MODELLING AND VALIDATION OF FATIGUE LIFE CALCULATION METHOD FOR SHORT FIBRE REINFORCED INJECTION MOULDED PARTS

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Abstract

The quasi-static and fatigue behaviour of a 30wt.% milled glass fibre reinforced polyetherimide was investigated. Classical influences on fatigue such as mean stress and stress gradient and additional plastic-relevant influences such as fibre orientation, weld line, moisture and elevated temperature were characterized. Based on the test results, phenomenological models describing these influences on fatigue life calculation method by local stress concept were deduced. As validation for the method a continuous simulation chain from moulding to fatigue failure was applied to a real part. The simulation results were compared with fatigue tests of the part. It is shown, that the method leads to accordance of failure position and slope of the S/N-curve. Also fatigue strength is calculated quite well but conservative.

1. Introduction

Short fibre reinforced (sfr) thermoplastic parts more and more substitute components made of metal so far. Especially in the automotive industry the usage of these materials rises for cyclically loaded parts too because of their high potential in light weight design, functional integrations and the advantage of the cost efficient manufacturing process by injection moulding. For dimensioning of cyclically loaded parts, the knowledge of fatigue data and influence on fatigue behaviour is necessary. As shown in [1, 2, 3, 4, 5] the local stress concept which was developed for metals is also applicable for sfr plastics, if the simulation chain is extended with the manufacturing process and thereby induced anisotropic material behaviour (cf. Fig. 1).
In this concept the local S/N-curve is calculated by general material behaviour (in terms of S/N-curves) and mathematical models describing influences such as stress concentration, mean stress, local fibre orientation, weld lines, moisture, and so on. With additional knowledge of stress distribution and load-time-history the calculation of damage accumulation can be performed to describe fatigue endurance.
In this paper the material behaviour of a 30wt.% milled glass fibre reinforced polyetherimide (PEI-GX30) is evaluated by quasi-static tests and fatigue tests. With these tests, influences regarding fibre orientation, weld line, temperature, moisture and type of loading are analysed. Based on the test results phenomenological models describing these influences are deduced.

The fibre orientation and the characteristic layer structure in injection moulded parts additionally, influence the stress distribution in the test specimen [12]. Therefore the orientation influence model is evaluated in two different ways. Conventionally, by plotting nominal endurable stress amplitude against average fibre orientation in load direction. And otherwise, by using of local endurable stress amplitude in consideration of stress rearrangement due to characteristic layer structure in specimen and local fibre orientation proportion in load direction. After modelling the simulation chain was applied to a lens holder using a fictitious load case. Validation of the simulation method was performed with fatigue tests of the real part.

