Integral treatment of butt joints for the fatigue life assessment in the low cycle fatigue regime

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Abstract

The framework for a fatigue assessment of welded joints under service loading conditions of crane structures from the low cycle to the high cycle fatigue regime includes the consideration of elastic-plastic material behavior, variable amplitude loading, and acceptable calculation times. Therefore, an integral treatment of butt joints has been developed for fatigue life estimation. The butt weld is considered in its entirety, so that it can be described by its cyclic behavior. The evaluation of the cyclic stress-strain behavior and tri-linear strain-life curves of butt joints for different high-strength, fine-grained structural steels, derived by strain-controlled fatigue tests, is the basis for this description. This procedure is not limited to conventionally applied gas metal arc welding only, but also the fatigue assessment of laser beam welding is possible, for example. Cyclic transient effects have been analyzed and a distinctive cyclic softening is described by linearization of Ramberg-Osgood parameters, depending on the damage content of each cycle derived from constant amplitude, strain-controlled tests. On the basis of the cyclic behavior in combination with memory and Masing behavior, a simulation of the stress-strain paths of investigated butt welds, under constant and variable amplitude loading, has been performed. Damage parameters are used to accumulate the damage cycle by cycle in order to derive the fatigue lifetime. Finally, calculated fatigue lives were compared with experimentally determined lives, showing the impact of this procedure.

Keywords Integral treatment · Welded joint · Butt weld · Cyclic behavior · Damage parameter · Fatigue life estimation

1 Introduction

In the design and manufacture of modern steel assemblies, permanent joining by welding is still common. The crane industry makes use of gas metal arc welding (GMAW), i.e., metal active gas welding, as a traditional and prevalent welding process, e.g., for the manufacture of truck and crawler cranes. Due to recent process developments, laser beam welding and the hybrid combination of laser beam and gas metal arc welding have appeared as expedient alternatives. However, for applications with highly stressed structures, as in the case of loading situations of the telescopic boom of

truck cranes, for example, Fig. 1a, the service loads are related to the low cycle fatigue regime. Within such structures, butt joints are essential load-carrying welds (Fig. 1b). Therefore, the following points need to be considered in the fatigue estimation:

- In highly stressed areas, welded joints are limiting factors in design, e.g., butt joints in the telescopic boom
- Crane-specific load scenarios result in variable amplitude loading (VAL) and elastic-plastic stresses and strains (LCF)
- A large number of load cases requires a method for fatigue life estimation that is easy to use

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The fatigue assessment of welded joints according to recommendations and standards, Eurocode 3 [3], the crane design standard DIN EN 13001-3-1 [4], Hobbachers IIW recommendations [5], and the FKM guideline [6], is based on fatigue classes (FAT), i.e., characteristic stress ranges $\Delta\sigma_C$ at $2 \cdot 10^6$ cycles to failure. These FAT classes were derived from

Fig. 1 **a** Truck crane on the test site (photo from [1]) and **b** representation of a transverse butt weld in the tensile-stressed upper shell [2]

experimental results from specimens and components. Specimens for experimental fatigue investigations of steel structures with medium sheet thickness, i.e., 5 mm to approximately 20 mm, are usually of larger scale and tested under stress control to verify the fatigue assessment and FAT classes. To date, these fatigue recommendations are mostly limited to steels with a maximum yield strength of 960 MPa and the assessment by FAT classes does not include the low cycle fatigue (LCF) regime and elastic-plastic material behavior. Therefore, they are restricted to cycles to failure of $N \geq 1 \cdot 10^4$.

An overview of the fatigue design concepts, which are applied in the assessment of welded joints, is given in Fig. 2 and, in more detail, by Radaj et al. [8, 9]. The nominal stress (and strain) approach requires the definition of a nominal stress or strain, i.e., a reference cross-section, and assignment of a specific notch detail. FAT values for nominal stress and various notch details have been defined [3–6]. Even though FAT classes are defined for survival probabilities of 97.7%, analyses of fatigue results of butt welds, including data points for $N_f < 5 \cdot 10^4$ from Olivier and Ritter [10], Leitner et al. [11], Berg and Stranghöner [12], and Möller [2] have found that the assessment by FAT 90 (or even FAT 80/FAT 71) tends to be unsafe at high loading levels in and close to the LCF regime.

