Fatigue analysis of threaded connections using the local strain approach

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Abstract

The fatigue assessment of bolts and bolted joints is done using nominal approach, for example the German VDI guideline 2230 [1]. For threaded components, the nominal approach and therefore the guideline is no more applicable. The calculation of the fatigue strength of threaded connections according to the German FKM guideline “Analytical strength assessment for machine components” [2] does not lead to satisfying solutions. So far, there is no procedure for the assessment of general threaded connections. Based on the mechanics of the local strain approach the paper shows a fatigue assessment of threaded components and general threaded connections. Prediction results are compared to own experimental data from tested bolt and nut connections in different nominal sizes, different strength categories and subjected to high and low mean stress. A simple model to describe the local cyclic creep as a function of stress amplitude is developed. Furthermore the phenomena related to transferability (size, stress gradients, multiaxiality, crack growth) are discussed.

Keywords: fatigue life prediction; simulation; finite element method; bolts; threaded connections; local strain approach; high mean stress; sharp notched components; damage parameter

1. Introduction

Bolted joints belong to the most important connections in construction engineering. Bolts are sharp notched components, thus the fatigue strength is critical. For bolt connections with standard screws, the bolted joint is the critical part, hence the nominal approach can be used (e.g. guideline VDI 2230, Eurocode 3). For different connections, like screw connections with thin-walled inner threads, in which failure occurs in the inner thread (Fig 2), or big screws (>M38), for which the testing of load capacity is very elaborate, the nominal stress concept is no more applicable. Therefore it is necessary to assess the fatigue strength by local approaches. In the following, a general concept for the fatigue life prediction of threaded connections is presented. The concept is derived for constant amplitude.

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The local strain approach of components is described in [3], here the elastic and elastic-plastic stresses and strains arising at the critical locations of the component are computed. The failure criterion is crack initiation.

In Fig 1 the general procedure is shown, for the prediction of bolted joints the input data could be separated in:

- material dependent input data: Static and cyclic stress-strain curves, strain-live curves and cyclic stress relaxation curves are required
- and load- and geometry dependent input data: The sequence of reversal points of external loads an macrographs of the notch radius.

The determination of the local stress-strain hysteresis is done by FE-computation. For the assessment of the damage of each local stress cycle, the strain-live curve is used. The mean-stress is assessed by damage parameters. One, often used, is the damage parameter $P_{\text{SWT}}$ according to Smith, Watson and Topper [4], another parameter based on a fracture mechanics approach is the parameter $P_{\text{j}}$ according to Vormwald [5].

The connections are tested and assessed under different strength categories and under high ($S_{\text{m}}=0.7\times R_{\text{p0.2}}$) and low mean stress. Low mean stress is expressed by the stress ratio $R=0.1$. To consider the applicability of the concept
for different nominal sizes, M10 and M16 bolted joints were tested. The examined screws were rolled before heat
treatment, thus no residual stress state had to be assessed before calculation. For bolted joints failure always occurs
in the first load-bearing thread turn of the bolt. For tapped and thin-walled nut connections failure occurs in the first
load-bearing inner nut thread.

![Diagram of different types of screws and nuts](image)

Fig 2: Overview of different basic conditions applied to the investigated and predicted threaded connections

Generally the cyclic $\sigma$-$\varepsilon$-curve is used for the assessment of variable amplitude loads for the local-strain-approach.
For the local prediction of threaded connections under constant-amplitude (CA) and high mean stress, it is not
accurate to use the cyclic $\sigma$-$\varepsilon$-curve. The local stress relaxation could not be considered adequate in the FE-model
itself. In the area of fatigue live local elastic hysteresis occur. Due to this small elastic hysteresis generally no strain-
hardening or strain-softening occurs under high mean stress and small constant amplitude. The hysteresis remain on
the static $\sigma$-$\varepsilon$-curve due to high static pretension ($S_m=0.7*R_{P0.2}$) of the connection.

In the area of fatigue strength large, partly plastic, hysteresis occur which show strain-hardening or strain softening
behaviour. Therefore a concept of considering local stress relaxation is introduced in the following chapter 2.2.

