Evaluation of the Fatigue Strength of a Steel-Aluminum Tapped Thread Joint with Local Concepts

D. Olveda[a], R. Waterkotte[b], M. Oechsner[a]

[a] Technische Universität Darmstadt, Fachgebiet und Institut für Werkstoffkunde, Darmstadt
[b] Operational Strength Competence Center, Schaeffler Technologies AG & Co. KG, Herzogenaurach

Abstract: *VDI (Association of German Engineers) guideline 2230 (VDI, 2013) provides a basis on which the fatigue strength of bolt-nut joints can be estimated. However, it is not suitable for use in reference to general threaded joints, as the VDI guideline is based on the nominal stress concept and it is often not possible to define a nominal surface area for such general joint types. Furthermore, regulations that do not explicitly deal with the design of threaded joints – such as the FKM guideline "Analytical Strength Assessment of Components" (FKM, 2013) – also deliver unsatisfactory estimates of the fatigue strength of threaded joints.*

This paper deals with the design of a steel/aluminum tapped thread joint. The concept developed by Schneider (Schneider,2011) is used as the basis for assessment up to the occurrence of technical cracks. Crack propagation, up to component failure, is described with linear elastic fracture mechanics and using the finite element method (FEM). For the purpose of validating the concept, the calculated lives are compared with experimental tests.

Keywords: *Fatigue, Fatigue Life, Fracture Mechanics, Threaded Connections*

1. Introduction

Screw connections are designed according to the VDI guideline on the basis of the nominal stress concept. The assumption is made here that the bolt will fail. Dimensioning of general threaded joints for which a nominal surface area cannot be defined and/or in which the nut component fails can therefore not take place according to the guideline. In such cases, the local concept is an approach that allows the fatigue strength to be estimated.

A method for calculating the fatigue strength of threaded joints based on the local concept is presented in (Schneider, 2011), refer to figure 1. The local concept is used to calculate the fatigue life until the occurrence of technical cracking. Crack propagation until fracturing occurs is measured by means of an additional crack propagation calculation using linear elastic fracture mechanics. It is thus possible to make a direct comparison between the calculated fatigue life values and the S-N curve produced for the components by the tests.

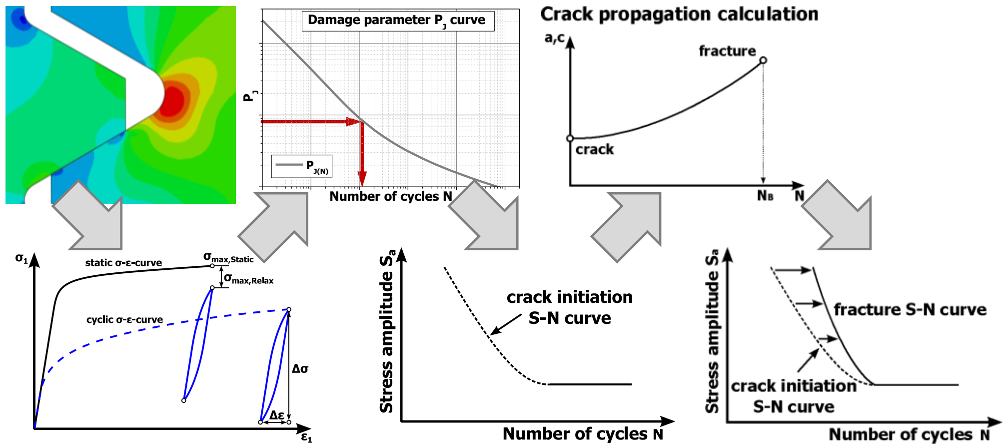

Figure 1. Procedure for assessing general threaded joints according to (Schneider, 2011)

In addition to the fatigue life calculation, the test procedure also presents a particular challenge with regard to the assessment. Due to the complexity of the threaded joint being tested, the cracks do not extend to the outer edge of the joint, which makes it more difficult to detect component failure.

2. Tested Joint

The joint being tested is a steel bolt with a through hole that is screwed into an aluminum body with a cut internal thread (M22 x 1), refer to figure 2. The steel bolt is fitted into the aluminum body via the support surface, with a maximum of 4-5 thread turns engaged. The aluminum body is made from the wrought alloy EN AW-6082-T6.

