On the fatigue and fracture behavior of necked double shear lugs for aircraft applications

Zum Ermüdungs- und Bruchverhalten von verjüngten doppelschnittigen Augenverbindungen für Anwendungen im Flugzeugbau

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The fatigue and fracture behavior of double shear lugs subjected to axial loading is investigated. The focus is on specific shapes, so-called waisted or necked lugs. These structural components used in aircraft interior are prone to fatigue loads. Three different sizes of necked double shear lugs made of high strength aluminum 2024-T351 and steel 17–4 PH are tested using constant amplitude cyclic loadings with a load ratio \( R = 0.01 \). Measurement data is used to identify the number of cycles to crack initiation and final fracture. Fatigue tests show that cracks initiate either at the inside or outside surface of necked lugs. However, no clear dependency on the load amplitude, lug size and material could be found. Numerical simulations using both conventional finite element method (FEM) and extended finite element method (XFEM) are performed to calculate the stress intensity factors (SIFs) for multiple crack lengths of straight and necked double shear lugs. Calculated stress intensity factors for straight lugs fit well to stress intensity factors reported in literature. Stress intensity factor curves of inside and outside cracks of necked lugs plotted with respect to crack length, cross each other, which could have an influence on the fracture behavior observed in fatigue tests.

Keywords: Fracture behavior / necked double shear lugs / constant amplitude fatigue tests / displacement measurement data / stress intensity factor

Es wird das Ermüdungs- und Bruchverhalten von doppelschnittigen Augenverbindungen unter axialer Belastung untersucht. Der Fokus liegt auf speziellen Geometrien, sogenannten taillierten oder verjüngten Augenverbindungen. Diese Struktur-elemente werden im Flugzeuginterieur verwendet und sind Ermüdungsbelastungen ausgesetzt. Drei verschiedene Größen von verjüngten doppelschnittigen Augenverbindungen aus hochfestem Aluminium 2024-T351 und Stahl 17–4 PH wurden zyklisch bei mehreren konstanten Amplituden und einem Lastverhältnis von \( R = 0.01 \) getestet. Die Messdaten werden verwendet, um die Anzahl der Zyklen bis zu Rissinitiierung und finalem Versagen zu identifizieren. Außerdem haben die Ermüdungsversuche gezeigt, dass Risse, ohne eindeutige

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Abhängigkeit bezüglich Lastamplitude, Probengröße und Material, entweder an der Innen- oder Außenfläche entstehen. Numerische Simulationen mit der konventionellen Finiten Elemente Methode (FEM) sowie der erweiterten Finiten Elemente Methode (XFEM) wurden zur Berechnung von Spannungsintensitätsfaktoren (SIFs) für mehrere Risslängen bei geraden und verjüngten Augenverbindungen durchgeführt. Die berechneten Spannungsintensitätsfaktoren für gerade Augenverbindungen stimmen gut mit Spannungsintensitätsfaktoren aus der Literatur überein. Spannungsintensitätsfaktoren von Rissen an der Innen- und Außenfläche von verjüngten Augenverbindungen ergeben, über die Risslänge aufgetragen, kreuzende Verläufe. Dies könnte einen Einfluss auf das, in den Ermüdungsversuchen beobachtete, Bruchverhalten haben.

Schlüsselwörter: Bruchverhalten / Verjüngte doppelschnittige Augenverbindung / Ermüdungsversuche mit konstanter Amplitude / Verschiebungsmessdaten / Spannungsintensitätsfaktor

1 Introduction

Double shear lugs are commonly used as connecting elements in aircraft to attach interior components (e.g. overhead bins, galley and lavatory) to the fuselage structure. There are two major advantages of such kind of attachments. First these components can be easily removed during maintenance. Due to the bolted connection no screws must be released and no special tools are needed for removal. The second advantage of bolt and lug connections are that they act as pivots and hence introduce no local bending moments in the surrounding structure.

