjected to in- and out-of-plane loads in a ship structure. In that case, boundary conditions in the panel assessment should impose the displacements generated by the global response of the ship structure, for example, bending of the ship's hull girder. However, this requires careful consideration since some of connections between the panel and the remaining structure can be asymmetric. The asymmetric connections cause unequal transmission of global displacements to the top and bottom face plates creating the additional bending moment in the panel. Therefore, the future investigation should determine how connections influence the secondary bending of the plates and if this can change the type of panel failure.

References

[1] Sikora, J.P. and Dinsenbacher, A.L. (1990) "SWATH Structure: Navy Research Development Applications", *Marine Technology*, 27, 4, pp. 211-220.

[2] Wiernicki, C.J., Liem, F., Woods, G.D. and Furio, A.J. (1991) "Structural Analysis Methods for Lightweight Metallic Corrugated Core Sandwich Panels Subjected to Blast Loads", *Naval Engineers Journal*, 103, 3, pp. 192-203.

[3] Marsico, T.A., Denney, P. and Furio, A. (1993) "Laser-Welding of Lightweight Structural Steel Panels", Proceedings of Laser Materials Processing Conference ICALEO 1993, pp. 444-451.

[4] Roland, F. and Reinert, T. (2000) "Laser Welded Sandwich Panels for the Shipbuilding Industry", *Lightweight Construction – Latest Developments*, February 24-25, London, pp. 1-12.

[5] Klanac, A. and Kujala, P. (2004) "Optimal design of steel sandwich panel applications in ships", *In: Proceedings of 9th International Symposium on Practical Design of Ships and Other Floating Structures, PRADS-2004*, Lübeck-Travemünde, Germany, pp. 907-914.

[6] Kujala, P. and Klanac, A. (2005) "Steel sandwich panels in marine applications", *Brodogradnja-Shipbuilding*, 56, pp. 305-314.

[7] Kortenoeven, J., Boon, B. and de Bruijn, A. (2008) "Application of sandwich panels in design and building of dredging ships", *Journal of Ship Production*, 24, pp. 125-134.

[8] Fung, T.C., Tan, K.H. and Lok, T.S. (1996) "Shear Stiffness D_{QY} for C-Core Sandwich Panels", *Journal of Structural Engineering*, 122, 8, pp. 958-965.

[9] Nordstrand, T.M. and Carlsson, L.A. (1997) "Evaluation of Transverse Shear Stiffness of Structural Core Sandwich Plates", *Composite Structures*, 37, pp. 145-153.

[10] Knox, E.M., Cowling, M.J. and Winkle, I.E. (1998) "Adhesively Bonded Steel Corrugated Core Sandwich Construction for Marine Applications", *Marine Structures*, 11, 4-5, pp. 185-204.

[11] Fung, T.C. and Tan, K.H. (1998) "Shear Stiffness for Z-Core Sandwich Panels", *Journal of Structural Engineering*, 124, 7, pp. 809-816.

[12] Kujala, P. and Roland, F. (2002) "Recent Developments in Design and Production Methods of Steel Sandwich Panels". *3rd International Shipbuilding Conference, ISC-2002*. October 8-10. St. Petersburg, Russia.

[13] Liang, C.C., Yang, M.F. and Wu, P.W., (2001) "Optimum Design of Metallic Corrugated Core Sandwich Panels Subjected to Blast Loads", *Ocean Engineering*, 28, pp. 825-861.

[14] Hutchinson, J.W. and Xue, Z. (2005) "Metal Sandwich Plates Optimized for Pressure Impulses", *International Journal of Mechanical Sciences*, 47, pp. 545-569.

[15] Vaziri, A. and Hutchinson, J.W. (2007) "Metal Sandwich Plates Subject to Intense Air Shocks", *International Journal of Solids and Structures*, 44, pp. 2021-2035.

[16] Liang, Y., Spuskanyuk, A.V., Flores, S.E., Hayhurst, D.R., Hutchinson, J.W., McMeeking, R.M. and Evans, A.G. (2007) "The Response of Metallic Sandwich Panels to Water Blast", *Journal of Applied Mechanics*, 74, pp. 81-99.