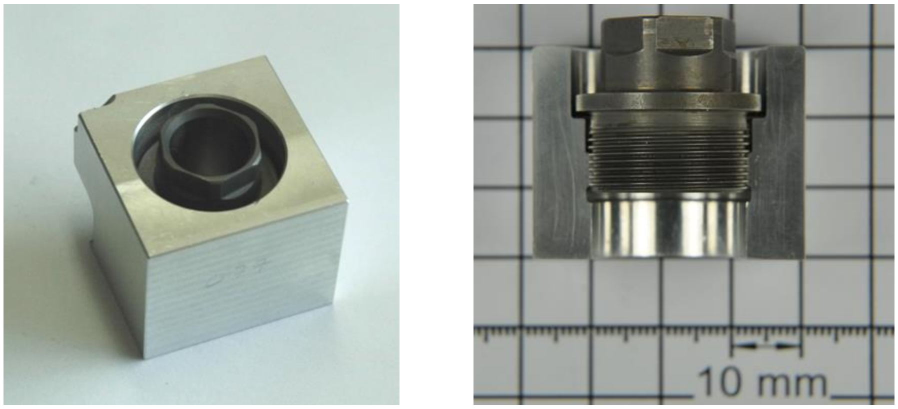

Figure 2. Steel/aluminum tapped thread joint: Left = top view, right = half-section

3. Fatigue Life Calculation

3.1 Geometry and meshing

The basis for the assessment according to (Schneider, 2011) is the calculation of the local load at the base of the thread. An axially symmetrical 2D FE model with an elastic-plastic material law is used for this purpose. Tests in (Schneider, 2011) and (Seybold, 2006) show that, at the point of maximum stress at the base of the thread, the calculation results of 2D models are only minimally different to those of 3D models.

Figure 3 shows the model used, together with its boundary conditions. The lower end face of the nut is fixed ($u_1 = u_2 = u_{R3} = 0$). Operating loads are applied via a reference point that is kinematically coupled with the bolt support surface. The axial preloading force is specified using the elongation of the elements within a partitioned range. The FE program Abaqus uses the load command "`Bolt load`" for this purpose (Abaqus, 2012). In the contact areas of the support surface and thread flanks, a Coulomb friction of μ = 0.1 was assumed.

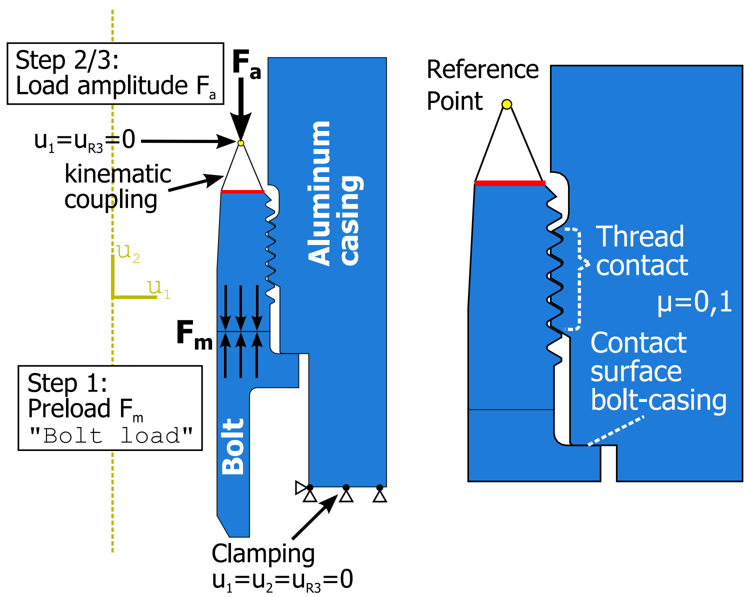

Figure 3. Model connection left: with boundary conditions; right: with contact pairs

The meshing of the overall component and the base of the thread is shown in figure 4. It was possible to achieve even meshing of the thread geometry of the nut and bolt using several partitioned ranges. At least 30 elements were used in the base of the nut thread here, which corresponds to the recommendations in (Seybold, 2006). An element length of 0.01 − 0.02 mm was selected along the flanks of the nut and the bolt. The global element length was set at approx. 0.5 mm. Approximately 33 000 elements are therefore required for the nut and 7 300 elements for the bolt when calculating the joint.

