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RESEARCH PAPER

Evaluation of the approach based on the maximum principal stress from the IIW-Recommendation for welded joints under proportional, multiaxial stress states

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Abstract
The IIW-Recommendation for fatigue design of welded joints and components presents two different evaluation approaches for multiaxial stress states under constant amplitude: an approach based on the maximum principal stress, which is only applicable under certain conditions, and the Gough-Pollard approach for the remaining cases. In the course of this work, this maximum principal stress-based approach is analyzed. It is examined in which cases the method is applicable, the advantages and disadvantages compared to the approach according to Gough-Pollard are discussed, and an evaluation according to the von Mises equivalent stress is presented as a third alternative. This is followed by a validation based on literature data on laser-welded steel joints using the nominal stress, hot spot stress, and effective notch stress concept.

Keywords Multiaxial fatigue · IIW-Recommendation · Welded structures · Steel · Fatigue criteria · Validation

Abbreviations

$\Delta\sigma_{\perp}$	Stress range perpendicular to the weld, MPa
$\Delta\sigma_{\parallel}$	Stress range parallel to the weld, MPa
$\Delta\tau$	Shear stress range, MPa
$\Delta\sigma_R$	Range of the normal stress resistance, MPa
$\Delta\tau_R$	Range of the shear stress resistance, MPa
N	Number of cycles, -
CV	Comparison value, -
FAT_{σ}	FAT-class for normal stress, MPa
FAT_{τ}	FAT-class for shear stress, MPa
k_{σ}	Slope of the normal stress S-N curve, -
k_{τ}	Slope of the shear stress S-N curve, -
$\Delta\sigma_{max.\,P.}$	Maximum principal stress range, MPa
σ_{I}	Maximum principal stress, MPa
σ_{II}	Minimum principal stress, MPa
$\Delta\sigma_{vM}$	Von Mises equivalent stress range, MPa
N_{exp}	Experimentally determined number of cycles, -
N_{calc}	Calculated number of cycles, -
α	Angle between the direction normal to the weld and the direction of the maximum principal stress, °
t	Plate thickness, mm
σ_{hs}	Hot spot stress, MPa

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1 Introduction

Multiaxial stresses may lead to a significant reduction in fatigue life. This can be considered in the design of such components by the application of multiaxial fatigue methods. In the IIW-Recommendation [1], the Gough-Pollard approach [2] is recommended for the evaluation of multiaxial stress states. In addition, a “simplified approach” based on the max. principal stress is presented for application with constant amplitudes and proportional loading.

There is currently no publication that validates the reliability of this maximum principal stress-based approach and compares it with the Gough-Pollard approach. Therefore, the aim of this work is to validate the maximum principal stress-based approach for the evaluation of proportional, multiaxial stresses with constant amplitudes, which is given in the IIW-Recommendation as an easily applicable alternative to the Gough-Pollard criterion. It is investigated for which applications (specimen type and assessment concept) this approach is suitable. Additional suggestions for further improvements are presented.

2 Theoretical background

2.1 Maximum principal stress-based approach

Out of many approaches described in the literature for the evaluation of multiaxial stresses, two are mentioned in the IIW-Recommendation [1]. For the case of multiaxial, constant amplitude loading, a simplified fatigue assessment using the maximum principal stress is recommended in section 4.3 of the IIW-Recommendation, on the condition that the direction of the maximum principal stress must be within ±60° of the direction perpendicular to the weld (Fig. 1).

The condition can also be described mathematically as a function of the stress components; see Eq. (1):

$$\left|\frac{1}{2}\tan^{-1}\left(\frac{2\tau}{\sigma_\perp - \sigma_\parallel}\right)\right| \leq 60^\circ \tag{1}$$

However, the equation given there is not the conventional formula for determining the maximum principal stress

$$\Delta\sigma_{\max.P.} = \frac{1}{2}\left(\Delta\sigma_\perp + \Delta\sigma_\parallel + \sqrt{\Delta\sigma_\perp^2 + 2\Delta\sigma_\perp\Delta\sigma_\parallel + \Delta\sigma_\parallel^2 + 4\Delta\tau^2}\right) \tag{2}$$

but a simplification in which the parallel stress component has been neglected:

$$\Delta\sigma_{simp} = \frac{1}{2}\left(\sigma_\perp + \sqrt{\Delta\sigma_\perp^2 + 4\Delta\tau^2}\right). \tag{3}$$

While section 4.2 of the IIW-Recommendations does not state the validity of the approach for only one particular stress concept and therefore seems to imply that it is valid for all, section 2.2.4.2 (Calculation of effective notch stress) of the IIW-Recommendations explicitly recommends evaluation by maximum principal stress for the case of multiaxial proportional loading without mentioning Eq. (3) or referring to Section 4.3. Furthermore, in contrast to chapter 4.2, the condition that the maximum and minimum principal stresses must have the same sign is stated, while no mention of the condition described in Eq. (1) is given. This second condition can be described mathematically according to Eq. (4):

$$\Delta\sigma_{simp} = \frac{1}{2}\left(\sigma_\perp + \sqrt{\Delta\sigma_\perp^2 + 4\Delta\tau^2}\right). \tag{4}$$

with

$$\Delta\sigma_{simp} = \frac{1}{2}\left(\sigma_\perp + \sqrt{\Delta\sigma_\perp^2 + 4\Delta\tau^2}\right). \tag{5}$$

A graphical interpretation of this second condition is that Mohr's circle must not intersect the shear stress axis, as shown in Fig. 2.