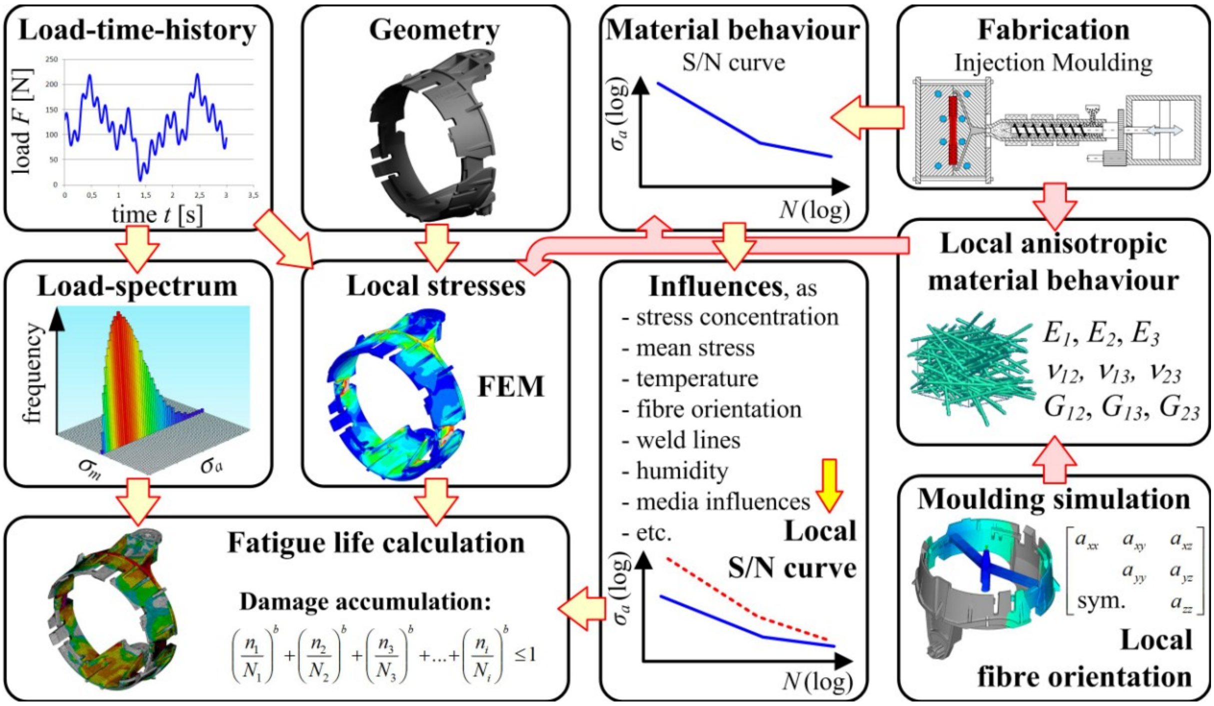

Figure 1. Local stress concept for fatigue life calculation of short fibre reinforced injection moulded parts

2. Experimental

The investigated material is a polyetherimide filled with 30wt.% of milled glass fibres (PEI-GX30). For characterisation of material behaviour standardised dog bone type specimens ([6], ISO-527-2, type 1A, cf. Fig. 2) and short specimens milled from plates (100x100x4 mm³) in orthogonal directions (cf. Fig. 3) are used. To characterise the influence of a weld line the standardised specimen is manufactured by using a second gate as illustrated in Fig. 2. The storage of specimens takes place in indoor climate whereby after injection moulding the mass of each specimen is determined with a precise scale. Therefore the estimation of the content of moisture in the specimen at the time of testing is possible.

The tensile tests and fatigue tests were performed on servo-hydraulic and electro-mechanical test rigs of the companies Zwick/Roell, BOSE and MTS which are not explained in this paper. For strain measurement an extensometer was mounted directly on the specimen. The majority of the tests were executed under laboratory conditions (23° C, 50 % relative humidity). To realize elevated temperatures a temperature chamber was used.

Because of different loading conditions (tension and three point bending test) quasi-static tests were executed strain controlled with a strain rate of $d\varepsilon/dt = 0{,}909$ %/min. This strain rate corresponds to a piston speed of about 1 mm/min in the case of a clamping length of 110 mm.

Constant amplitude fatigue tests were performed stress controlled with a stress ratio of $R = 0.1$ and a frequency of $f = 10$ Hz. To avoid hysteretic heating the temperature was measured during fatigue tests.

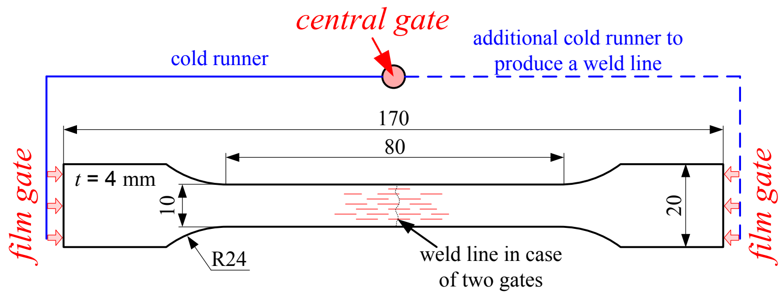

Figure 2. Standardised dog bone type specimen according to [6] Type 1A with an optional possibility to create a weld line (WL) in the middle of the specimen by using a second runner