[17] Vaziri, A., Xue, Z. and Hutchinson, J.W. (2007) "Performance and Failure of Metal Sandwich Plates Subjected to Shock Loading", *Journal of Mechanics of Materials and Structures*, 2, 10, pp. 1947-1963.

[18] Ehlers, S., Tabri, K., Romanoff, J. and Varsta, P. (2010) "Numerical and Experimental Investigation on the Collision Resistance of the X-Core Structure", *Ships and Offshore Structures*, 7, 1, pp. 21-29.

[19] Kolsters, H. and Zenkert, D. (2002) "Numerical and Experimental Validation of a Stiffness Model for Laser-Welded Sandwich Panels With Vertical Webs and a Low-Density Core", *In: Hans Kolsters, Licentiate Thesis – Paper B*, Kunliga Tekniska Högskolan, Stockholm, Sweden.

[20] Kolsters, H. and Zenkert, D. (2010) "Buckling of Laser-Welded Sandwich Panels: Ultimate Strength and Experiments", *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, 224, 1, pp. 29-45.

[21] Briscoe, C.R., Mantell, S.C., Okazaki, T. and Davidson, J.H. (2012) "Local Shear Buckling and Bearing Strength in Web Core Sandwich Panels: Model and Experimental Validation", *Engineering Structures*, 35, pp. 114-119.

[22] Taczała, M. and Banasiak, W. (2004) "Buckling of I-Core Sandwich Panels", *Journal of Theoretical and Applied Mechanics*, 42, 2, pp. 335-348.

[23] Romanoff, J. (2001) "The Effect of a Filling Material on the Local Ultimate Strength of an All Steel Sandwich Panel", *Journal of Structural Mechanics*, 35, 1, pp. 19-39.

[24] Romanoff, J., Laakso, A. and Varsta, P. (2009) "Improving the Shear Properties of Web-Core Sandwich Structures Using Filling Material", *Analysis and Design of Marine Structures*, Ch. 14, pp. 133-138, *Taylor & Francis Group*, London, UK.

[25] Kujala, P., Kotisalo, K. and Kukkanen, T. (1998) "Fatigue of All Steel Sandwich Panels – Applications on Bulkheads and Decks of a Cruising Ship", *In: Proceedings of the 7th International Symposium on Practical Design of Ships and Other Floating Structures, PRADS – 1998*, September 20-25, The Hague, Netherlands.

[26] Metschkow, B. (2006) "Sandwich Panels in Shipbuilding", *Polish Maritime Research*, Special Issue 2006/S1, pp. 5-8.

[27] Kniep, M., Klanac, A., Van Heusden, S., Polić, D. and Frank, D. (2010) "Design and Production of a Steel Sandwich Funnel Deckhouse", *11th International Symposium on Practical Design of Ships and Other Floating Structures, PRADS-2010*, Vol. 2, pp. 1065-1070, Sep. 19-24, Rio de Jeneiro, Brazil.

[28] Frank, D., Klanac, A., Kniep, M., Polić, D. and Ehlers, S. (2010) "Optimization System for Design of Laser-Welded Steel-Sandwich Structures", *11th International Symposium on Practical Design of Ships and Other Floating Structures*, *PRADS-2010*, Vol. 2, pp. 1079-1087, Sep. 19-24, Rio de Jeneiro, Brazil.

[29] Augustyniak, M. and Porembski, G. (2006) "FEM Strength Analysis of Sandwich Panels for Ship Structure Applications", *Polish Maritime Research*, Special Issue 2006/S1, pp. 24-26.

[30] Romanoff, J. and Klanac, A. (2008) "Design Optimization of Steel Sandwich Hoistable Car-Decks Applying Homogenized Plate Theory", *Journal of Ship Production*, 24, 2, May 2008.

[31] Kujala, P., Romanoff, J. Tabri, K. and Ehlers, S. (2004) "All Steel Sandwich Panels Design Challenges for Practical Applications on Ships", *In: Proceedings of 9th International Symposium on Practical Design of Ships and Other Floating Structures, PRADS-2004*, Lübeck-Travemünde, Germany, pp. 915-922.

[32] Romanoff, J., Naar, H. and Varsta, P. (2011) "Interaction Between Web-Core Sandwich Deck and Hull Girder of Passenger Ship", *Marine Systems & Ocean Technology*, 6, 1, pp. 39-45.