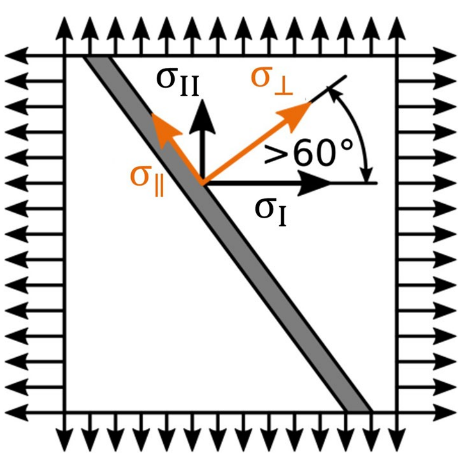

Fig. 1 Graphical representation of the condition for the application of the maximum principal stress-based approach in section 4.3 of the IIW-Recommendation

2.2 Gough-Pollard approach

For the general case of multiaxial loads with constant or variable amplitudes, the fatigue assessment by means of the Gough-Pollard criterion [2] is recommended. In this approach, the sums of the squared stress ratios for pure normal stress and pure shear stress are considered as the failure-relevant quantity, which must not exceed a comparison value CV:

$$\left(\frac{\Delta\sigma_\perp}{\Delta\sigma_R(N)}\right)^2 + \left(\frac{\Delta\tau}{\Delta\tau_R(N)}\right)^2 \leq CV \tag{6}$$

$\Delta\sigma_\perp$ and $\Delta\tau$ describe the amplitude of the stress due to normal and shear stress, respectively, in the coordinate system of the weld. In case of variable amplitudes, a damage equivalent stress needs to be calculated beforehand in order to transform the spectrum stresses in constant amplitude loading. $\Delta\sigma_R$ and $\Delta\tau_R$ are the fatigue strengths under pure normal or pure shear stress for a given number of cycles N. In the case of proportional stress, the comparison value CV = 1. If non-proportional stresses and thus rotating principal stress directions are present, which typically leads to a reduction of the fatigue life, this is taken into account by reducing the comparison value to CV = 0.5 [1, 3].

A proof of the fatigue strength for a specified fatigue life with given stresses can be implemented comparatively easily with the Gough-Pollard criterion. In this case, the bearable stresses for the given fatigue life are determined from the FAT classes and used in Eq. (1) along with the acting stresses. If the number of cycles N is to be determined for

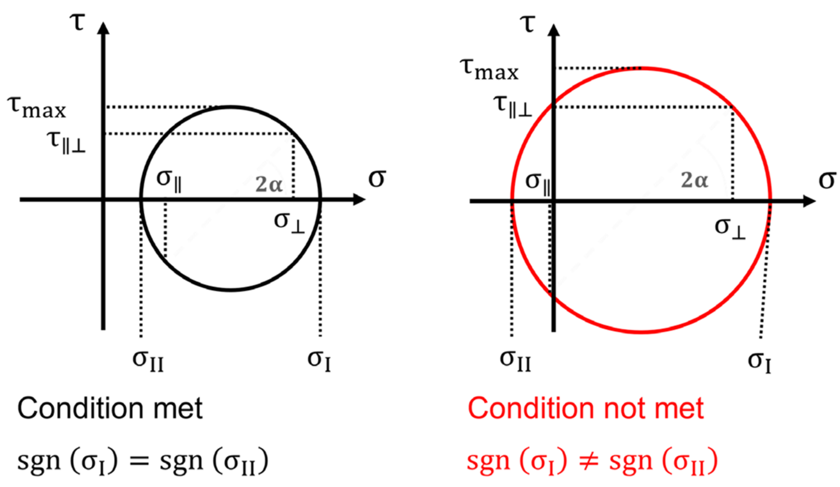

Fig. 2 A graphical representation of the condition for the application of the maximum principal stress-based approach in section 2.2.4.2 of the IIW-Recommendation

given stresses, the procedure is more complex. In the first step, the fatigue strengths for normal stress (FAT_σ) and shear stress (FAT_τ) are determined by means of the Basquin equation [4] from the FAT classes and the associated slopes of the Wöhler lines k_σ and k_τ:

$$\Delta\sigma_R = FAT_\sigma \cdot \left(\frac{2\cdot 10^6}{N}\right)^{\frac{1}{k_\sigma}}. \tag{7}$$