However, such connections do have also well-known disadvantages. Lugs are sensitive to fatigue failure because high stress concentrations, fretting corrosion and pre-stresses due to interference fits are present at the lug hole. However, a complete failure of such components in an aircraft is in many cases unacceptable [1]. Therefore, detailed knowledge of the fatigue and fracture behavior of such components is of great importance for safety of aircraft. Such knowledge is especially necessary if components must fulfill damage tolerance requirements. Damage tolerance in aircraft engineering means that components have to withstand a given loading even if a small crack is present at the beginning of the fatigue life time. To calculate the residual fatigue life time of a component with a certain crack the stress intensity factor (SIF) is needed, considering linear elastic fracture mechanics.

Straight and tapered lug shapes have been investigated by many authors [1–4]. Stress intensity factors, normalized to the bearing stress, are also given for such shapes in tabulated form [5]. Geometry factors, to calculate the stress intensity factors for given loading and crack length, for through thickness cracks in straight lugs are tabulated in guideline ESDU 81029 and the structure analysis handbook HSB 63353-01 [6–7]. In these guidelines the stress intensity factor is normalized to the gross section stress far away from the pin. Furthermore, an analytical method to calculate the stress intensity factors for through the thickness cracks and corner cracks in straight double shear lugs exits [8–9]. In a recent publication the stress intensity factors of straight lugs are calculated with analytical and numerical methods and subsequently used for analytical crack growth calculations, which are then compared to test data [10].

In all references mentioned above the considered crack initiation location is at the lug hole, the contact region between bolt and lug, because the highest stress concentration appears at this location in straight lugs. Besides the common case of a crack at 90° to the lug axis, some authors studied crack angles in the full range of 0°–180° [11].

The necked lug shape is only mentioned in few references available to the authors [12–14]. However, these articles deal with stress distribution and stress concentration factors but give no information on stress intensity factors. To the authors knowledge no data on stress intensity factors is available.
which covers the special shape of necked double shear lugs.

As already mentioned, for damage tolerance considerations of necked double shear lugs the residual life time after crack initiation is of interest. Also, for the implementation of structural health monitoring systems on necked lugs the knowledge of crack growth behavior is necessary. Relevant questions in this field are: What is the critical crack length of necked lugs before final failure and is it possible to detect cracks in an earlier stage? What is the residual life time of necked lugs with a certain crack length?

Therefore, this contribution gives special emphasis to the fatigue fracture behavior of necked double shear lugs with cracks of multiple lengths and initiation locations. Necked lugs are investigated experimentally and numerically. Experimental investigations include fatigue tests with subsequent analysis of fracture surfaces and displacement measurement data. Additionally, finite element models are developed to calculate stress intensity factors numerically, which are then compared to results reported in literature.

2 Fatigue tests

2.1 Specimen details

The lug specimens for fatigue tests have a necked shape and are made by turning and milling, Figure 1. These fatigue tests include necked lug specimens with three different geometries, labeled D27, D29 and D31 according to the outer lug diameter $D$, Table 1. Features without dimensions are a standard groove for a sealing ring and a M10-thread for mounting the necked lug to the tie-rod tube [15]. These features are assumed to have no influence on the fatigue and fracture behavior of the investigated necked lugs. The materials used for the lug specimens are high strength aluminum alloy EN AW-2024 T351 and high strength steel 17-4 PH1025, designated with endings “-Al” and “-St” respectively, Table 1.

2.2 Test setup and procedure

The fatigue tests are conducted using a hydraulic multipurpose test rig accommodating a servo hydraulic cylinder from manufacturer Zwick Roell with a maximum load capability of 100 kN. Special clamping devices are used along with an alignment device to assure axial loading of specimens [15], Figure 2. In constant amplitude fatigue tests a frequency of 10 Hz for load amplitudes of 5.78 kN–22.5 kN is used. The load ratio is kept constant at $R = 0.01$. The fatigue tests are carried out using the software Cubus together with the servo hydraulic controller Control-Cube of manufacturer CaTs$^3$. All tests are performed load controlled utilizing the sensor data of the load cell (1), Figure 2. Additionally, the displacement sensor signal of the internal inductive extensometer of the hydraulic cylinder is recorded. Along with the sensor data also photo-