2. Fatigue analysis of threaded connection using the local strain approach

2.1. FEM Simulation of the local stresses

To obtain local notch stress-strain curves 2-dimensional FE-models were created. Analyses were performed with
the ABAQUS finite element program. These were compared to 3d-models which were more sumptuous in
computing time, with the result that 2d-calculations are sufficient. The geometry of bolted joints is derived as
average value of the “ISO general purpose metric screw threads” [6]. As the corner radius is important for the
resulting local stress-strain curves, micrographs of the current corner radius were conducted and applied to the FE-
model.

In the notch region the FE-Model is fine, at least 15 elements in the radius are used. This leads to converging results
[7]. For meshing 8-node quadratic elements are applied, with quadratic approaches for elastic calculations and linear
approaches for elastic-plastic calculations. As stress relaxation could not be considered in the FE-Model, kinematic
hardening law is applied. Surface- to surface contact in the thread is used with a friction coefficient of $\mu=0.1$. The maximum stress concentration is located in the first load-bearing bolt thread (Fig 3 [8]).

2.2. Concept of deriving local hysteresis by considering cyclic stress relaxation for fatigue assessment

As cyclic stress relaxation could not be considered in the FE-model, a simple concept of deriving local hysteresis is presented in the following. In the following principal stress -strain curves are plotted as these show better correlation with test results compared to assessment by equivalent stress-strain-curves (cp. chapter 8)

1) In a first step the static stress –strain curve is used and the maximum static stress $\sigma_{o,\text{Static}}$ is assessed (Fig 4) as bolted joints are usually used under high static pretension ($S_n=0.7*R_{P0.2,0}$).

2) In a second step the cyclic stress-strain curve is applied to the FE-model and the notch stress-strain curve is plotted (Fig 5). Only the cyclic part of the hysteresis is calculated by the cyclic $\sigma-\epsilon$-curve. The local stress $\Delta\sigma$ and local strain amplitude $\Delta\epsilon$ are derived.

3) As cyclic stress relaxation occurs in the sharp notched corner, in a third step, cyclic stress relaxation experiments are conducted. Stress relaxation experiments are carried out by strain controlled tests, mean strain and strain amplitude is controlled. High mean strain ($\epsilon_m$$\approx$1%) is applied (Fig 6) to the smooth
specimen. The magnitude of mean strain \( \varepsilon_m \) has to be chosen so that \( \varepsilon_m + \varepsilon_a \) is less than elongation without necking \( A_g \) to avoid cyclic creep. The calculated strain amplitude \( \Delta \varepsilon_a \) from step 2 is then superimposed which leads to the stress relaxation of the maximum stress \( \Delta \sigma_{o,Relax} \).

**Fig 6:** Strain-controlled stress relaxation testing under high mean strain.

- **Fig 7:** Combining maximum static stress an cyclic hysteresis by considering local stress relaxation

4) In a fourth step the cyclic hysteresis is attached to the maximum static stress \( \sigma_{o,Static} \) by considering the local stress relaxation \( \Delta \sigma_{o,Relax} \) (Fig 7).

By applying this procedure, local \( \sigma-\varepsilon \)-hysteresis are derived by considering local stress relaxation, without application of a complex material model in the FE.

2.3. Assessment of local stress-strain-curves

The achieved hysteresis could be assessed by several damage parameter (e.g. \( P_{SWT} \), \( P_\varepsilon \), \( P_b \), \( P_I \)). In the following \( P_{SWT} \) according to Smith, Watson and Topper [4] and \( P_I \) according to Vormwald [5] are introduced. Both Parameters are compared in detail in chapter 4.

\[
P_{SWT} = \sqrt{\sigma_o \varepsilon_o E}
\]

\[
P_I = 1.24 \cdot \frac{\Delta \sigma_{o,Relax}}{\sigma_o} + \frac{1.02}{\sqrt{\varepsilon_o}} \cdot \Delta \sigma_{o,Relax} \cdot \Delta \sigma_{o,Max}
\]

As damage parameter \( P_I \) delivers more appropriate results it is discussed furthermore in detail. The local mean stress in the notch is very high for high global pretension \( (S_m=0.7 \cdot R_{P0.2}) \) of the bolted joint. Regarding the fracture mechanics based parameter \( P_I \) this results in the fact that the crack is always open for the region of high endurance limit. The crack opening stress \( \sigma_{op} \) is much lower than the minimum stress \( \sigma_o \) of the hysteresis, even under consideration of local stress relaxation.