[33] Ehlers, S. (2004) "Fatigue Life of All Steel Sandwich Panel Joints", Master's Thesis, *University of Rostock*, Germany.

[34] Pyszko, R. (2006) "Strength assessment of a version of joint of sandwich panels", *Polish Maritime Research*, Special Issue 2006/S1, pp. 17-20.

[35] Fricke, W., Paetzold, H. and Zipfel, B. (2009) "Fatigue Tests and Numerical Analyses of a Connection of Steel Sandwich Plates", *Welding in the World*, 53, 151-157.

[36] Bright, S.R. and Smith, J.W. (2004) "Fatigue Performance of Laser-Welded Steel Bridge Decks", *The Structural Engineer*, 82, 21, pp. 31-39.

[37] Caccese, V. and Yorulmaz, S. (2009) "Laser Welded Steel Sandwich Panel Bridge Deck Development: Finite Element Analysis and Stake Weld Strength Tests", *Project Report No. C2006-014-RPT-01*, *University of Maine*, Orono, ME, USA, September 22, 2009.

[38] Briscoe, C.R., Mantell, S.C., Davidson, J.H. and Okazaki, T. (2011) "Design Procedure for Web Core Sandwich Panels for Residential Roofs", *Journal of Sandwich Structures and Materials*, 13, 1, pp. 23-58.

[39] Socha, G., Koli, K. and Kujala, P. (1998) "Mechanical Tests and Metallurgical Investigation on Weld Samples", *Report AWCS – Project No. BE 96-3932 - Task A4*, Helsinki University of Technology, Espoo, Finland.

[40] Boroński, D. and Szala, J. (2006) "Fatigue Life Tests of Steel Laser-Welded Sandwich Structures", *Polish Maritime Research*, Special Issue 2006/S1, pp. 27-30.

[41] Boroński, D. and Szala, J. (2006) "Tests of Local Strains in Steel Laser-Welded Sandwich Structure", *Polish Maritime Research*, Special Issue 2006/S1, pp. 31-36.

[42] Sandwich Consortium (2002) "Balance User Group Report No. 3", Version 3, May 8, 2002.

[43] Kozak, J. (2006) "Fatigue Life of Steel Laser-Welded Panels", *Polish Maritime Research*, Special Issue 2006/S1, pp. 13-16.

[44] Kozak, J. (2007) "Forecasting of Fatigue Life of Laser Welded Joints", *Zagadnienia Eksploatacji Maszyn*, 149, 1, pp. 85-94.

[45] Det Norske Veritas – DNV (2012) "Steel Sandwich Panel Construction", *Classification Notes No. 30.11*, April 2012.

[46] Hughes, D.J., Koukovini-Platia, E. and Heeley, E.L. (2014) "Residual Stress in a Laser Welded EUROFER Blanket Module Assembly Using Non-Destructive Neutron Diffraction Tecniques", *Fusion Engineering and Design*, 89, pp.104-108.

[47] Sonsino, C.M. (2009) "Effect of Residual Stresses on the Behaviour of Welded Joints Depending on Loading Conditions and Weld Geometry" *International Journal of Fatigue*, 31, pp. 88-101.

[48] Romanoff, J. and Varsta, P. (2006) "Bending Response of Web-Core Sandwich Beams", *Composite Structures*, 73, 4, pp. 478-487.

[49] Romanoff, J. and Varsta, P. (2007) "Bending Response of Web-Core Sandwich Plates", *Composite Structures*, 81, 2, pp. 292-302.

[50] Romanoff, J., Remes, H., Socha, G., Jutila, M. and Varsta, P. (2007) "The Stiffness of Laser Stake Welded T-joints in Web-Core Sandwich Structures", *Thin-Walled Structures*, 45, 4, pp. 453-462.

[51] Romanoff, J., Varsta, P. and Remes, H. (2007) "Laser-Welded Web-Core Sandwich Plates under Patch-Loading", *Marine Structures*, 20, 1, pp. 25-48.

[52] Remes, H. (2008) "Strain-Based Approach to Fatigue Strength Assessment of Laser-Welded Joints", *Helsinki University of Technology*, Doctoral dissertation 102.