Substituting in Eq. (5) gives the following expression:

$$\left(\frac{\Delta\sigma_\perp}{FAT_\sigma \cdot \left(\frac{2\cdot10^6}{N}\right)^{\frac{1}{k_\sigma}}}\right)^2 + \left(\frac{\Delta\tau}{FAT_\tau \cdot \left(\frac{2\cdot10^6}{N}\right)^{\frac{1}{k_\tau}}}\right)^2 \le CV. \tag{8}$$

At the point of failure, the above inequation must be satisfied with equality. Simple transformation gives the following expression:

$$\left(\frac{\Delta\sigma_\perp}{FAT_\sigma\left(\frac{2\cdot10^6}{N}\right)^{\frac{1}{k_\sigma}}}\right)^2 + \left(\frac{\Delta\tau}{FAT_\tau\left(\frac{2\cdot10^6}{N}\right)^{\frac{1}{k_\tau}}}\right)^2 - CV = 0 \tag{9}$$

At this point, the number of cycles N is determined for which the equation is satisfied. Solving the equation with respect to N leads to the expression

$$\Delta\sigma_\perp{}^2 FAT_\tau^2 + \Delta\tau^2 FAT_\sigma^2 N^{*\frac{1}{k_\sigma}-\frac{1}{k_\tau}} - CV \cdot FAT_\tau^2 FAT_\sigma^2 N^{*\frac{1}{k_\sigma}} = 0 \tag{10}$$

with $N^* = \left(\frac{2\cdot10^6}{N}\right)^2$.

As N^* is the only unknown, Eq. (5) can be understood as a polynomial function whose exponents depend on the slopes of the Wöhler lines k_σ and k_τ. In accordance with the IIW-Recommendations, it can be assumed in the majority of cases that $k_\sigma = 3$ and $k_\tau = 5$. To keep all exponents integer, $N^{*\frac{1}{15}}$ can be further substituted by N^{**} resulting in a polynomial function of degree 5 depending on N^{**}:

$$CV \cdot FAT_\tau^2 FAT_\sigma^2 N^{**5} - \Delta\tau^2 FAT_\sigma^2 N^{**2} - \Delta\sigma_\perp{}^2 FAT_\tau^2 = 0 \tag{11}$$

where

$$N^{**} = \left(\left(\frac{2\cdot10^6}{N}\right)^2\right)^{\frac{1}{15}} \tag{12}$$

Solving a polynomial function of degree 5 requires an initial guess of the first solution so that a closed solution cannot be derived. Hence, an alternative iterative approach needs to be used. By an iterative process in the form of optimization, the inequation can be solved. Even though this is not difficult to implement, it might lead to difficulties in the engineering practice.

2.3 Using von Mises stress hypothesis as a multiaxial criterion

It is known that the von Mises criterion may lead to unreliable results if certain conditions are not met. First, von Mises stresses are by definition positive. Therefore, a signed von Mises stresses needs to be evaluated to evaluated meaningful stress amplitudes. Second, for ductile materials, a von Mises criterion cannot be used to assess non-proportional loading, such as constant amplitudes with phase shift [5]. If both conditions are met, the von Mises stress is a reliable approach to assess the fatigue life of multi-axial, proportionally loaded welded joints [6]. The endurable local von Mises stresses are similar between pure shear stresses and stresses normal to the weld.

In the upcoming version of Eurocode 3, reference is also be made to the von Mises equivalent stress for a fatigue assessment of multiaxially loaded welds [7] if the effective notch stress approach with a reference radius of $r_{ref} = 1$ mm is used: Eq. (7):

$$\Delta\sigma_{vM} = \sqrt{\Delta\sigma_{\perp}^{2} + \Delta\sigma_{\parallel}^{2} - \Delta\sigma_{\perp}\Delta\sigma_{\parallel} + 3\Delta\tau^{2}}. \quad (13)$$

In this case, a class FAT 200 is recommended for use.

3 Fields of application of the maximum principal stress-based approach

As described in the previous section, the IIW-Recommendation refers in two places to an assessment of multiaxially loaded welds by means of the maximum principal normal stress. However, two separate conditions for the use of this approach are given. This leads to the following questions:

For which stress concept is the approach valid? The IIW-Recommendation does not specify in section 4.3 for which stress concept the approach is valid. Considering the maximum principal stress-based approach is based on studies on passenger ship door opening structures, where a fatigue strength assessment using the maximum principal stress was investigated using the hot-spot stress concept [8], it is safe to assume that the approach is intended for this concept. An indication for the applicability to the notch stress concept is provided by the fact that in section 2.2.4.2, which deals with the determination of the notch stress, reference is made to an evaluation by means of maximum principal stress. No indications are given regarding the admissibility of the nominal stress approach. To settle this question, investigations carried out in the course of this work focus on all three stress concepts.