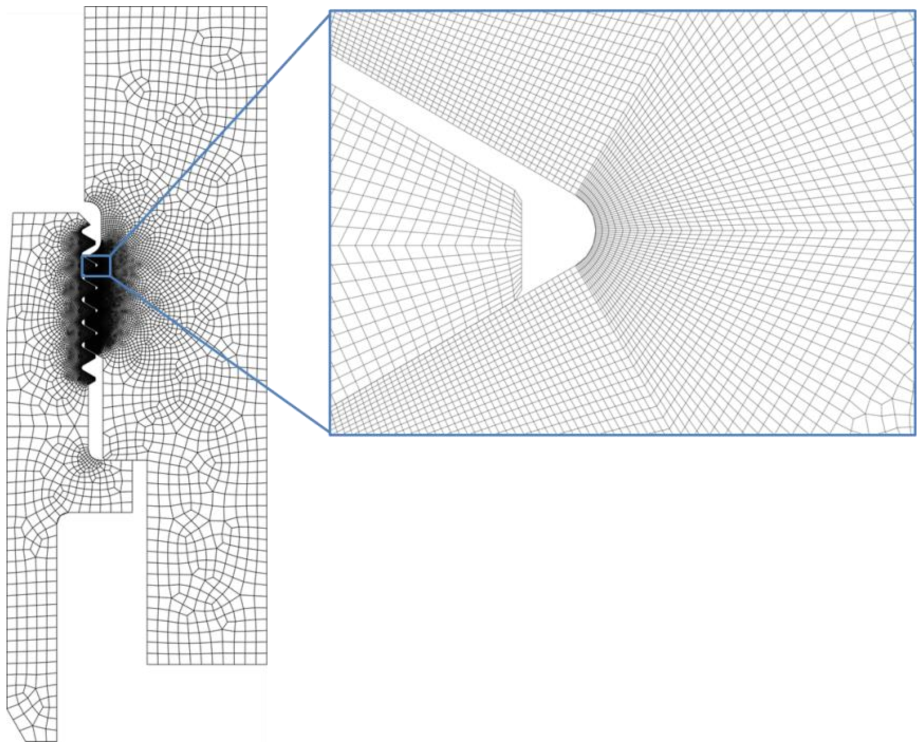

Figure 4. Meshing of the tested threaded joint

3.2 Material model and load-time function

The material behavior of the bolt was assumed to be linear-elastic, whereby an elasticity module of $E = 210$ GPa and a Poisson's ratio of $\nu = 0.3$ were used. In the case of the aluminum body, elastic-plastic material behavior was used as the basis. In addition to the elasticity module of $E = 64.9$ GPa that was determined through experiments and the Poisson's ratio of $\nu = 0.34$, static and cyclical flow curves are used that are determined through experiments (refer to figure 5).
The hardening law used for the calculation depends on the load case. In the case of a static load, an isotropic hardening is used as the basis, taking the static flow curve into consideration. The cyclical load is calculated using the material model according to LEMAITRE and CHABOCHE and the cyclically stabilized flow curve.
The load-time function is dependent on the load type. In the case of static loading, a calculation up to a highest load of F_O is sufficient. If a cyclical load is to be calculated, a further calculation stage is used in addition to the highest load in order to apply the lowest load F_U (figure 5, right).

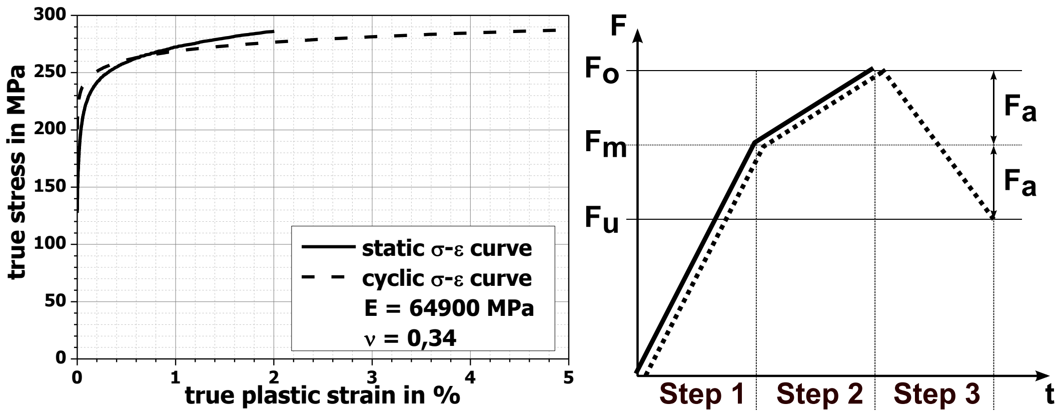

Figure 5. Left: Static and cyclical flow curve EN AW-6082-T6, Right*:* Load-time function $F_{(t)}$