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**Table 1.** Geometry parameters of specific lugs investigated in fatigue tests.

| Lug specimen | $d$ [mm] | $D$ [mm] | $W$ [mm] | $L$ [mm] | $t$ [mm] | $R_t$ [mm] |
|--------------|----------|----------|----------|----------|----------|------------|
| D27-Al       | 17.462   | 27.0     | 9.20     | 32.87    | 8.05     | 16.0       |
| D29-Al       | 20.638   | 29.0     | 10.31    | 33.58    | 10.31    | 10.0       |
| D31-Al, D31-St| 23.812   | 31.0     | 9.20     | 32.87    | 11.23    | 16.0       |
graphs of the tested lugs are taken periodically every 5 s using an industrial camera (IDS UI-3370CP-C-HQ Rev.2).

2.3 Fatigue test data analysis

2.3.1 Photographs

During fatigue tests photographs of the necked lugs are taken periodically and subsequently analyzed. With these pictures it is possible to identify the crack initiation of cracks starting from the outside of the lug at the transition region between shaft and largest diameter of the lug. For one specific lug the crack initiated at the outside and its propagation could be observed till failure using the recorded pictures, Figure 3. After \( N_0 \approx 36065 \) cycles the crack appeared on the surface of the specimen for the first time, Figure 3a. The cycle count is estimated using the file timestamp of the corresponded image. Shortly before failure, after \( N \approx 39200 \) cycles, the crack is clearly visible and stretches over the full width of the lug, Figure 3b. Finally, the lug failed after \( N_f \approx 39236 \) cycles, Figure 3c. Based on this visual observation of lug D31-Al (specimen number 16), also the corresponding displacement measurement data is analyzed.

2.3.2 Displacement sensor measurement data

The displacement measurement data of lug D31-Al (specimen number 16) shows a significant growth in amplitude and mean value in the last cycles of the fatigue test, Figure 4. For the analysis of measurement data the numerical mathematics software MATLAB is used. The detailed analysis of the displacement signal includes four main analyses steps.

1. In the first step the raw measurement signal is cropped to a window where crack growth till final rupture of the specimen takes place. This evaluation window is defined to begin at 90 % of the total...
2. Then the raw signal is resampled using the function “resample” of MATLAB’s Signal Processing toolbox in order to capture the turning points of the measurement signal more precisely. The measurement was conducted using a sample rate of 100 Hz. After resampling the signal includes 100 signal points within one period.

3. With the resampled displacement measurement data a damage indicator is calculated with

\[ u_{DI} = 2u_a u_m \]  

(1)

where \( u_a \) is the amplitude and \( u_m \) is the mean value of the oscillating displacement signal. It is assumed to identify the crack initiation with this damage indicator.

4. To identify the point of crack initiation a straight line is fitted to the first half of the damage indicator \( u_{DI} \). Then the initiation is defined at the last point where \( u_{DI} \) has a larger distance to the straight line than the scatter of the damage indicator in the center of the evaluation window, Figure 4.

The cycles to crack initiations of all tested specimens are identified using this procedure.

3 Numerical calculation of stress intensity factor

To accomplish the experimental investigations on necked double shear lugs multiple numerical simu-
lations are performed. Stress intensity factors of predefined cracks starting from the inside (contact region between lug and bearing) as well as cracks starting from the outside surface (transition region between shaft and largest diameter of the lug) are investigated using the finite element software Abaqus/CAE. A three dimensional finite element model of a straight lug is developed based on recommendations in literature [8, 10], Figure 5. Subsequently, a second finite element model for a necked lug was derived from the straight lug model, Figures 6, 7.

3.1 Boundary conditions for finite element models

Two finite element model geometries are investigated to numerically calculate stress intensity factors. For all models the same boundary conditions and contact definitions apply: The loading, a uniform distributed stress with a magnitude of $\sigma = 50$ MPa, is applied at the back side of the lug (loaded area $A_{\text{load}} = Wt$, resulting concentrated load $F = \sigma Wt$). The pin is fixed in all degrees of freedom through a rigid body constraint connecting the inner diameter of the pin $d_{\text{pin}}$ to its geometric center. A contact is modeled between pin and lug using frictionless tangential behavior and a “hard” contact in normal direction.