In the case of more complex structures, where it is not possible to define nominal stress, the structural stress (or strain) concept can be applied, as further described by the IIW recommendations of Hobbacher [5] and Fricke [13] as

well as [8], where FAT classes for structural stresses can also be found. Due to the linear-elastic extrapolation, which is used in most of the concept variants, the existing stress concentration at the notch and notch support effects at this location are not captured. Furthermore, structural stress and strain concepts reveal their limitations when confronted with root notches.

As a consequence and in addition to the nominal and structural stress (or strain) concepts, local concepts (cf. [5, 7–9, 13]) are increasingly used for the design of welded joints. FAT classes for notch stresses result in fictitious (linear-elastic) stresses at the notch root. The notch stress approaches attracted wide interest and developed over recent decades, so that they are a useful assessment approach for welded joints, especially in the case of the reference radius concept (cf. [8, 13]). However, this approach cannot be applied in elastic-plastic stress-strain states, as is the case in the LCF regime or, rather, in the notch root of a weld for high loading applications. In order to cover this case, the notch strain concept (cf. [5, 7–9, 13]) is used, where the cyclic material behavior forms the basis for the simulation and assessment of the stress-strain state in the notch, in addition to the geometry of the joint, as introduced by Lawrence et al. [14]. The effort involved in such an assessment should not be underestimated and increases further, if transient effects and microstructural differences, as given by investigations on the effect of the microstructure of the different weld zones on the fatigue

Fig. 2 Overview of fatigue design concepts for welded joints [7]

strength from various authors [15–20], are taken into account. Recent work of Saiprasertkit et al. [21–24] uses an analytical approximation for the description of the effective notch strain from the notch strain concept with a reference radius of $r_{\text{ref}} = 1.00$ mm in the case of load-carrying cruciform joints to show a conservative estimation of FAT 200 within the LCF and HCF regimes. On the contrary, this work aims at providing a fatigue life estimation by an integral treatment of butt welds under low to high constant and variable amplitude loading for elastic-plastic stress-strain conditions with moderate effort, as described in this paper.

Finally, fracture mechanics concepts, e.g., stress intensity or crack propagation approaches, assume a pre-existing crack-like defect for the life assessment, but will not be in the focus of this work.

2 Materials and welding process

Based on unalloyed structural steels [25] and normalized rolled fine-grained structural steels (N, NL) [26] with yield strengths R_{eH} or $R_{\text{p0.2}}$ of 235 to 460 MPa, the steel designation for high-strength, fine-grained structural steels according to [27] is also based on the minimum yield strength. In a further subdivision, a distinction can be made between high-strength ($R_{\text{p0.2}} \leq 960$ MPa) and ultra-high-strength ($R_{\text{p0.2}} > 960$ MPa) fine-grained structural steels. The yield strength specification is followed in the designation by information on the manufacturing process. A basic distinction is made between water quenched and tempered (Q, QL) [28] and thermomechanically treated (M, TM) [29] steels. In the context of this work, the S960QL (material no.: 1.8933), two thermomechanically rolled products of grade S960M (manufacturer “1” and “2”) and the ultra-high-strength S1100QL (material no.: 1.8942) fine-grained structural steel, suitable for welding, have been investigated. Starting from a conventional hot rolling above the recrystallization temperature of austenite, followed by normalizing annealing in normalized steels, water quenched and tempered steels are rapidly cooled in water, resulting in very good strength properties due to the bainitic and martensitic microstructure [30]. Microstructural transformations by subsequent tempering can, above all, improve their toughness properties. Thermomechanical rolling, i.e., a combined mechanical-thermal rolling process, which is partially carried out below the recrystallization temperature, comprises a large number of process variants (e.g., accelerated cooling), which, together with the alloying concept (microalloy), result in high toughness and strength [30].