[53] Jiang, X.X., Li, J.M., Cao, R., Zhu, L., Chen, J.H., Wu, Y.X. and Li, Z.G. (2014) "Microstructures and Properties of Sandwich Plane Laser-Welded Joint of Hull Steel", *Materials Science & Engineering A,* 595, pp. 43-53.

[54] Boronski, D. (2006) "Cyclic Material Properties Distribution in Laser-Welded Joints", *International Journal of Fatigue*, 28, pp. 346-354.

[55] Jutila, M. (2009) "Failure Mechanism of a Laser Stake Welded T-joint", *Master of Science Thesis, Helsinki University of Technology*, Espoo, Finland.

[56] Radaj, D., Sonsino, C.M. and Fricke, W. (2006) "Fatigue Assessment of Welded Joints by Local Approaches", 2nd ed., *Woodhead Publishing*, Cambridge, UK.

[57] Neuber, H. (1968) “Über die Berücksichtigung der Spannungskonzentration bei Festigkeitsberechnungen”, *Konstruktion*, 20, pp. 245-251.

[58] Fricke, W. (2008) “Guideline for the Fatigue Assessment by Notch Stress Analysis for Welded Structures”, *IIW-Doc. XIII-2240r1-08/XV-1289r1-08*.

[59] Sonsino, C.M. (2009) “A Consideration of Allowable Equivalent Stresses for Fatigue Design of Welded Joints According to the Notch Stress Concept with the Reference Radii r_{ref} = 1.00 and 0.05 mm”, *Welding in the World*, 53, 3-4, pp. 64-75.

[60] Zhang, G., Eibl, M., Singh, S., Hahn, O. and Kurzok, J.P. (2002) “Methods of Predicting the Fatigue Lives of Laser Beam Welded Lap Welds under Shear Stresses”, *Welding Cutting*, 1, pp. 96-103.

[61] Eibl, M., Sonsino, C.M., Kaufmann, H. and Zhang, G. (2003) “Fatigue Assessment of Laser Welded Thin Sheet Aluminium”, *International Journal of Fatigue*, 25, pp. 719-731.

[62] Sonsino, C.M., Bruder, T. and Baumgartner, J. (2010) “S-N Lines for Welded Thin Joints - Suggested Slopes and FAT Values for Applying the Notch Stress Concept with Various Reference Radii”, *Welding in the World*, 54, 11-12, pp. 375-392.

[63] Sonsino, C.M., Fricke, W., de Bruyne, F., Hoppe, A., Ahmadi, A. and Zhang, G. (2012) Notch Stress Concepts for the Fatigue Assessment of Welded Joints – Background and Applications. *International Journal of Fatigue*, 34, pp. 2-16.

[64] Hobbacher, A., editor, (2007) “Recommendations for Fatigue Design of Welded Joints and Components”, (update) *IIW-Doc XIII-2151-07/XV-1254-07,* revision 2007.

[65] Lazzarin, P. and Tovo, R. (1998) “A Notch Intensity Factor Approach to the Stress Analysis of Welds”, *Fatigue & Fracture of Engineering Materials and Structures*, 21, pp. 1089-1103.

[66] Livieri, P. and Lazzarin, P. (2005) “Fatigue Strength of Steel and Aluminium Welded Joints Based on Generalised Stress Intensity Factors and Local Strain Energy Values”, *International Journal of Fracture*, 133, pp. 247-276.

[67] Lazzarin, P. and Zambardi, R. (2001) “A Finite-Volume-Energy Based Approach to Predict the Static and Fatigue Behaviour of Components with Sharp V-shaped Notches”, *International Journal of Fracture*, 112, pp. 275-298.

[68] Lazzarin, P. and Zambardi, R. (2002) “The Equivalent Strain Energy Density Approach Re-Formulated and Applied to Sharp V-shaped Notches under Localized and Generalized Plasticity”, *Fatigue & Fracture of Engineering Materials and Structures*, 25, pp. 917-928.

[69] Berto, F. and Lazzarin, P. (2009) “A Review of the Volume-Based Strain Energy Density Approach Applied to V-notches and Welded Structures”, *Theoretical and Applied Fracture Mechanics*, 52, pp. 183-194.