3.3 Measuring the local stress-strain history

To determine the load, the tangential stresses and strains in the base of the thread are extracted. As an example, figure 6 shows the local stress-strain histories at the point of highest load, i.e. in the first load-bearing thread turn, for a force amplitude of $F_a = 10$kN ($R = 10$, $F_V = 18$kN). A differentiation must be made between the first principle stress σ_1, the tangential stress σ_t, and the equivalent tensile stress according to von Mises σ_V. In figure 6, it can be seen that the values for the first principle stress are virtually identical to the values for the tangential stress until the maximum stress σ_o is reached, while the von Mises stress already deviates from the main stress in this range. At high load amplitudes (as shown here) however, an incorrect evaluation of the actual load occurs after the load reversal in the case of these specific load parameters. When the load is reversed, the tangential proportion of the first principle stress declines to such an extent that, according to the convention $\sigma_1 > \sigma_2 > \sigma_3$, the highest stress value is read out but not the highest stress value in terms of amount. It can be concluded from this that the tangential stress σ_t is best suited to the evaluation of the local load.

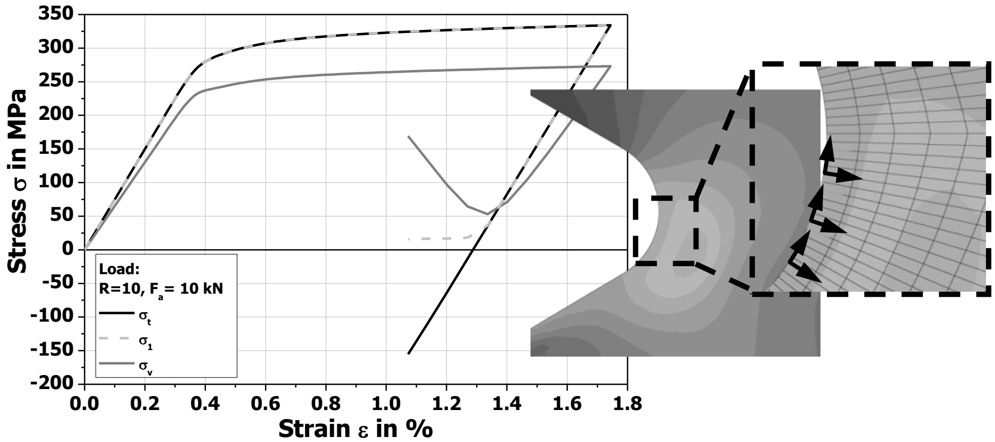

Figure 6. Various local stress-strain curves in the first load-bearing thread turn, $F_a = 10\text{kN}$, $R = 10$

3.4 Calculation of the incipient cracking S-N curve

The S-N curve for incipient cracking is calculated according to the method described in (Schneider, 2011) on the basis of the local concept. This requires both the hysteresis and its exact position to be estimated. To do this, the local maximum stress/strain that occurs when the screw is tightened is calculated using the static material law. The hysteresis is then calculated with a cyclical material law and subsequently applied to the static maximum stress/strain. The hysteresis is then shifted using the stress relaxation value derived by means of experiments. The position and hysteresis have thus been determined and can subsequently be assessed.
As a damage parameter, the parameter P_J is selected according to VORMWALD (Vormwald, 1989) and the number of load cycles for incipient cracking calculated for the relevant load case, taking the support effect into account. The S-N curves that is thus calculated is shown in figure 7.