\[
z_{op} = \varepsilon_o + \left( \varepsilon_{op} - \varepsilon_o \right)/E + 2 \cdot \left( \frac{(\sigma_{op} - \sigma_o)}{E} \right)^{1/2}
\]

Therefore it is possible to neglect the local stress relaxation in the region of high endurance limit and attach the cyclic hysteresis directly to the maximum static stress \( \sigma_{o,Static} \) without error. The stress- supporting factor is taken into consideration by shifting the P-N curve in P direction by the respective factor. The surface roughness is slight and can be neglected.
2.4. Consideration of crack propagation

In a last step, the crack propagation between initiation crack fatigue life and life to failure is considered in finite life. According to Kremer [9] it can be up to $N = 1 \times 10^6$ cycles. The crack propagation is calculated according to the German guideline “Fracture Mechanics Proof of Strength for Engineering Components” [10] by using FracSafe [11]. The crack model of a hollow cylinder with long incipient crack outside was chosen as stress gradients could be calculated by this crack model. Stress gradients are derived from elastic FE-simulation (Fig 9). The initial crack length is chosen as $a=0.1$ mm.

3. Calculation of the fatigue strength for M10 10.9 bolted joint under high tensile load ($S_m=0.7 \times R_{P0.2}$)

In the following, the introduced procedure is exemplary applied to a M10 10.9 bolted joint. The considered supporting effect is $n=1.2$. The cyclic material data is examined on smooth specimen revolved out of the screw itself. By measuring hardness ($HV=0.3$) in the corner radius and in the middle of the screw it is shown that mechanical properties are transferable. The stabilized cyclic stress-strain (CSS) and the strain–life curves are then determined by strain controlled tests. In Fig 10 the static and cyclic S-N curves of the bolt material 41Cr4 show cyclic softening behaviour. The strain-live curve ($\varepsilon$-$N$-curve) in Fig 11 is analysed as initiation crack curve. Due to time consuming testing, the endurance limit is determined stress controlled and then converted to endurance limit strain.

By applying static and cyclic $\sigma$-$\varepsilon$-curves, the local hysteresis for an external load of $F_A=3$ kN, which occurs in the area of infinite life, is calculated (Fig 12). The calculated strain amplitude $\varepsilon_a$ for the cyclic hysteresis is measured. In a next step, the strain amplitude $\varepsilon_a$ is tested concerning stress relaxation. In a strain controlled test, the strain amplitude $\varepsilon_a$ is therefore applied to the smooth specimen under high mean strain of $\varepsilon_m=1.1$ % (Fig 13). As Fig 13
shows, stress relaxation does not occur. Thus the cyclic hysteresis is attached directly to the maximum static stress $\sigma_{O,static}$ (Fig 12).

The same procedure is done for an external load amplitude of $F_A=9$ kN which is relevant in the upper area of finite life (Fig 14 and Fig 15). A strain amplitude of $\varepsilon_a=0.4\%$ is calculated under consideration of the cyclic $\sigma$-$\varepsilon$-curve (Fig 14). In the strain controlled experiment the calculated strain amplitude $\varepsilon_a$ is applied under high mean strain of $\varepsilon_m=1.1\%$. As Fig 15 shows stress relaxation of $\Delta\sigma_{O,Relax}=250$ MPa occurs. Therefore the cyclic hysteresis is attached under consideration of $\Delta\sigma_{O,Relax}=250$ MPa to the maximum static stress $\sigma_{O,static}$ (Fig 14).

For assessment with damage parameter $P_J$ the calculated crack opening stress $\sigma_{op}=-450$ MPa is much lower than the minimum stress $\sigma_u=300$ MPa of the hysteresis, even in the area of finite life.

By applying this procedure the crack initiation S-N Curve (Fig 16) is derived. For exact prediction of the finite life fatigue crack propagation is considered by applying the FKM-guideline [10]. The crack propagation factors for the analyzed material 41Cr4 ($R_m=1121$ MPa) are derived from similar material 42CrMo4 ($R_m=1100$ MPa) under high mean stress ratio $R_K=0.5$ as $C=7.58E-8$ and $m=2.63$. The predicted S-N curve to failure (Fig 16) is compared to the $P=50\%$ reference screw S-N curve.