Which conditions have to be considered? To clarify this question, both conditions were examined for all cases in the course of this work. However, the condition of the same sign of the maximum and minimum main stress is problematic for the nominal stress concept, as shown by the following example. Consider the specimen from [9] as an example of a typical tube-flange connection under combined bending and torsion. According to the superposition principle, the loads due to bending and torsion may be considered separately. For the given example, the torsion load results in a pure shear stress state, i.e., $\sigma_I = -\sigma_{II}$. In the nominal stress concept, the pure bending load leads to a uniaxial stress state normal to the weld; thus, $\sigma_{II} = 0$. The combination of both load cases for therefore in all cases results in a negative minimum principal stress; the condition is therefore not fulfilled. In contrast, when considering notch stresses, a stress perpendicular to the weld is accompanied by a parallel stress component due to the transverse contraction restraint in the notch at the weld transition or the weld root, resulting in a positive minimum principal stress. This leads to the situation that the condition for the notch stress concept may well be fulfilled depending on the ratio of the individual load components to each other, whereas this is never fulfilled for the nominal stress concept; see Fig. 3.

This problem occurs for all tube-flange connections investigated. To investigate the extent to which this condition is relevant when considering the nominal stress concept, those test series which do not fulfill the condition for this stress concept were also considered in the subsequent validation.

Should the maximum principal stress be used, or the simplified form? Since the simplified formulation is explicitly stated in the guideline and referred to as the maximum principal stress, it was assumed that this form should be used. However, the question arises as to what advantage the simplification provides, since the parallel stress component is needed to check both conditions.

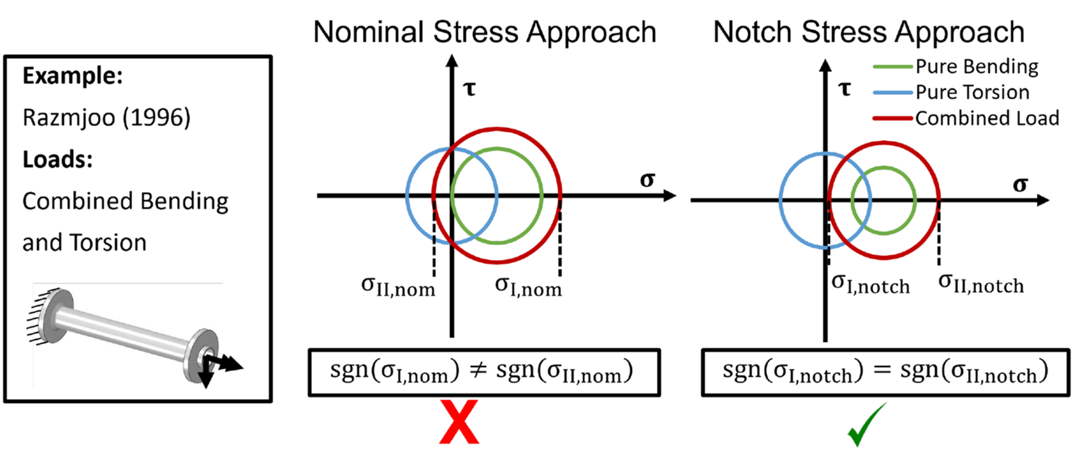

Fig. 3 Example of a load case of combined bending and torsion for a tube-flange specimen from [9], where the 2nd condition is met for the notch stress concept, but not for the nominal stress concept

4 Investigated test results

Test data on welded specimens under proportional, multiaxial loading from the literature were used for the validation. The test data collected in the publication by Pedersen [10] on welded specimens subjected to multiaxial loading served as the basis. In addition, test results on flat specimens with different inclined seams from [11] were taken into account; see Table 1 and Fig 4.

FE models were created for the respective specimen geometries. The local notch stresses were determined for a modelled notch radius of 1 mm. The hot spot stress was determined on the same models according to the approach "a" of the IIW-Recommendation as a function of the plate thickness *t*.

$$\sigma_{hs} = 1.67 \bullet \sigma_{0.4 \bullet t} - 0.67 \bullet \sigma_{1.0 \bullet t} \quad (14)$$

The nominal stresses were determined analytically. Since the stress ratio *R* and the residual stress state vary in the different test series, the fatigue enhancement factor *f*(*R*) given in the IIW-Recommendation was used. For all test series where no data on the residual stress state was given, high residual stresses were assumed in accordance with the IIW-Recommendation to ensure a conservative estimation. No or only low residual stresses were assumed for the test series with stress-relieved specimen. An overview of the specimen types studied and their validity for the maximum principal stress-based approach are shown in Table 2.

Since the test series from [5], [18], and [19], as well as the LaserMultiAx specimen with a weld orientation longitudinal weld, do not meet the conditions for both the nominal and notch stress concepts, they were not considered further for later validation. The remaining test series consist of a total of 118 tests.