3.2 Approaches to model crack tip singularity

3.2.1 Quarter-point singular elements

One method to model the crack tip singularity with finite element method is by using quarter-point singular elements. In the three-dimensional case, these are conventional hexagonal brick elements but with one side collapsed to a line to become wedge shaped elements. For linear elastic materials such elements are able to capture the $r^{-1/2}$ strain singularity, where $r$ is the distance from the crack tip, using a mid-side node shifted to the crack tip by 25% [16–17].

Figure 5. Finite element model of straight lug: a) geometry and parameter definition, b) typical mesh with conventional finite element method elements, c) typical mesh with enriched extended finite element method elements.

Bild 5. Finite Elemente Modell der geraden Augenverbindung: a) Geometrie- und Parameterdefinition, b) Typische Vernetzung mit konventionellen Finiten Elemente Methode Elementen, c) Typische Vernetzung mit erweiterten Finiten Elemente Methode Elementen.
Figure 6. Finite Element model of necked lugs with crack location inside at $\beta_1 = 90^\circ$: a) geometry and parameter definition, b) typical mesh with conventional finite element method elements, c) typical mesh with enriched extended finite element method elements.

Bild 6. Finite Elemente Modell der verjüngten Augenverbindung mit Rissposition innen bei $\beta_1 = 90^\circ$: a) Geometrie- und Parameterdefinition, b) Typische Vernetzung mit konventionellen Finiten Elemente Methode Elementen, c) Typische Vernetzung mit erweiterten Finiten Elemente Methode Elementen.

Figure 7. Finite Element model of necked lugs with crack location outside at $\beta_2 = 145^\circ$: a) geometry and parameter definition, b) typical mesh with conventional finite element method elements, c) typical mesh with enriched extended finite element method elements.

Bild 7. Finite Elemente Modell der verjüngten Augenverbindung mit Rissposition außen bei $\beta_2 = 145^\circ$: a) Geometrie- und Parameterdefinition, b) Typische Vernetzung mit konventionellen Finiten Elemente Methode Elementen, c) Typische Vernetzung mit erweiterten Finiten Elemente Methode Elementen.
3.2.2 Enrichment functions for finite elements

Based on the partition of unity method the extended finite element method (XFEM) was developed [18–19]. In this method enrichment functions are added to the finite element space in order to describe discontinuities in the displacement field. In the extended finite element method such enrichment functions are only added to elements in a specific region of the model (around the crack) to keep the number of additional unknowns and calculation costs small [20]. In order to model discontinuities of fracture mechanics related problems the enrichment functions includes terms to capture the singularity around a crack tip as well as discontinuous functions which handle the jump in displacement across crack surfaces. Hence, for extended finite element method elements in Abaqus/CAE the displacement vector $\mathbf{u}_{\text{XFEM}}$ with enrichment functions of the partition of unity method is [17, 20]

$$\mathbf{u}_{\text{XFEM}}(\mathbf{x}) = \sum_{i=1}^{N} N_i(\mathbf{x}) \left[ \mathbf{u}_i + H(\mathbf{x}) \mathbf{a}_i + \sum_{\alpha=1}^{4} F_{\alpha}(\mathbf{x}) \mathbf{b}_i^\alpha \right]. \tag{2}$$

where $r$ and $\theta$ are polar coordinates originating at the crack tip.