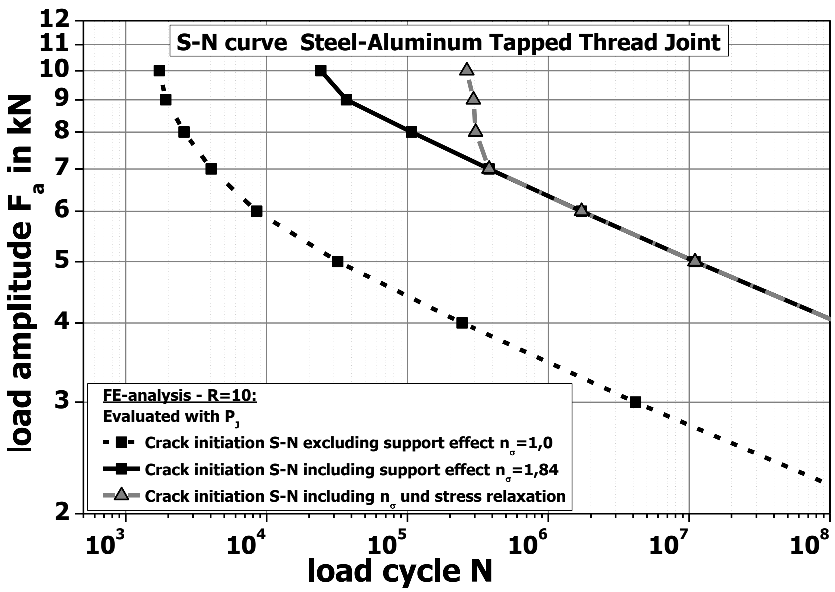

Figure 7. Calculated S-N curves for incipient cracking in the joint according to P_J

3.5 Calculation of crack propagation

The joints are not tested until incipient cracking occurs, which cannot be determined by measurement means, but until a specific crack size is reached. A comparison of the calculated and experiment-based S-N curves can therefore only be made if the crack propagation is taken into consideration. A number of simplified replacement models for calculating the number of stress cycles for crack propagation is provided in regulations such as the FKM guideline "Fracture Mechanics Proof of Strength for Engineering Components" (FKM, 2009). A further option for determining crack propagation is to use the FE method. The advantages of this type of calculation include the consideration of thread load distribution mapping and the contact between the thread flanks and the support surfaces, with which the friction is also taken into consideration.

In the axially symmetrical model, a crack is applied at the point of highest load and the stress intensity factor is determined. The crack length is varied in the direction of the highest load in order to test the influence of the crack length on the stress intensity factor. A linear-elastic calculation is carried out for this purpose; the mesh was refined in the vicinity of the crack edge (refer to figure 8).

Figure 8. Stress graph for the crack model, crack length $a = 0,7\text{mm}$, $F_O = 22,2\text{kN}$

After evaluation of the contour integrals, a dimensionless shape function can be determined through an interpolation of the results and taking the basic equation $K = \sigma\sqrt{\pi a} \cdot Y(a, d)$ into consideration. A power function was used as the interpolation formula here. The resulting shape function is as follows:

$$Y(a, d) = 0.419 \cdot \left(\frac{a}{d}\right)^{-0,486},$$

whereby a is the crack length and d is the bolt diameter. Figure 9 shows a comparison of the stress intensity factors of the calculation with those of the interpolation formula. The hypothetical nominal stress was defined as follows:

$$\sigma = F/\mathrm{A}$$

With A as the hypothetical bolt cross-section ($A = d^2 \cdot \pi/4$) and d as the outside bolt diameter $d = 22\text{mm}$.
The crack propagation is calculated according to linear elastic fracture mechanics. The resulting function is applied to the PARIS-ERDOGAN equation (${}^{da}/_{dn} = C \cdot K^m$) and integrated.

$$N = \int_{a_{\text{Begin}}}^{a_{\text{End}}} \frac{1}{C \cdot (\Delta K)^m} da = \int_{a_{\text{Begin}}}^{a_{\text{End}}} \frac{1}{C \cdot (f(a))^m} da$$

The number of stress cycles for crack propagation can be calculated with the help of this equation by applying the initial and final crack length ($a_{\text{Begin}}, a_{\text{End}}$) and the material parameters C and m.