In the fatigue limit as well as in the finite life strength the calculated S-N curve shows very good correlation with the tested screw S-N curve.
4. Multiaxiality and Damage parameter $P_{SWT}$

In the following, the effect of multiaxiality and the application of damage parameter $P_{SWT}$ is discussed.
Multiaxiality
The multiaxial state of stress can be quantified by the ratio of maximum principal stress $\sigma_1$ to equivalent stress $\sigma_{VM}$.

For a load amplitude $F_A = 6\text{kN}$ the calculated ratio $\frac{\sigma_1}{\sigma_{VM}} \approx 1.2$ is very small (Fig 17). The $P_J$-model allows the consideration for biaxial stress by the adjustment of the constraint factor $\alpha$. For a given biaxial state of stress the constraint factor $\alpha$ is obtained by linear interpolation between the limit conditions of plane stress ($\sigma_2 = 0$, $\alpha = 1$) and plane strain ($\sigma_2 = \nu \sigma_1$, $\alpha = 3$) which leads for $\nu = 0.3$ to

$$\alpha = \frac{1}{0.15} \frac{\sigma_2}{\sigma_1} + 1$$

As the multiaxial-factor $\alpha$ effects the crack opening stress $\sigma_{op}$ which is, under high mean stress ($S_{\text{m}} = 0.7 \times R_{0.2\%}$), still much smaller than the hysteresis minimum stress $\sigma_u$ (cp cap 2.3), there is no effect for threaded connection.

In conclusion, the effect of multiaxiality for threaded connections under high mean stress could be neglected as the ratio $\frac{\sigma_1}{\sigma_{VM}}$ is very small, and the constraint factor $\alpha$, for the $P_J$-model, does not effect the fatigue limit.

Damage parameter $P_{SWT}$ compared to $P_J$

Fig 18 and 19 predicted S-N curves by damage parameter $P_{SWT}$ [4] and $P_J$ based on principal stress and equivalent stress are shown. Compared to damage parameter $P_J$, the parameter $P_{SWT}$ is always dependent on the maximum stress $\sigma_1$. Parameter $P_J$ shows very different behaviour for high local mean stress. Once the crack opening stress $\sigma_{op}$ is smaller than the hysteresis minimum stress $\sigma_u$ ($\sigma_{op} < \sigma_u$), the crack opening stress $\sigma_{op}$ has to be set as $\sigma_u$. Hence the crack is fully open, further increase of the amount of hysteresis does not effect the damage parameter as it is only dependent on the strain-amplitude. Thus $P_{SWT}$ and $P_J$ lead to very different results (Fig 18 and 19).

Fig 19 in assessment by principal stress or equivalent stress. In general, the prediction for principal stress leads according to $P_{SWT}$ and $P_J$-model to results with good accuracy. Nevertheless, prediction after $P_J$-models is preferred, as the physical model is more elaborate [12] and results are, in general, slightly more conservative in the fatigue endurance limit, compared to $P_{SWT}$.
Prospective: Prediction of threaded connections under small mean stress ratio (R=0,1)

The local strain approach for threaded connection under small mean stress ratio (R=0,1) leads to non-conservative results compared to the test results. For screws, the endurance limit is independent of the means stress, which is different to the materials mean-stress-dependency. One probable explanation might be, that geometrical tolerances are not considered in the FE. By FE could be proven that geometric thread tolerances under high mean stress have almost no influence on fatigue strength due to plastic relocation of stress peaks. Thus the tolerance-effect under small mean stress (R=0,1) is large, due to missing plastic relocation of stress peaks. One suggestion, for the prediction of threaded connections under small mean stress ratio is, to consider geometric tolerances in the FE-models.

5. Conclusions

For the examined general threaded connections, under high mean stress (S_m=0,7·R_{0,2}%), the introduced local strain approach permits with good accuracy for engineering purposes of fatigue live until fracture. The concept was successfully applied and compared to test results for screws under different strength categories and nominal sizes. Furthermore the applicability for general threaded connections like tapped nuts and thin walled nuts was proven. The prediction is based on principal stress-strain hysteresis. Cyclic hysteresis is attached to static maximum stress by considering stress relaxation. The damage parameter P_J delivers more accurate results than the damage parameter P_{SWT}.

For the local strain prediction of threaded connections under small mean stress ratio (R=0,1) thread tolerances need to be considered to achieve results with good accuracy. One suggestion is to consider thread-pitch difference as P_{OUT}=99,7%*P_{SCREW}.

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