The steel materials in this investigation are characterized by the mechanical properties listed in Table 1—yield strength $R_{\text{p0.2}}$, tensile strength R_{m} , elongation at fracture A_5 , and impact energy KV (at three different temperatures). The characteristic values meet the requirements according to [28]:

- Minimum yield strength: $R_{\text{p0.2}} \geq 960$ MPa (S960), $R_{\text{p0.2}} \geq 1100$ MPa (S1100)
- Tensile strength: $980 \leq R_{\text{m}} \leq 1150$ MPa (S960), $1250 \leq R_{\text{m}} \leq 1550$ MPa (S1100)
- Minimum elongation at fracture: $A_5 \geq 10\%$ (S960)
- Notched bar impact energy: KV ≥ 40 J (S960 at -20 °C) and KV ≥ 30 J (S960 at -40 °C)

The specifications for the impact energy are temperature-dependent and correspond to the test carried out by the steel manufacturer.

Butt joints were manufactured, using the 8-mm-thick S960QL, S960M, and S1100QL steel sheets described previously, by gas metal arc welding (GMAW), i.e., metal active gas welding, applying the process parameters given in Table 2, as this is the traditionally and commonly used welding process in the crane industry and related areas. A cooling time $t_{8/5}$ of 5 to 10 s is an essential process requirement. For the ultra-high-strength, fine-grained structural steel S1100QL, the use of filler metal G 89 6 M Mn4Ni2CrMo with a minimum yield strength of $R_{\text{p0.2}} = 890$ MPa results in a welded joint with weld areas of lower strength (undermatching), especially in the heat-affected zone (HAZ). The butt joints were created in a multi-layer weld with one weld root, one backing and one or two top layers. Two overlapping top layers have been chosen for manually welded S960M and S1100QL, while a single top layer is used for manually S960QL welds, in order to compare them with a partially automated joining of the steel sheets. Welds, manufactured by manual GMAW, were executed by qualified welders from the crane industry. In the past, efforts were made to introduce automated welding and laser beam welding (LBW) or a combined LBW-GMAW as a joining process, in order to reduce distortions and increase the strength of joints, i.e., also the fatigue strength. Investigations on the fatigue behavior of these welds are still ongoing.

3 Stress-based fatigue life derived from force-controlled testing

Fatigue tests on butt joints have been performed on resonance and servohydraulic fatigue test rigs under force control at a load ratio of $R_F = 0.1$ [31, 33, 34]. The specimen was designed to have a free length between the clamping areas of 250 mm. Low test frequencies in the range of $0.1 \text{ Hz} \leq f \leq 7.0 \text{ Hz}$ were defined for tests based on the “Testing and Documentation Guideline for the Experimental Determination of Mechanical Properties of Steel Sheets for CAE-Calculations” [35] with a focus on low cycle fatigue. The test frequency was reduced with increasing force amplitude to a minimum of 0.1 Hz and was increased to 35 Hz for fatigue testing in the high cycle

Table 1 Mechanical properties of investigated steel grades [31]

Material	$R_{p0.2}$ (MPa)	R_m (MPa)	A_5 (%)	KV (J)		
				− 20 °C	− 40 °C	− 60 °C
S960QL	1042	1069	11	n.a.	43 ± 8	n.a.
S960M manufacturer 1	1032	1121	12	n.a.	60 ± 5	n.a.
S960M manufacturer 2	993	1041	11	114 ± 24	≥ 30 [32]	36 ± 32
S1100QL	1224	1418	12	41 ± 1	37 ± 1	28 ± 4

fatigue (HCF) regime. “Total rupture of the specimen” was defined as the final failure criterion.