[70] Berto, F. and Lazzarin, P. (2011) “Fatigue Strength of Structural Components under Multi-Axial Loading in Terms of Local Energy Averaged on a Control Volume”, *International Journal of Fatigue*, 33, pp. 1055-1065.

[71] Irwin, G., (1957) “Analysis of Stresses and Strains near the End of a Crack Traversing a Plate”, *Journal of Applied Mechanics*, 24, pp. 361-364.

[72] Griffith, A.A. (1921) “The Phenomena of Rupture and Flow in Solids”, *Philosophical Transactions of the Royal Society of London*, A 221, pp. 163-198.

[73] Rice, J.R. (1968) “A Path Independent Integral and the Approximate Analysis of Strain Concentration by Notches and Cracks”, *Journal of Applied Mechanics*, 35, pp. 379-386.

[74] Lazzarin, P., Livieri, P. and Zambardi, R. (2002) “A J-integral-Based Approach to Predict the Fatigue Strength of Components Weakened by Sharp V-shaped Notches”, *International Journal of Computer Applications in Technology*, 15, 4-5, pp. 202-210.

[75] Livieri P. and Tovo, R. (2009) “The Use of J_V Parameter in Welded Joints: Stress Analysis and Fatigue Assessment”, *International Journal of Fatigue*, 31, pp. 153-163.

[76] Eurocode 3. (2005) “Design of Steel Structures”, Part 1-9, Fatigue, EN 1993-1-9, *CEN*, Brussels.

[77] Lazzarin, P. and Berto, F. (2008) “Control Volumes and Strain Energy Density Under Small and Large Scale Yielding due to Tension and Torsion Loading”, *Fatigue & Fracture of Engineering Materials and Structures*, 31, pp. 95-107.

[78] Remes, H. and Fricke, W. (2013) “Influencing Factors on Fatigue Strength of Welded Thin Plates Based on Structural Stress Assessment”, *IIW Doc. XIII-2490-13*.

[79] Fricke, W., Remes, H., Feltz, O., Lillemäe, I., Tchuindjang, D., Reinert, T., Navierov, A., Sichermann, W., Brinkmann, M., Kontkanen, T., Bohlmann, B. and Molter, L. (2013) “Fatigue strength of laser-welded thin plate ship structures based on nominal and structural hot-spot stress approach”, Analysis and Design of Marine Structures, *Taylor & Francis Group*, London, UK.

[80] Lillemäe, I., Lammi, H., Molter, L. and Remes, H. (2012) “Fatigue Strength of Welded Butt Joints in Thin and Slender Specimens”, *International Journal of Fatigue*, 44, pp. 98-106.

[81] Pedersen, M.M., Mouritsen, O.Ø., Hansen, M.R., Andersen, J.G. and Wenderby, J. (2009) “Re-Analysis of Fatigue Data Using the Notch Stress Approach”, *IIW-Doc. XIII-WG3-10-09*.

[82] Sih, G.C. (1974) “Strain-Energy-Density Factor Applied to Mixed Mode Crack Problems”, *International Journal of Fracture*, 10, pp. 305-321.

[83] Sih, G.C. and Ho, J.W. (1991) “Sharp Notch Fracture Strength Characterized by Critical Energy Density”, *Theoretical and Applied Fracture Mechanics*, 16, pp. 179-214.

Errata

[P1] in Figure 8, the units on the horizontal axis should be [MPa mm] instead of [MPa^2 mm]

Corrigendum to Publication 1

Darko Frank, Heikki Remes, Jani Romanoff. Corrigendum to “Fatigue assessment of laser stake-welded T-joints”. International Journal of Fatigue, volume 33, issue 11, page 1504, 2011.

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Corrigendum

Corrigendum to ‘Fatigue assessment of laser stake-welded T-joints’ [Int. J. Fatigue 33 (2011) 102–114]

Darko Frank *, Heikki Remes, Jani Romanoff

Department of Applied Mechanics, Aalto University, Otakaari 4, 02150 Espoo, Finland

The author would like to notify the below change for the article ‘‘Fatigue assessment of laser stake-welded T-joints’’ published in vol. 33, issue 2, pp. 102–114. There is a modification in Table 3 and the correct Table appears below:

Table 3
Fatigue assessment results and test results for specimens from [21] ($R = 0$).