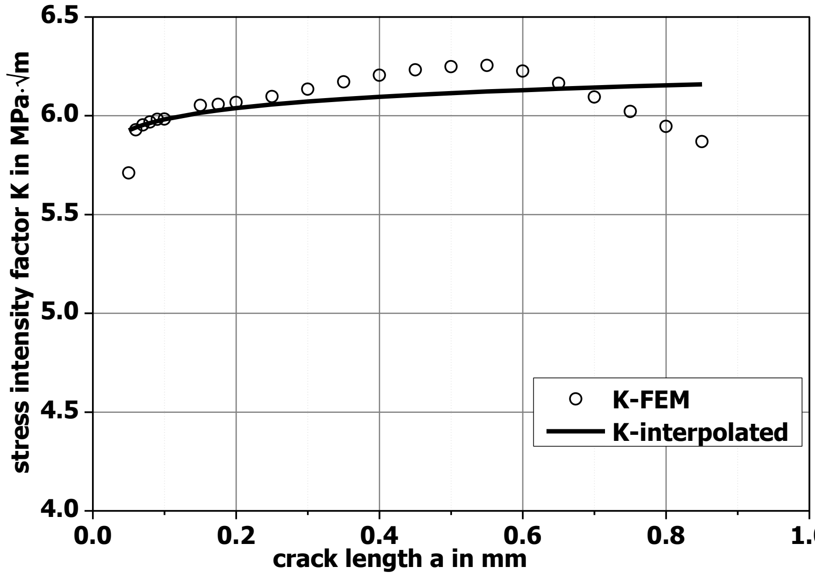

Figure 9. Interpolation $K - a$ and calculated results with a load of $F_O = 22,2\text{kN}$

4. Component Tests

4.1 Test setup

Test setup for testing the threaded joint is shown in figure 10 (left). The assembled threaded joint is placed on a shim, the purpose of which is to compensate for possible bending loads. Below the shim is a supporting body that is connected with the load cell of the high-frequency pulser (HFP). The force is applied via the end face of the bolt being tested using a pin, which exerts a pulsating compressive load.

Cracks form in the uppermost thread turn of the load transfer of the aluminum housing (figure 10, right). Crack propagation initially occurs in a radial direction and, if further propagation occurs, continues axially in the direction of the support surface of the nut and bolt. Ultrasonic testing equipment is used to measure the crack growth. Figure 10 shows a schematic representation of a measurement of the test specimen.

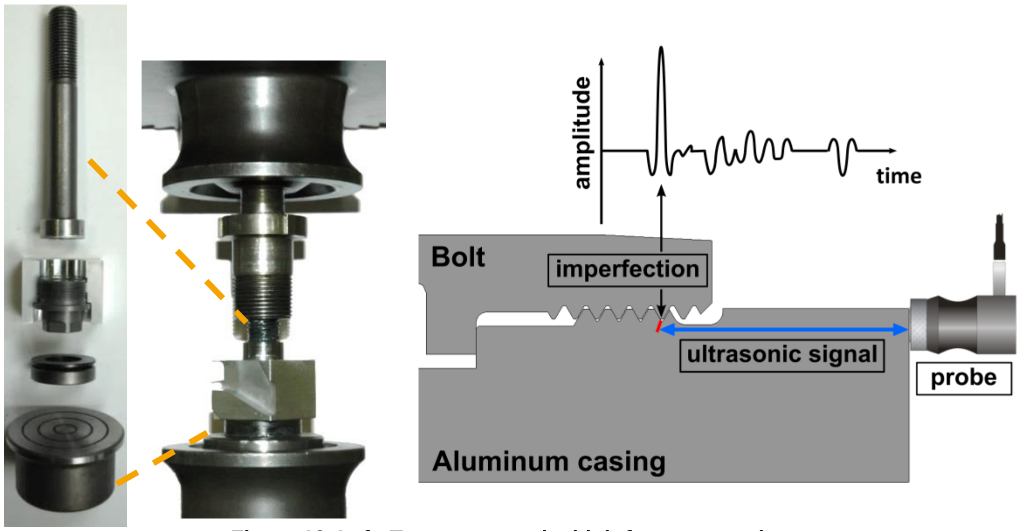

Figure 10. Left: Test setup on the high-frequency pulser;
right: Schematic representation of the crack measurement using ultrasound

4.2 Test procedure - determination of a cut-off criterion

A fracture in the joint that is not due to the direction of crack propagation does not occur during the course of the test and can therefore not be used as a cut-off criterion. Additionally, there is no frequency dip in the crack propagation, which also eliminates the possibility of machine monitoring. Iterative crack detection using ultrasound (US) was therefore carried out. Figure 11 shows a process diagram for crack detection. Here, the test specimen is measured before initial fitting using the ultrasonic testing device and subsequently tested up to N_1 load cycles. The S-N curve for estimating the number of stress cycles is derived from the previous calculation. After the number of stress cycles N_1 has been reached, the test sample is tested again using ultrasound. If no identifiable crack is present, the test is extended by ΔN stress cycles and the inspection is then repeated. This procedure continues until the presence of a crack can be verified.