The evaluation of the fatigue test results in the HCF regime, both under constant amplitude loading (Wöhler curve) and variable amplitude loading (Gaßner curve) with a random load time history derived from a Gaussian-like load spectrum [34, 36], has been carried out according to the maximum likelihood estimation (MLE) [37], Fig. 3. Both Wöhler and Gaßner curves for butt-welded S960QL, S960M, and S1100QL fine-grained steels are evaluated for all steel grades together. In Fig. 3, the lines are represented for survival probabilities of $P_S = 10, 50$, and 90% . The Wöhler line is characterized by the slope $k = 3.1$, the nominal stress amplitude $\sigma_{a,n}$ ($N_r = 1 \cdot 10^6, P_S = 50\%$) = 60 MPa, and the scatter $T_\sigma = 1:1.98$ —the Gaßner line is, on the other hand, described by $k = 4.2$, $\sigma_{a,n}$ ($N_r = 1 \cdot 10^6, P_S = 50\%$) = 184 MPa, and $T_\sigma = 1:1.56$. Wöhler and Gaßner lines are in good agreement with those of other evaluation methods shown in [31, 33, 34]. This is due to the fact that the evaluation is limited to the HCF and that there are no differences in applying the method of the least squares and the maximum likelihood method including just one run-out. Differentiation between the various test series (combination of base material and welding process) shows a dependence of the fatigue strength on the weld quality and welding process [31, 33, 34]. It has been found that partially automated welding

results in a reduced misalignment and an increase in fatigue strength. In the LCF regime, force-controlled fatigue testing is sensitive to plasticity and flow, so that small changes in force can have a considerable influence on the fatigue life of the welded joint [19]. This restriction can be counteracted by strain-controlled fatigue testing.

4 Integral treatment and cyclic behavior of butt welds

4.1 Integral treatment of welded joints

The complexity of and effort in the application of local fatigue assessment approaches increases drastically, if the elastic-plastic material model of welded joints is supplemented by a local differentiation of the material behavior and the consideration of transient effects. Therefore, an integral treatment of a butt joint is introduced as a basis for the fatigue life assessment. This integral treatment uses the cyclic material behavior, evaluated from strain-controlled fatigue testing, but characterizes butt welds by the cyclic stress-strain behaviors and strain-life curves with an integral approach from the base material across the weld to the base material (Fig. 4).

4.2 Cyclic behavior of butt welds

A servohydraulic test rig with a maximum load of 100 kN has been used for strain-controlled fatigue tests of the small-scale flat specimens (Fig. 5). Although the greater sheet thickness of 8 mm does not fall within the range of thin sheets, the tests were carried out in accordance with the specifications of SEP1240 [35]. As a result of the strain ratio of $R_\epsilon = -1$, an anti-buckling device is used. Depending on the strain level, the test frequencies were selected as 0.1 Hz ($\epsilon_{a,t} > 0.4\%$), 0.5 Hz ($0.4\% \geq \epsilon_{a,t} > 0.2\%$), and 4.0 Hz ($\epsilon_{a,t} \leq 0.2\%$). From the test results, strain-life curves and cyclic stress-strain curves are derived, which describe the cyclic material behavior (base material) and the cyclic behavior of the butt weld. For this purpose, an extensometer with a 25 mm measuring length was used in the strain-controlled tests. In the case of the butt

Table 2 Main process parameters for GMAW of butt joints made of high-strength, fine-grained structural steels

Process parameter	Specification
Welding procedure	Gas metal arc welding (GMAW)
Materials	S960QL, S960M, S1100QL
Filler metal	G 89 6 M Mn4Ni2CrMo
Preheating temperature	80 °C
Working temperature	80 °C
Cooling time $t_{8/5}$	5 to 10 s
Shielding gas	M21
Number of layers	3–4 (1 root, 1 backing, 1–2 top layers)
Applied voltage/current/welding speed:	
Root layer:	21 V / 145 A / 6 m/min
Backing and top layers:	25–27 V / 185–190 A / 9 m/min

Fig. 3 **a** Fatigue test setup. **b** Load time history. **c** Load spectrum. **d** Fatigue test results

weld, this extensometer contains the entire weld area (weld metal, HAZ, and base metal on both sides).

Two approaches are used to evaluate the strain-life curve: the classical description of the Basquin-Coffin-Manson-Morrow (BCMM) [38–41] strain-life curve and the description by the tri-linear strain-life curve [42]. In the latter description, continuation of the slope of the elastic line from range 2 into 3 ($b_2 = b_3$) is selected, since no results are available for $N > 1 \cdot 10^6$. The comparison of the BCMM strain-life curves with the tri-linear strain-life curves for the S1100QL butt welds (Fig. 6a) shows differences between the two estimation methods—with a more accurate description by the tri-linear strain-life curve and cyclic stress-strain curve derived from

compatibility equations. Therefore, the tri-linear strain-life curve is preferred in describing the strain-life relation and will be used to estimate the fatigue life. There are approx. 1–2 decades in number of cycles to crack initiation between the base material and butt weld. In [19], it has also been demonstrated that a fatigue life reduction has been found for machined specimens compared with the base material state. Thus, it can be seen that the strain-life curves determined on base material specimens cannot be directly transferred to other material states, such as weld seams.