5 Validation of the maximum principal stress-based approach

In the course of the validation, the fatigue life for the tests from the literature was calculated on the basis of the previously determined nominal and notch stresses. These were then compared with the experimentally determined number of cycles to derive a conclusion about the quality of the approach and the conservativity. An overview of the FAT classes used for the evaluation of the individual test series is given in Table 3. The IIW Guideline does not specify whether the FAT class for normal or shear stress is to be used for assessment by the maximum principal stress-based approach. Since the maximum principal stress is a normal stress, it was assumed that this is to be used. The assessment by means of von Mises is also carried out using the FAT classes for normal stress. In the case of the notch stress concept, a FAT 200 was used instead of a FAT 225 to evaluate the von Mises equivalent stress, following the recommendation of [20].

In addition to the maximum principal stress-based approach, the Gough-Pollard approach and an evaluation based on the von Mises equivalent stress were examined. The results of the tests are shown in Fig. 5 in which the experimental fatigue life is plotted against the calculated fatigue life.

Table 1 Overview of the specimen types investigated

Primary author / year / source	Specimen type	R	Loading Primary	Loading Secondary	t (mm)
Sonsino / 2001 / [12]	Tube-Flange	-1	Bending	Torsion	10
Amstutz / 2011 / [13]	Tube-Flange	0	Bending	Torsion	10
Witt / 1997 / [14]	Tube-Flange	-1	Bending	Torsion	8
Yousefi / 2001 / [15]	Tube-Flange	-1	Bending	Torsion	8
Bäckström / 1997 / [8]	Tube-Flange	varies	Bending	Torsion	5
Razmjoo / 1996 / [9]	Tube-Flange	0	Tension	Torsion	3.2
Yung / 1989 / [16]	Tube-Flange	-1	Bending	Torsion	8
Khurshid / 2016 / [17]	Flat specimen - 45° Weld	0.1	Tension	-	10,5
Sonsino / 1995 / [5]	Tube-Tube	-1	Bending	Torsion	6
Archer / 1987 / [18]	Hollow section with gusset	$R\sigma = 0$ $R\tau = -1$	Bending	Shear	6
Dahle / 1997 / [11]	Box beam	-1	Bending	Torsion	10
LaserMultiAx / [11]	Flat specimen - 0° Weld	0	Tension	-	4
LaserMultiAx / [11]	Flat specimen - 22.5° Weld	0	Tension	-	4
LaserMultiAx / [11]	Flat specimen - 45° Weld	0	Tension	-	4
LaserMultiAx / [11]	Flat specimen - 60° Weld	0	Tension	-	4
LaserMultiAx / [11]	Flat specimen - 90° Weld	0	Tension	-	4

Table 2 Validity of the maximum principal stress-based approach for the investigated test series

Primary author / year	Meets conditions for simplified method?					
	Nominal stress		Hot-spot stress		Notch stress	
	±60°	Signs identical	±60°	Signs identical	±60°	Signs identical
Sonsino / 2001	Yes	No	Yes	No	Yes	Yes
Amstutz / 2011	Yes	No	Yes	No	Yes	Yes
Witt / 1997	Yes	No	Yes	No	Yes	Yes
Yousefi / 2001	Yes	No	Yes	No	Yes	Yes
Bäckström / 1997	Yes	No	Yes	No	Yes	Yes
Razmjoo / 1996	Yes	No	Yes	No	Yes	Yes
Yung / 1989	Yes	No	-	-	Yes	Yes
Khurshid / 2016	Yes	Yes	-	-	Yes	Yes
Sonsino / 1995	Yes	No	Yes	No	No	No
Archer / 1987	Yes	No	Yes	No	No	No
Dahle / 1997	Yes	No	-	-	No	No
LaserMultiAx - 0°	Yes	No	Yes	No	Yes	No
LaserMultiAx - 22.5°	Yes	Yes	Yes	Yes	Yes	Yes
LaserMultiAx - 45°	Yes	No	Yes	No	Yes	No
LaserMultiAx - 60°	Yes	Yes	Yes	Yes	No	Yes
LaserMultiAx - 90°	No	No	No	No	No	Yes

When considering the maximum principal stress-based approach, generally conservative results are obtained for the nominal stress concept. For less than 3% of the investigated specimens, the calculated number of cycles N_{cal} is higher than the experimentally determined number of cycles N_{exp} . These are specimens of the test series from [13] and [17]. For the hot spot stress concept, slightly more than 3% of the results are non-conservative. Also affected here are test results from [13] as well as a single one of the LaserMultiAx test series with a weld orientation angle of 60°.

For the notch stress concept, on the other hand, the fatigue strength evaluation leads to non-conservative results for about 20% of the investigated specimens. These are mainly the tests from [13], [17], and [16], as well as individual tests from [14], [15], and [21].