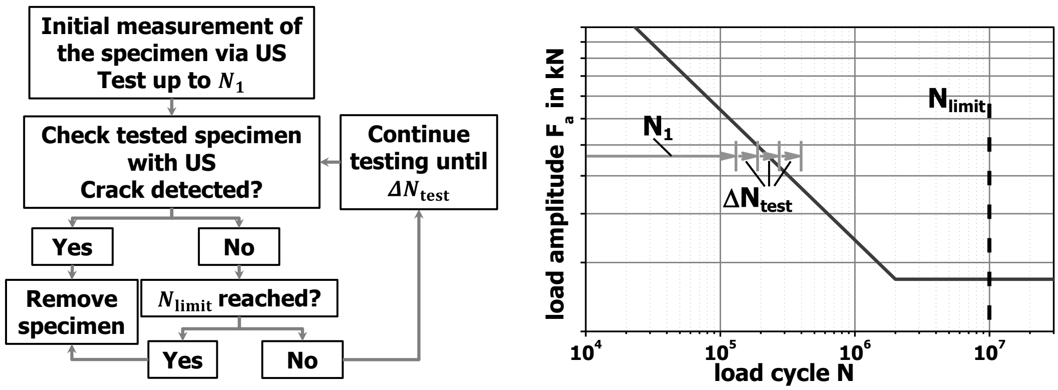

Figure 11. Process diagram for iterative crack detection

The test specimens are opened up after the test in order to inspect the cracks that have been detected using ultrasound. This is done by creating a recess that is level with the defect and statically pulling the test specimen apart. Test specimens in which no crack was identified were not included in the evaluation. The S-N curve for the components that is derived after crack detection is shown in figure 12.

4.3 Test evaluation

Due to the iterative process, the tested specimens have cracks of differing sizes. The reason for this is that the detection of cracks between the iteration periods is not always clear. It is thus possible that test specimens in which cracking has already occurred are not clearly detected until several iteration periods have been completed and the crack is therefore larger. In order to define uniform failure conditions, the crack initiation fatigue life of each individual test specimen was calculated on the basis of the experimental fatigue life values and using the crack propagation calculation described above. For this purpose, the fracture surfaces of the individual test specimens were laid open using the procedure described above and the cracks measured.

Figure 12 shows the failure S-N curves and the S-N curves without (calculated) crack propagation.

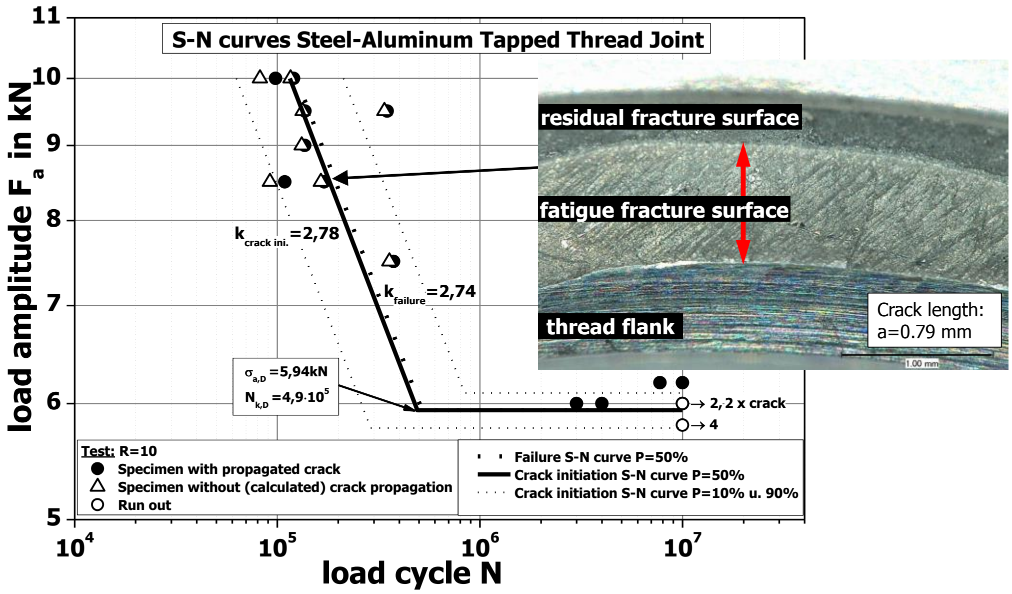

Figure 12. S-N curve defined using experiments after subtraction of the number of stress cycles for crack propagation

5. Comparison of Results

Figure 13 shows the comparison of the S-N curves that were calculated and those that were defined using experiments.