Cyclic stress-strain curves are described according to Ramberg-Osgood [43]. In addition to the direct regression of the test results, cyclic stress-strain curves have been derived

Fig. 4 Schematic presentation of the integral treatment of butt joints and resulting stress-strain states under strain-controlled fatigue testing

from compatibility with the strain-life curve in the form of BCM and the tri-linear strain-life curve. The three descriptions are compared for the S1100QL butt welds in Fig. 6b. The stress-strain curves from the compatibility with the BCM strain-life curves tend to underestimate the results for lower plastic strains ($0.2\% < \epsilon_{a,t} < 0.5\%$) and to overestimate the results for large plastic strains ($\epsilon_{a,t} > 0.6\%$). In contrast, the direct regression and the cyclic stress-strain curve describe the tri-linear strain-life curve more accurately. This also applies in a similar way for the curves of the other base materials. All evaluated cyclic stress-strain curves are based on the results for the cyclically stabilized state and thus do not reflect any transient effects. Cyclic material parameters of the investigated high-strength, fine-grained steels and butt-welded joints have been documented and analyzed in more detail in [2, 19].

4.3 Cyclic transient behavior

A first impression regarding transient effects is given by a comparison of the initial loading with the cyclic stabilized

state and, especially the cyclic stress-strain curve. Distinctive cyclic softening from initial loading to cyclic stabilization can be observed for high-strength steel base materials as well as butt joints (cf. Fig. 4 (right)). However, deeper insight into the cyclic transient behavior is gained from changes in the hysteresis loops from cycle to cycle. The transient behavior is shown more clearly in the evolution of the cyclic yield strength $R'_{p0.2}$ or the cyclic hardening coefficient K' and the cyclic hardening exponent n' . An overview is provided by the representation of K' and n' in relation to the normalized number of cycles to crack initiation N/N_i for S960QL in Fig. 7, from which a drop in the cyclic hardening coefficient K' can be derived as a result of softening and crack initiation. The cyclic hardening exponent n' also shows a decreasing trend, although for S960QL steel and butt welds, it remains almost constant with increasing N/N_i , apart from a few minor changes. For both cyclic parameters, a linearization is performed for continuous evolution, so that (linear) functional relations for $K' = f(N/N_i)$ and $n' = f(N/N_i)$ are found. Due to the change in the characteristic values resulting from cyclic softening and crack initiation, the

Fig. 5 Strain-controlled fatigue testing and investigated flat specimen geometries

Fig. 6 Comparison of the BCMM evaluation and tri-linear approach of S1100QL butt welds for **a** strain-life curves and **b** cyclic stress-strain curves

normalized number of cycles from strain-controlled fatigue tests can be directly interpreted as total damage, so that $D = N/N_i$ follows. This definition results in the linearized descriptions for K' and n' depending on the damage according to Eqs. 1 and 2, where the index “0” denotes the initial state. More complex, non-linear relationships are also conceivable, but for the following investigation, this approximation is sufficient for the description of the cyclic transient behavior.

$$K'_j(D_j) = \Delta K' \cdot D_j + K'_0 \quad (1)$$

$$n'_j(D_j) = \Delta n' \cdot D_j + n'_0 \quad (2)$$

5 Fatigue life estimation approach

For the fatigue life estimation from the low cycle to the high cycle fatigue regime, a strain-based approach, using damage parameters to assess simulated stress-strain paths, is used. The approach is based on the integral treatment of the butt weld already examined and its characterization by the cyclic (transient) behavior (Fig. 8). This approach includes the following steps:

Fig. 7 Description of the cyclic transient behavior by (linear) functional relations between Ramberg-Osgood parameters and total damage for **a** the cyclic hardening coefficient K' and **b** the cyclic hardening exponent n'

1. The starting points of the evaluation are the butt-welded specimens described before, which provide “integral characteristic values of the cyclic behavior of transverse loaded butt joints” as a result of strain-controlled fatigue tests. For the initial loading, stress-strain curves based on the initial parameters K'_0 and n'_0 are applied. Likewise, additional stresses (and strains) resulting from an angular misalignment are applied in the first load step.
2. In the second step, the cyclic transient behavior of these “integral weld seams” is directly used in the analytical simulation of stress-strain paths, considering memory and Masing behavior without explicitly determining a fictitious notch stress or strain. Hysteresis loops are related to the load history. Different loading histories therefore need to be simulated computationally with this procedure. According to the force-controlled tests of the butt welds with $R_F = 0$, constant and variable amplitude loading is simulated in order to verify this method. The application of this method allows the inclusion of transient effects, such as cyclic softening, in the fatigue assessment with moderate effort. Based on the description of the cyclic transient behavior, the first load with stress relief is calculated using K'_0 and n'_0 from the initial Ramberg-Osgood

resulting hysteresis loops are in good agreement. Smaller differences occur at the minimum stress under compression, where cyclic creep might have an influence on the turning point. However, fatigue lives have been calculated by application of introduced damage parameters. Except for a short calculated fatigue life using $P_{HL,mod}$, small variations can be found for most of the damage parameters and in comparison with the experimentally determined value, in this specific example. In any case, the previously defined P_m seems to be a good choice. In other loading situations, advantages and disadvantages become clearer, as can be seen from [2].

This procedure offers the advantage of a simplified fatigue life estimation, based on consideration of elastic-plastic stresses. Using this approach, a detailed and complex finite element simulation for the assessment of notch stresses or strains, which should additionally take transient effects into account, is avoided.

6 Fatigue life estimation

6.1 Constant amplitude loading (CAL)

According to the procedure described before, a fatigue life estimation under constant amplitude loading for the integral treatment of butt welds considering the cyclic transient behavior using damage parameters as defined in Eqs. 3 to 7 has been performed, where P_m is the introduced generalized damage parameter including mean stresses and mean strains. The

results, applying the damage parameter P_m , are presented in Fig. 10, since P_m can be adjusted to the LCF regime (mean strains) and HCF regime (mean stresses) by choice of the corresponding factors in addition to the consideration of stress and strain amplitudes. In the nominal stress system, fatigue lives estimated with the help of P_m are compared with experimentally derived cycles to failure and fatigue classes FAT 50/71 (dot-dash-lines corresponding to a survival probability of $P_S = 97.7\%$) derived for the different test series, which are characterized by the combination of base material and welding process execution. Figure 10a shows that the estimation results in too long fatigue lives for S960QL butt welds (green triangles), where specimens include a comparably high angular misalignment of $\alpha = 3.9^\circ$ on average, if this angular misalignment is not taken into account in the fatigue life simulation (gray curve for $P_S = 50\%$). Including an average angular misalignment $\alpha = 3.9^\circ$ in the estimation procedure, it can be seen, from the course of the estimated fatigue life curve (cf. black curve) corresponding to a survival probability of $P_S = 50\%$, that the accuracy of the fatigue life estimation is increased. Therefore, calculated fatigue lives of the other test series in Fig. 10b, c, and d already include the angular misalignment (black curves for $P_S = 50\%$). It can be seen that the estimated fatigue lives coincide very well with the load-controlled experimental results for S960QL (Fig. 10a) and S1100QL (Fig. 10b), while more conservative fatigue lives are found for S960M (supplier 2, Fig. 10d). S960M (supplier 1) shows a good agreement at higher load levels and tends to be non-conservative at lower load amplitudes (Fig. 10c).