3.3 Straight lug finite element model

Straight lug models are developed to compare with results found in literature [5–8]. The geometry of the lug is simplified to reduce calculation costs, Figure 5a. Geometry parameters are chosen to yield a diameter ratio $R_o/R_t = 2$. Table 2. The aluminum lug and the steel pin are modeled with linear elastic material models, Table 3. Two types of meshes are used to fit simulation method with conventional finite elements (FEM) and enriched finite elements (XFEM), Figure 5b and Figure 5c respectively. These meshes mainly consists of linear hexagonal elements (C3D8). For meshes utilizing the conventional finite elements quadratic hexagonal elements (C3D20) are used for the crack tip region (elements inside $r_0$), Figure 5a and Figure 5b. In finite element models utilizing extended finite element method the enrichment functions are added to the elements in contact with the crack as well as to five additional rows of elements around these elements, Figure 5c.

| Table 2. Geometry parameters of straight and necked lug finite element models. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Lug type        | $R_o$ [mm]      | $R_t$ [mm]      | $W$ [mm]        | $L$ [mm]        | $t$ [mm]        | $R_t$ [mm]      |
| straight lug    | 15.0            | 30.0            | 60.0            | 90.0            | 5.0            | -              |
| necked lug      | 15.0            | 30.0            | 30.0            | 90.0            | 5.0            | 30.0           |

| Table 3. Material parameters of finite element models. |
|-----------------|-----------|-----------|
| Part            | $E$ [MPa] | $\nu$ [-] |
| lug             | 70.0      | 0.33      |
| pin             | 210.0     | 0.30      |
3.4 Necked lugs finite element models

The finite element models for the necked lug are based on the model for the straight lug. In comparison to the straight lug model two crack locations are investigated for necked lugs. The first model comprises one crack at the inside surface of the lug 90° to the lug axis, Figure 6. The second model has one crack at the outside surface of the lug 145° to the lug axis, Figure 7. Geometry parameters of necked lug models are similar to those of the straight lug model, Table 2 and Table 4. The same linear elastic material models apply for straight and necked lugs, Table 3. The utilized meshes for necked lugs follow the same strategy used for the straight lug, Figures 6, 7.

3.5 Stress intensity factor calculation and extraction

The stress intensity factors are calculated using the software Abaqus/CAE. Herein, the J-Integral is calculated for each node on a defined crack front for multiple contours. For linear elastic materials the J-Integral in three dimensional models can be related to the stress intensity factor for mode I, II and III by [21]

\[
J = \frac{(1 - \nu^2)}{E} (K_I^2 + K_H^2) + \frac{1}{2G} K_{III}^2,
\]

where \( E \) is the Young’s modulus and \( G = \frac{E}{2(1 + \nu)} \) is the shear modulus. Based on the J-Integral the individual stress intensity factors can be derived for linear elastic materials using the interaction integral method [22].

The stress intensity factors calculated in this way are extracted and further processed using a python script. For the current finite element simulations five contour integral values are requested. However, only the values of the third to the fifth contour integral are averaged to get accurate and converged results as suggested in the Abaqus/CAE documentation [17]. In order to get one stress intensity factor result for each mode extracted results of each node are averaged a second time. For the second averaging the results of first two edge nodes on both sides of the crack front are ignored, because on free surfaces the stress intensity factor tends to zero [23].

3.6 Stress intensity factor normalized to bearing stress \( \sigma_{br} \)

The stress intensity factors calculated and extracted from Abaqus/CAE are normalized in order to compare with stress intensity factor results found in literature. This normalization is necessary because the stress intensity factors in literature are given either with different loadings or when normalized then to different stresses. For this purpose, the normalized stress intensity factor for mode I cracks of length \( a \) is defined as

\[
\alpha_I = \frac{K_I}{\sigma_{br} \sqrt{\pi a}},
\]

where \( K_I \) is the SIF for mode one cracks and \( \sigma_{br} = F/(dt) \) is the bearing stress. Additionally, this normalization allows to compare stress intensity factors of both straight and necked lug shapes.