Specimen	Cycles to failure, N_f	Nominal stress range, $\Delta\sigma_n$ [MPa]	Notch stress range, $\Delta\sigma$ ($r_{ref} = 1.0$ mm) [MPa]	Standard deviation of notch stress range, $\Delta\sigma$ ($r_{ref} = 1.0$ mm) [MPa]	Notch stress range, $\Delta\sigma$ ($r_{ref} = 0.05$ mm) [MPa]	Standard deviation of notch stress range, $\Delta\sigma$ ($r_{ref} = 0.05$ mm) [MPa]	Stress intensity range, ΔK_I [MPa mm$^{0.5}$]	Standard deviation of stress intensity range, ΔK_I [MPa mm$^{0.5}$]
Series FWA								
FW01A	5381	187.5	943.2	74.6	4005.0	260.4	725.2	48.0
FW02A	93,069	112.5	540.9	23.7	2283.6	108.6	414.9	20.4
FW03A	18,591	150			3048.0	91.9	551.6	17.0
FW04A	2222	225	1200.8	43.7	4994.9	156.3	910.3	30.3
FW05A	249,169	75	374.3	12.6	1558.2	54.9	278.3	10.3
FW08A	146,342	75	384.3	16.1	1619.4	59.7	290.7	11.6
Series FWB								
FW01B	2494	225	1152.5	20.5	4673.9	103.0	846.4	19.0
FW02B	7625	187.5	902.4	23.2	3860.5	102.9	696.4	21.1
FW03B	19,865	150	734.2	18.5	3109.0	73.3	564.1	14.6
FW04B	63,414	112.5	563.4	16.1	2402.8	57.8	438.3	11.5
FW05B	181,782	75	395.1	6.6	1639.2	31.3	293.5	5.9
FW06B	233,919	75	400.0	14.7	1674.2	51.9	300.7	9.6
Series FWC								
FW01C	4013	225	1141.9	31.3	4826.0	106.1	878.5	20.6
FW02C	9435	187.5	948.6	21.1	3979.9	70.2	718.1	13.3
FW03C	32,902	150	738.4	20.1	3140.4	101.3	571.0	20.1
FW04C	26,038	150	751.2	8.6	3141.7	46.0	569.7	9.0
FW05C	58,579	112.5			2322.2	66.7	420.5	11.9
FW06C	349,212	75	384.7	8.8	1608.9	41.4	288.2	7.9
FW07C	3700	225			4572.7	115.6	827.6	20.7
FW08C	281,018	75			1526.5	38.1	272.3	6.9
Series FWE								
FW01E	3723	150	1090.2	56.4	4475.0	200.5	829.1	35.3
FW02E	42,957	100	717.1	37.5	2951.0	132.3	543.8	23.4
FW03E	157,424	75	500.1	20.1	2073.7	73.9	384.1	13.5
FW04E	12,563	125	852.5	58.5	3526.6	219.0	652.5	37.7
FW05E	1277	150	1090.3	114.6	4452.4	378.6	809.9	74.7
FW06E	28,102	100	742.0	47.2	3038.1	165.4	560.1	28.7
FW07E	507,653	50	357.3	22.4	1470.7	81.6	271.2	14.1
FW08E	1,000,102	50	325.4	10.3	1353.8	39.5	249.3	7.0

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* Corresponding author. Fax: +358 9 451 4173.
E-mail address: darko.frank@tkk.fi (D. Frank).

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Scientists across the Globe are working on development of new, eco-friendly, sustainable solutions and various ways of reducing pollution. Transportation industry is putting in a significant effort into development of lightweight structural solutions such as sandwich panels, which will decrease demand for excessive engine power and thus reduce the amount of exhaust gasses. However, pollution is not exclusively caused by internal combustion engines, but also by structural waste after vehicles or ships are retired from service. For that reason, recyclable materials like steel are favorable for structural applications due to their environmental-friendliness. Before steel sandwich panels can be used in transport applications, their durability under fatigue loading needs to be determined. This is by no means a trivial problem, one of many that science has to explore in a quest for bringing balance back into the eco-system.

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