Fig. 9 Comparison between experimentally derived and simulated stress-strain paths for a constant amplitude stress-controlled loading situation with $R_F = -1$ as well as estimated fatigue lives depending on the choice of damage parameter

Fig. 10 Fatigue life estimation under constant amplitude loading applying the damage parameter P_m compared with fatigue classes (FAT) based on the cyclic transient behavior of the butt-welded steels **a** S960QL, **b** S1100QL, **c** S960M (supplier 1) and **d** S960M (supplier 2)

6.2 Variable amplitude loading (VAL)

Under variable amplitude loading, the simulated stress-strain path is more complex than the one for constant amplitude loading. Again, the fatigue life estimation is carried out for the integral treatment of butt welds with the described procedure considering cyclic transient behavior. Due to the intersection of the black curves for $P_S = 50\%$ with the green symbols, Fig. 11a, b, and c show that the highest stress amplitudes of load-controlled tests have been assessed by the approach applying the damage parameter P_m . For manually welded butt joints made of S960M (supplier 1, cf. Fig. 11c), there is a very good agreement between estimated and experimentally determined fatigue lives under variable amplitude loading. In the other cases, S960QL (Fig. 11a), S1100QL (Fig. 11b), and S960M (supplier 2, Fig. 11d), there is a tendency to be more conservative, when the stress amplitude decreases. Compared with the linear damage accumulation for $P_S = 50\%$ (here: using the allowable damage sum acc. to [5] of $D_{all} = 0.5$), this approach is not based on Wöhler (SN) lines derived under constant amplitude loading and is therefore independent of the slope of the Wöhler line in the HCF regime. As can be seen from Fig. 11, the transition from low cycle to high cycle fatigue is represented in a good way using this method, so that the calculated Gaßner (or Wöhler) curve is not purely linear (in double-logarithmic scale). However, in the HCF regime, the approximation of a straight line for the Gaßner curve becomes obvious and is

reasonable. At lower load levels, the estimation from the integral treatment of butt joints shows a good agreement for S960QL (cf. Fig. 11a) and S960M (supplier 1, cf. Fig. 11c), while the linear damage accumulation is closer to the experimental data for S1100QL (Fig. 11b) and S960M (supplier 2, Fig. 11d).

7 Discussion of the fatigue life estimation

Estimated (calculated) fatigue lives N_{calc} for the integral treatment of butt welds, considering the cyclic transient behavior using damage parameter P_m , are directly compared with experimentally derived fatigue lives N_{exp} for both constant and variable amplitude loading. Resulting data in the range of 1:4 from the optimum $N_{calc} = N_{exp}$ (factor of 4) show a good agreement within the overall scatter of welded joints. In the case where N_{calc} is larger by more than a factor of 4 compared with N_{exp} , the estimation is on the unsafe side, while it is defined to be too safe, if $N_{calc} = 0.25 \cdot N_{exp}$.

In Fig. 12, the direct comparison between calculated and experimentally determined fatigue lives for constant amplitude loading, applying the damage parameter P_m , confirms the good agreement which Fig. 10 indicates, if the angular distortion is taken into account—apart from the still very conservative estimate for the S960M (supplier 2). It can be seen that most results for S960QL (cf. Fig. 10a), S1100QL (cf.

Fig. 11 Fatigue life estimation under variable amplitude loading using the damage parameter P_m compared with the linear damage accumulation with $D_{all} = 0.5$ based on the cyclic transient behavior of the butt-welded steels **a** S960QL, **b** S1100QL, **c** S960M (supplier 1) and **d** S960M (supplier 2)

Fig. 10b), and S960M (supplier 1, Fig. 10c) are in the 1:4 range. In addition to the results of S960M (supplier 2), some of the other results at lower load amplitudes tend to be too safe. However, test results at low load levels are rare, since the focus of this investigation is set on the regime from LCF to higher load levels of the HCF. Therefore, the significance of the fatigue life estimation for very low load levels is limited, based on the results of this investigation. On the other hand, a

very good agreement between estimated and experimentally derived fatigue lives at high load levels is found, at least for S960QL, S1100QL, and S960M (supplier 1) butt welds.