4 Results and discussion

4.1 Characteristic crack initiation locations

The executed fatigue tests and subsequent data analysis, including periodically taken pictures during tests and subsequent fracture surface analysis, revealed two characteristic crack initiation locations of necked double shear lugs. The crack initiates either at the inside (contact region of bearing and lug) or at the outside surface (transition region between shaft and largest diameter of the lug), Figure 8. For each necked lug specimen tested at a load ratio of \( R = 0.01 \) the crack initiation location

| \( d_{i,\text{pin}} \) [mm] | \( t_{\text{pin}} \) [mm] | \( a \) [mm] | \( r_i \) [mm] | \( r_o \) [mm] |
|----------------|----------------|----------|---------|---------|
| 10.0           | 10.0          | 3.0–12.0 | 0.5     | 2.0     |
and their number of occurrences is documented, Table 5. At this time it is unclear which factors are relevant for a crack to initiate and propagate from the inside or outside surface of the lug. This behavior is especially pronounced for lug specimens D29-Al and D31-Al for which both crack initiation locations could be observed. However, for lug specimens D31-Al and D31-St the geometries are equal and the materials are different, which again leads to different behavior for crack initiation and propagation. But only considering the material as cause for crack initiation location at the inside is not true, because lug specimen D27-Al also only failed with cracks starting from the inside.

Hence, neither the geometry nor the material of tested necked lugs are clear indicators for a crack initiating from the inside or outside surface. More detailed investigations are needed in order to draw precise conclusions for such a fatigue fracture behavior of necked double shear lugs.

4.2 Cycles to crack initiation and final failure

The current investigations also includes the question if there exists a considerable crack growth period for necked double shear lugs. For this purpose, the cycles to crack initiation are identified using the measured data of the displacement sensor of the hydraulic cylinder, as described in Section 2.3.2. The cycles to failure of tested specimens are also identified using the displacement sensor measurement data to compare with counted cycles of the test rig. The calculated cycles at crack initiation \( N_0 \) as well as the cycles to failure \( N_f \) at all tested load levels for each lug are given as 50 % survival probability values according to DIN 50100:2016-12, Table 6.

![Figure 8. Characteristic fracture surfaces with assumed crack initiation locations a) inside and b) outside.](image)

Table 5. Crack initiation locations of necked lugs tested at a load ratio of \( R = 0.01 \).

| Lug specimen | Material | Location (number of occurrences) |
|--------------|----------|----------------------------------|
| D27-Al       | 2024-T351 | inside (11)                      |
| D29-Al       | 2024-T351 | inside (3) + outside (6)         |
| D31-Al       | 2024-T351 | inside (3) + outside (4)         |
| D31-St       | 17-4PH   | inside (7)                       |

Table 6. Identified cycles to crack initiation and measured cycles to failure for all tested lugs (*number of occurrences).

| Lug specimen | \( F_{\text{max}} \) [kN] | \( N_0(P = 50\%) \) [cycles] | \( N_f(P = 50\%) \) [cycles] | Crack growth [cycles] [%] | Location (no.*) |
|--------------|----------------|-------------------------------|-------------------------------|--------------------------|-----------------|
| D27-Al       | 6.30           | 544410                        | 554418                        | 10008                    | inside (3)      |
|              | 8.70           | 86299                         | 88639                         | 2339                     | inside (4)      |
|              | 12.00          | 28886                         | 30165                         | 1279                     | inside (4)      |
| D29-Al       | 5.78           | 265711                        | 267038                        | 1327                     | inside (3)      |
|              | 8.67           | 76300                         | 78254                         | 1954                     | outside (3)     |
|              | 13.00          | 19626                         | 20655                         | 1029                     | outside (3)     |
| D31-Al       | 7.00           | 512440                        | 531564                        | 19124                    | inside (2)      |
|              | 8.70           | 94214                         | 98327                         | 4113                     | inside (3)      |
|              | 12.00          | 42565                         | 44701                         | 2136                     | outside (2)     |
| D31-St       | 17.50          | 169506                        | 175466                        | 5960                     | inside (1)      |
|              | 19.00          | 163997                        | 169424                        | 5428                     | inside (3)      |
|              | 22.50          | 45483                         | 48339                         | 2856                     | inside (3)      |
Depending on the tested load level a considerable crack growth period of 0.5 %–6 % could be identified for the lug specimens, Table 6. More specifically, the relative crack growth period is the longest for the highest load levels (mean 5.0 %) and minimal for the lowest load levels (mean 2.3 %) tested for each specimen. However, it is remarkable again that there seems to exist no direct relationship between load level and crack initiation location.