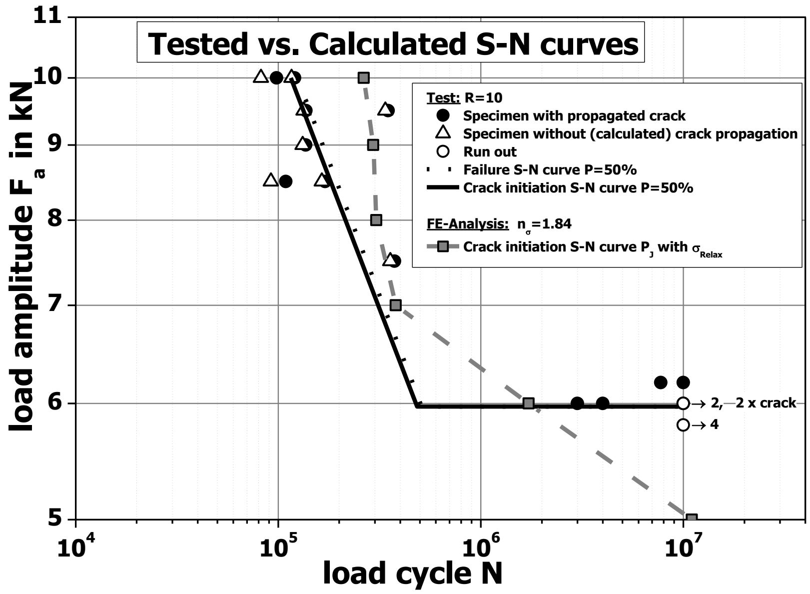

Figure 13. Comparison of the S-N curves defined by calculation and by experiments

6. Summary

A calculation-based estimation of the rating life of a threaded joint, which cannot be calculated using regulations (VDI, 2003 / FKM, 2013), was carried out during this project. The basis for this calculation is the concept according to (Schneider, 2011). In addition, a stress intensity solution that can be used to describe the crack propagation that occurs in the component being analyzed here was calculated on the basis of the threaded joint's FE model.

Using ultrasonic testing, it was possible to carry out fatigue tests on the joint, which produced different-sized cracks. An individual failure criterion was then determined by individual calculation of the number of stress cycles for crack propagation for the individual tests, using the numerical model. The experimental S-N curve for incipient cracking that was extrapolated from this can be compared with the calculated S-N curve.

The comparison of the results showed that the fatigue life had been overestimated with regard to fatigue resistance. Further tests on the model are needed here in order to improve the results. A calculation using the 3D model may be necessary. This might, for example, allow a more reliable mean load to be determined based on the tightening procedure and the influence of the thread pitch to also be mapped.

7. References

1. Verein Deutscher Ingenieure (VDI): Systematic calculation of highly stressed bolted joints – Joints with on cylindrical bolt 2230 Part 1, 2003.
2. Forschungskuratorium Maschinenbau (FKM): Analytical Strength Assessment of Components, 6th revised ed. Frankfurt am Main, 2013.
3. Schneider, R.: Örtliche Bewertung der Schwingfestigkeit von Gewindeverbindungen, Dissertation Darmstadt, 2011.
4. Seybold, R.: Finite-Elemente-Simulation örtlicher Beanspruchungen in Schraubengewinden, Dissertation. Darmstadt 2006.
5. Abaqus Users Manual, Version 6.12-1, Dassault Systémes Simulia Corp., Providence, RI.
6. Vormwald, M.: Anrisslebensdauervorhersage auf der Basis der Schwingbruchmechanik für kurze Risse, Dissertation, Darmstadt 1989.
7. Forschungskuratorium Maschinenbau (FKM): Fracture Mechanics Proof of Strength for Engineering Components, 3rd ed. Frankfurt, M. 2009.

8. Acknowledgements

Supported by:

Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

IGF project 16920 N/1 by the FKM - Forschungsvereinigung Forschungskuratorium Maschinenbau e.V. - , Lyoner Straße 18, 60528 Frankfurt am Main, Germany, was subsidized by the German Federal Ministry for Economic Affairs and Energy via the AiF as part of its subsidization program for industrial research and development partnerships (IGF) following a resolution by the German Federal Parliament.