Considering the approach according to Gough-Pollard, a conservative estimation of the results is also observed for the nominal stress concept. In this case, a non-conservative estimation occurs only for a single specimen (<1 %) of [17]. For the evaluation according to the hot spot stress concept, slightly over 10% of the specimen

Table 3 An overview of the FAT classes that were used for the fatigue assessment according to the three approaches investigated

Primary author / year	FAT					
	nominal stress		Hot-spot stress		Notch stress*	
	σ	τ	σ	τ	σ	τ
Sonsino / 2001	71	80	100	80	225	160
Amstutz / 2011	71	80	100	80	225	160
Witt / 1997	71	80	100	80	225	160
Yousefi / 2001	71	80	100	80	225	160
Bäckström / 1997	71	80	100	80	225	160
Razmjoo / 1996	80	80	100	80	225	160
Yung / 1989	80	80	-	-	225	160
Khurshid - 45° / 2016	36	80	-	-	225	160
LaserMultiAx - 0°	80	100	100	100	225	160
LaserMultiAx - 22.5°	80	100	100	100	225	160
LaserMultiAx - 45°	80	100	100	100	225	160
LaserMultiAx - 60°	80	100	100	100	225	160
LaserMultiAx - 90°	80	100	100	100	225	160

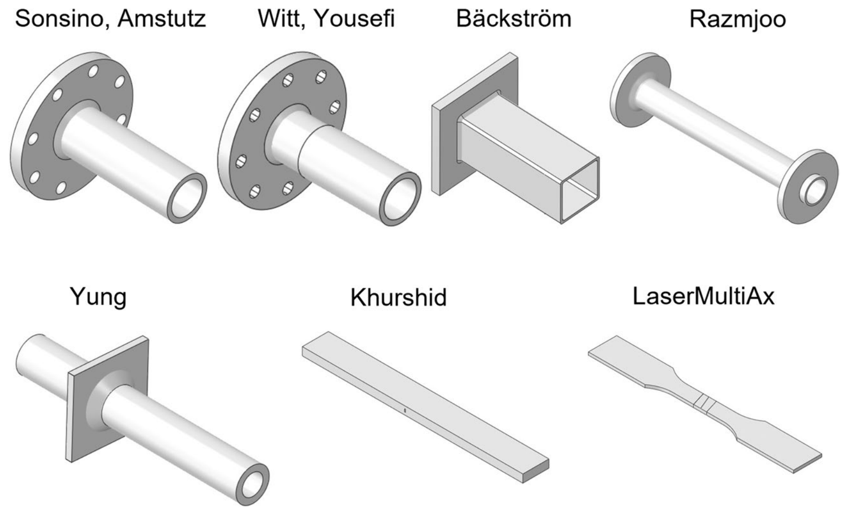

Fig. 4 Geometry of the investigated specimens

yield non-conservative results. Of those, 9 are part of the LaserMultiAx test series with a weld orientation angle of 60°, one of the test series with a weld orientation angle of 22.5°, and one belongs to [9]. For the notch stress concept, non-conservative results are found for about 10% of all specimens. These are limited to the test series of [17] and [16].

For the fatigue assessment according to the von Mises equivalent stress, a conservative estimate is obtained for both the nominal stress concept (<1%) and the hot spot stress concept (<1%), as well as the notch stress concept (<3%). However, for the former, especially for higher numbers of cycles $N > 10^6$, many results are overly conservative.

6 Discussion

For a direct comparison of the results obtained from the different approaches and stress concepts, the logarithmic deviation $\log_{10}(N_{\text{exp}}) - \log_{10}(N_{\text{calc}})$ is shown in Fig. 6 as a measure of the estimation quality of the 3 approaches.

For the notch stress concept, the maximum principal stress-based approach shows in comparison to the other two approaches a significantly higher number of results with a non-conservative estimation of the fatigue life. Based on these results, the use of this approach cannot be recommended for the notch stress concept. As an alternative, the von Mises approach can be used in this case, which reliably produces conservative results for the notch stress concept without becoming overly conservative.

The pronounced conservatism of the results for von Mises can be attributed to the FAT class used. According to the recommendation of [20], for the notch stress concept with a reference radius of 1 mm, a FAT 200 is to be applied for pure normal stress and a FAT 280 for shear stress. Since a single stress resistance must be specified for the fatigue assessment of multiaxial stress conditions in the von Mises approach, FAT 200 was chosen in the course of this work to avoid a non-conservative estimation. The von Mises equivalent stress is by a factor of $\sqrt{3}$ higher for a loading by pure shear stress than it is for a loading by pure normal stress of the same magnitude; see Eq. 13:

$$\Delta\sigma_{\text{vM}}\left(\Delta\sigma_{\perp}\right) = \frac{1}{\sqrt{3}}\Delta\sigma_{\text{vM}}(\Delta\tau) \tag{15}$$