4.3 Results of finite element simulations

Normalized stress intensity factors $\alpha_I$ for multiple crack lengths $a$ calculated numerically with Abaqus/CAE are compared with values reported in literature [5–8], Figure 9. Calculation results are connected with straight lines in order to better visualize their trends, Figures 9–11. The normalized stress intensity factors tabulated in guideline ESDU 81029 and HSB 63353 yield the highest values for ratios $a/b < 0.6$ [6, 7]. A conservative estimation of stress intensity factors by these guidelines make sense due to safety reasons, even though the diverging trend to other stress intensity factor results is unexpected. Current finite element calculations give the highest stress intensity factor results for the ratio $a/b = 0.8$. In general, the stress intensity factor values calculated with finite element method and extended finite element method approach are considered to fit well to the results reported in literature, Figure 9. However, stress intensity factors calculated with extended finite element method approach yield higher values then stress intensity factors calculated with finite element method approach by a nearly constant offset of approximately 2 %–3 %.

Another comparison of calculated stress intensity factors depicts results of finite element calculations for the straight and necked lug with a
crack at 90° to the loading direction, Figure 10. Again the nearly constant offset of stress intensity factors calculated with extended finite element method and finite element method can be observed. The higher stress intensity factors for necked lugs are expected, because of higher stresses due to more fragile geometry. The trend of stress intensity factors for straight and necked lugs is similar. For both finite element method and extended finite element method results the stress intensity factors of the investigated necked lug are approximately 10 %–15 % higher than calculated stress intensity factors for the straight lug.

Stress intensity factors for necked lugs with an inside and outside crack are compared in Figure 11. It is remarkable that for large ratios $a / b$ the stress intensity factors for inside cracks are larger and for small ratios $a / b$ the stress intensity factors for outside cracks are larger. The transition occurs between $0.3 < a / b < 0.4$ for stress intensity factors calculated with both finite element method and extended finite element method approach, Figure 11. These crossing of trends of stress intensity factors for inside and outside cracks could be one reason for different locations of crack initiation and propagation observed at fatigue tests. However, more detailed and further investigations on stress intensity factors for necked lugs are needed to give more precise explanations for the observed behavior.

5 Conclusions

In the present work, a broad investigation of the fracture behavior of straight and necked double shear lugs was conducted. Fatigue tests with three different necked lug geometries made out of two different materials revealed two different crack initiation locations. Geometry and material of specimen nor fatigue test load level could not be found as clear indicators for a certain crack initiation location. Further investigations are needed in order to predict the crack initiation location for necked double shear lugs precisely. Nevertheless, a considerable crack growth period could be identified using the displacement sensor measurement data. The crack growth period of tested specimens is approximately 0.5 %–6 % depending on the tested load level. A distinct crack growth period is a necessary requirement for the application of structural health monitoring systems on such components.

Stress intensity factors for straight and necked double shear lugs are calculated with finite element simulation software Abaqus/CAE. The strain singularity at the crack tip is captured using conventional finite element method approach with quarter-point singular elements and extended finite element method approach. For straight lugs the calculation of stress intensity factors by utilizing both approaches yield results which fit well to stress intensity factors reported in literature, Figure 5.

The calculated stress intensity factors for necked lugs are approximately 10 %–15 % larger compared to calculated stress intensity factors of straight lugs.

A comparison between stress intensity factors for inside and outside cracks in necked lugs revealed a crossing trend. While stress intensity factors are larger for inside cracks at $\beta_1 = 90°$ at ratios $a / b > 0.4$, stress intensity factors are larger for outside cracks at $\beta_2 = 145°$ for ratios $a / b < 0.3$. This crossing of trends of stress intensity factors for inside and outside cracks could have an influence on variable crack initiation locations observed in fatigue tests. Besides geometry, material and load level other contributing influence factors for crack initiation locations should be identified in the future. Hence, further investigations are needed to predict the crack initiation location and cycles to crack initiation for necked double shear lugs more precisely.

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