Figure 13 shows the comparison between calculated and experimentally determined fatigue lives for variable amplitude loading, applying the damage parameter P_m , again taking the angular distortion into account. For VAL, the estimation is less accurate than for CAL and leads to some results on the

Fig. 12 Comparison between calculated and experimentally determined fatigue lives for constant amplitude loading applying the damage parameter P_m

Fig. 13 Comparison between calculated and experimentally determined fatigue lives for variable amplitude loading applying the damage parameter P_m

unsafe side—at least in a few cases of high loads for S1100QL and one result for S960M (supplier 1). For many results in the LCF regime, when elastic-plastic behavior and mean strains come into play, but also at low stress amplitudes of the HCF regime, where linear-elastic behavior can be assumed, the experimentally determined fatigue lives exceed the calculated ones, which gives a conservative estimation beyond the factor of 4. However, again, the same applies as for low load levels from constant amplitude loading: the significance of the estimation is low due to few test results in this regime.

Based on the integral treatment of butt welds, the cyclic behavior of the seam weld is determined and successfully used for a fatigue life estimation of corresponding joints under CAL and VAL. The estimation for CAL is in good agreement with the experiment showing some results that are too safe, while the VAL estimation tends to be very conservative, but still having some unsafe results. In both cases, consideration of the transient behavior for the fatigue life estimation is beneficial, especially at high load levels at the border to the LCF regime. The conservative estimations in the LCF regime using this method is still superior compared with the linear damage accumulation, which just gives a constant slope of the calculated Gaßner line depending on the slope of the Wöhler curve. A limitation in the LCF regime can then just be constituted by knowledge about the yield or tensile strength of the joint. Therefore, further work on this approach is expedient, in order to improve the fatigue life estimation in the regime from HCF to LCF.

8 Conclusions

A method for fatigue life estimation based on an integral treatment of transversely loaded butt joints has been introduced. The following conclusions can be drawn from this investigation and the developed fatigue life estimation using an integral treatment of welds:

- (a) A description of the substructure from base material to base material by its cyclic behavior (integral treatment) is the basis. The characterization by an accumulated set of parameters results in a unification and simplification, compared with locally detailed modeling of the weld. As might be seen from the hardness distribution of a section cut from the weld seam, huge variations in micro-hardness from one measurement point to another exist (cf. [2, 51, 52]). By implementation of a distribution of local characterization parameters in local fatigue concepts by FE modeling and simulation, calculation time increases drastically.
- (b) For the assessment from the low cycle to the high cycle fatigue regime, the cyclic elastic-plastic behavior was considered. The cyclic transient behavior shows a distinctive cyclic softening of the base materials and butt

welds, which is described by a damage-dependent definition of the cyclic characteristic values K' and n' of the Ramberg-Osgood equation. This is the main proposal to describe transient effects within this approach. Other transient effects, mean stress relaxation and cyclic creep, were not explicitly considered. In particular, cyclic creep requires further strain-rate-dependent investigations.

- (c) Additional influences on the fatigue performance result from global geometrical factors, such as axial and angular misalignments. Axial misalignments are small and can be neglected. The angular distortion depends on the execution of the weld with respect to the boundary conditions. Furthermore, the heat input of the welding process influences the angular misalignment or residual stresses for fixed connections to the entire structure. While LBW creates a smaller angular misalignment, the increased heat input of GMAW induces a larger distortion. Therefore, the angular misalignment is considered with the help of additional stresses (and strains), which improves the fatigue life estimation.
- (d) The choice of damage parameter— P_{SWT} , P_ε , $P_{HL,mod}$, P_J , and P_{RAJ} were evaluated—influences the fatigue life estimation. Finally, a generalized damage parameter P_m (combination of P_B and P_ε) has been introduced, which can be adjusted to the regime, where damage is dominated by mean stresses (HCF) or mean strains (LCF) in addition to stress and strain amplitudes. This has been achieved by additional factors for the mean stress and mean strain in the mathematical formulation.
- (e) The application of the integral life estimation method has been illustrated by lifetime estimations for constant and variable amplitude loading. It has been found that the estimation is in good agreement with experimental stress-controlled results under constant amplitude loading, while the estimated life under variable amplitude loading tends to be on the safe side for lower loading situations. In general, the (double-logarithmic) non-linear transition from LCF to HCF can be estimated with this method.

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