for

$$\Delta\sigma_{\perp} = \Delta\tau \tag{16}$$

This has the consequence that the stress resistance for the uniaxial load cases of pure normal and shear stress can only be accurately modeled with the von Mises approach if they correspond to the following ratio:

$$\frac{1}{\sqrt{3}}\Delta\sigma_R = \Delta\tau_R \tag{17}$$

Since the resulting FAT class of 115 for shear stress is far below the recommended value of 280, it can be assumed that for the von Mises approach a conservative estimation can be expected as soon as a significant part of the damage results from shear stresses. This is consistent with the observed conservatism of the results for the fatigue assessment according to the von Mises approach. A reduction of the conservatism is possible by choosing a higher FAT class for the assessment, but this has the consequence that for the case of pure normal stress a non-conservative fatigue assessment is to be expected.

The non-conservative results observed for Gough-Pollard and the maximum principal stress-based approach can be attributed in large part to the neglect of parallel stresses in these approaches. Such parallel stresses occur in welds when loaded normal to the weld due to local transverse contraction restraint in the notch but are usually accounted for by the respective FAT class, so that a pure evaluation of the normal stress component neglecting the parallel stress is justified. In the case of the results from [17] and the LaserMultiAx project, additional parallel stresses occur due to the weld being tilted to the loading direction. This results, in the case of the LaserMultiAx specimens with a weld orientation angle of 60°, in even higher parallel stresses than the stresses normal to the weld. Since, in contrast to the von Mises approach, parallel stresses are not taken into account by the Gough-Pollard equation and the maximum principal stress-based approach, the fatigue strength evaluation is in these cases significantly less conservative and, in some cases, even non-conservative. This is reflected in Fig. 5, where the cycles of the LaserMultiAx-specimens calculated for von Mises stress approximately match, while for Gough-Pollard and the maximum principal stress-based approach the results become less conservative or even non-conservative with increasing weld orientation angle and thus increasing proportion of parallel stress. This effect can be observed for all three stress concepts. One possibility to take this into account for the Gough-Pollard approach is the

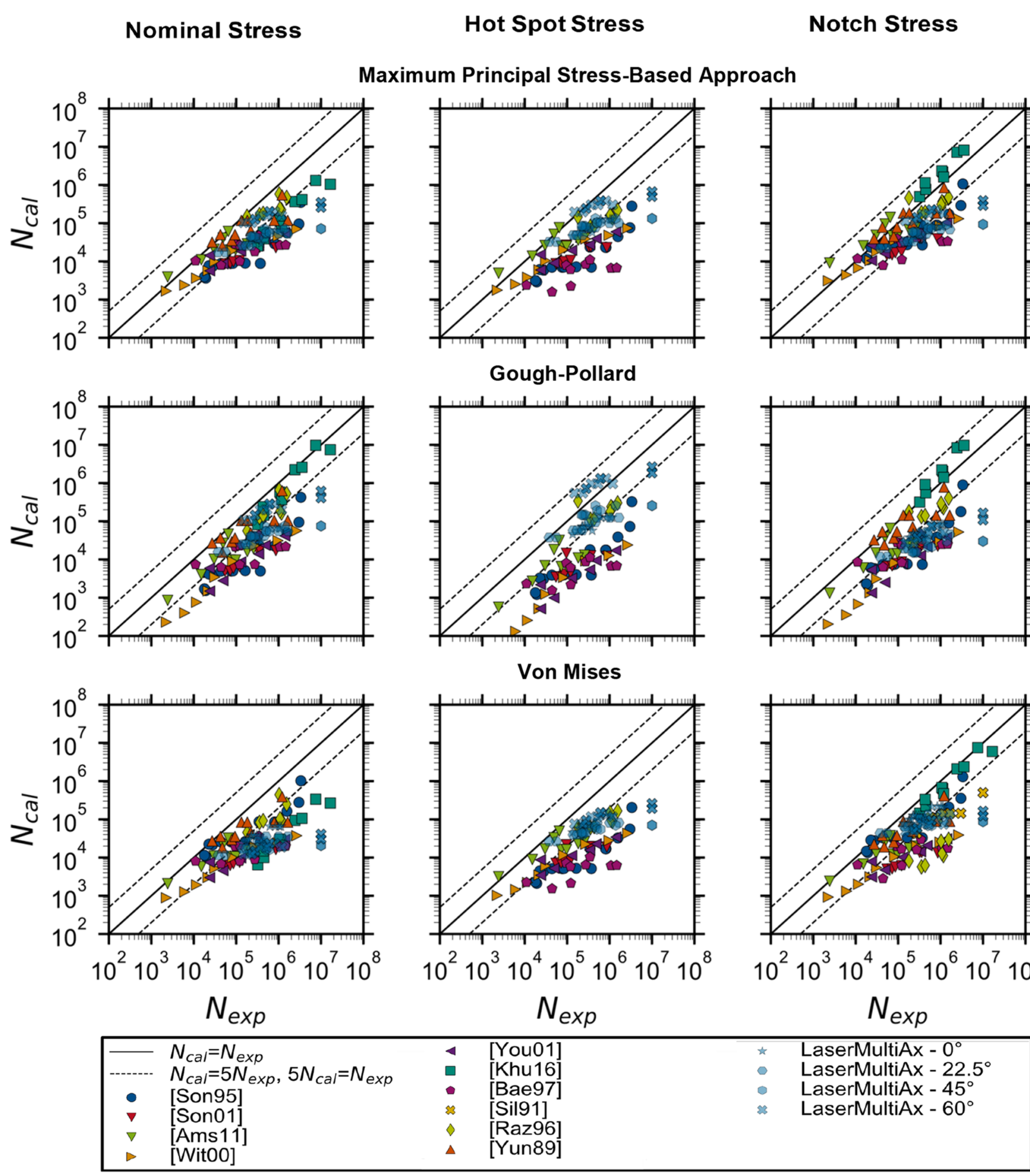

Fig. 5 Experimental vs. calculated number of cycles for the maximum principal stress-based approach, the Gough-Pollard approach, and an evaluation based on the von Mises equivalent stress for the nominal, hot spot, and notch stress concepts respectively

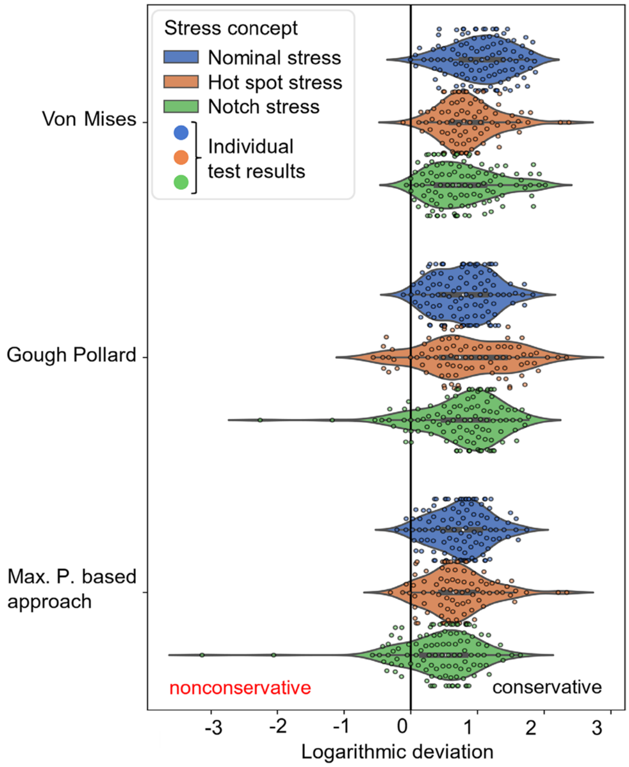

Fig. 6 Logarithmic deviation of the results of the three investigated approaches for the nominal, hot-spot, and notch stress concepts

extended approach presented in [22], which takes the parallel stress component into account; see Eq. 14:

$$\left(\frac{\Delta\sigma_{\perp}}{\Delta\sigma_{\perp,R}(N)}\right)^2+\left(\frac{\Delta\sigma_{\parallel}}{\Delta\sigma_{\parallel,R}(N)}\right)^2+\left(\frac{\Delta\tau}{\Delta\tau_R(N)}\right)^2\leq CV \quad (18)$$

A possible solution for the maximum principal stress-based approach would be to evaluate the maximum principal stress without neglecting the parallel stress. However, a review of these possibilities has not been done in this paper and remains to be verified.

7 Conclusion

In this paper, the maximum principal stress-based approach based on the maximum principal stress for the fatigue evaluation of welded joints under proportional multiaxial loading was investigated. The maximum principal stress-based approach simplifies the determination of the fatigue life for given stresses compared to the Gough-Pollard approach, since the iterative calculation process required in the latter can be avoided. At the same time, the description of the approach in its current form still leads to some ambiguities regarding the admissibility for different stress concepts and the conditions to be considered. The investigation has shown that the simplified formula for determining the maximum principal stress given in section 4.3 does not offer any obvious advantage to the user. The reason for this is that the parallel stress, which has been neglected in the formula, is required for checking the conditions and must therefore be known anyway. At the same time, the maximum principal stress can usually be directly obtained from FE software, so its consideration in its original form should not result in any additional effort. The results of the validation show that the maximum principal stress-based approach for the nominal and hot spot stress concepts reliably produces conservative results of comparable or better quality to the Gough-Pollard approach. For the notch stress concept, on the other hand, a significantly higher number of non-conservative results were observed than for other approaches considered. In this case, the von Mises approach is a good alternative that reliably provides conservative results.

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Declarations

Competing interests The authors declare no competing interests.

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