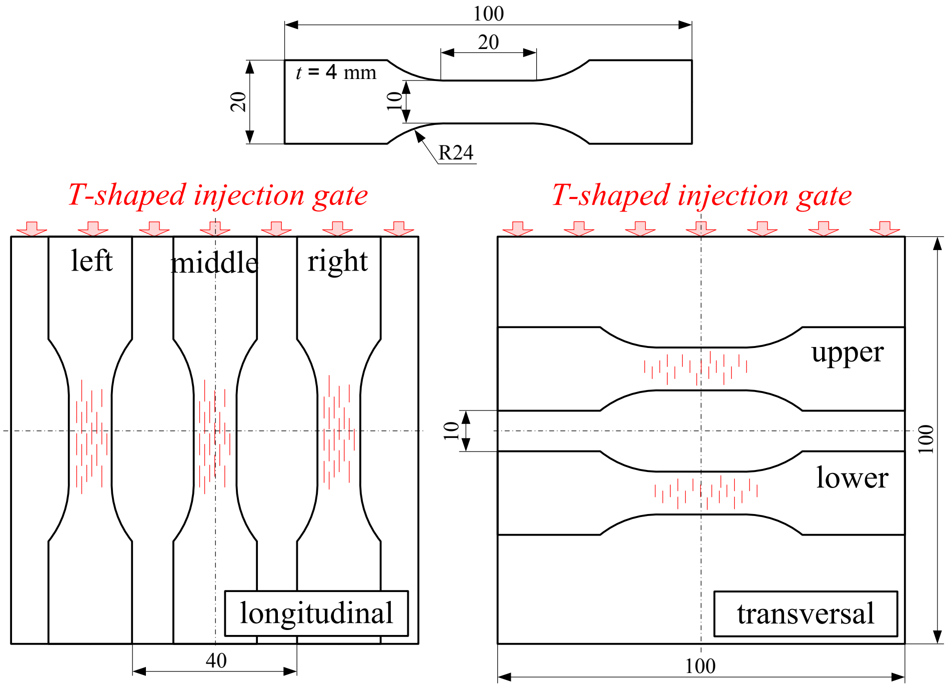

Figure 3. Short dog bone specimen modelled after the geometry of ISO-527-2 [6] type 1A milled from plates in orthogonal directions longitudinal (left) and transversal (right) to main fibre orientation

The following results of quasi-static and fatigue tests are not given by absolute values. They are plotted normalised to maximum stress σ_M obtained from in tensile tests of the dry standardised test specimen at room temperature.

2.1 Results of tensile tests

In Fig. 4 the results of quasi-static tension and bending tests on standardised test specimens with different contents of moisture (*com*) are presented. It is shown, that loading (tension vs. bending) has a wide influence on the strength of the material. Under bending load the ultimate strength is about 70 % higher than under tensile load. Furthermore the investigated material seems to be insensitivity against moisture because of its low absorption of water and good hydrolysis resistance. But in Fig. 4 it is shown that especially maximum stress of tensile tests depends significantly on content of moisture.

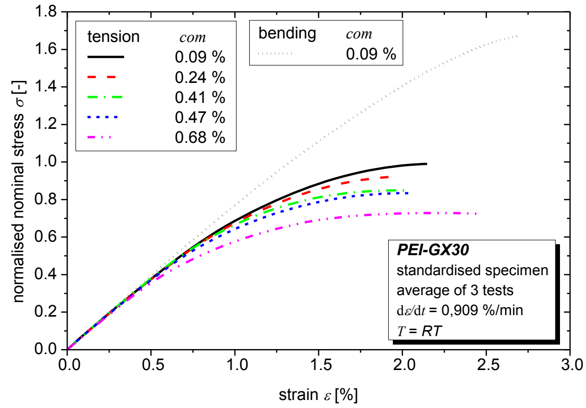

Figure 4. Results of quasi-static tension and bending tests of standardised test specimens with different contents of moisture *com*

2.2 Results of fatigue tests

As shown in Fig. 5 the investigated material has no distinctive fatigue limit or change of slope in test range in accordance with [7, 8, 9]. Furthermore the slope of S/N-curves is independent from specimen type (standardised or short specimen), from main fibre orientation (longitudinal vs. transversal), from type of loading (tension vs. bending) and from ambient temperature (23° C vs. 120° C). Only S/N-curves of the weld line are a little bit steeper.
When considering fatigue strengths of S/N-curves under tension and bending load in Fig. 5 left, it can be seen that the material has a distinctive support effect (cf. also [9, 10]). Due to the weld line fatigue strength drops by about 55 % from fatigue strength of unaffected standardised specimen.
The influence of main fibre orientation is shown in Fig. 5 right at room temperature and 120° C. At 120° C this influence is slightly more pronounced than at room temperature. The average factor between fatigue strength of longitudinal to transversal extracted short specimens is about 1.3. Due to the elevated temperature of 120° C the fatigue strength of longitudinal specimen drops by about 70 % from fatigue strength at room temperature.

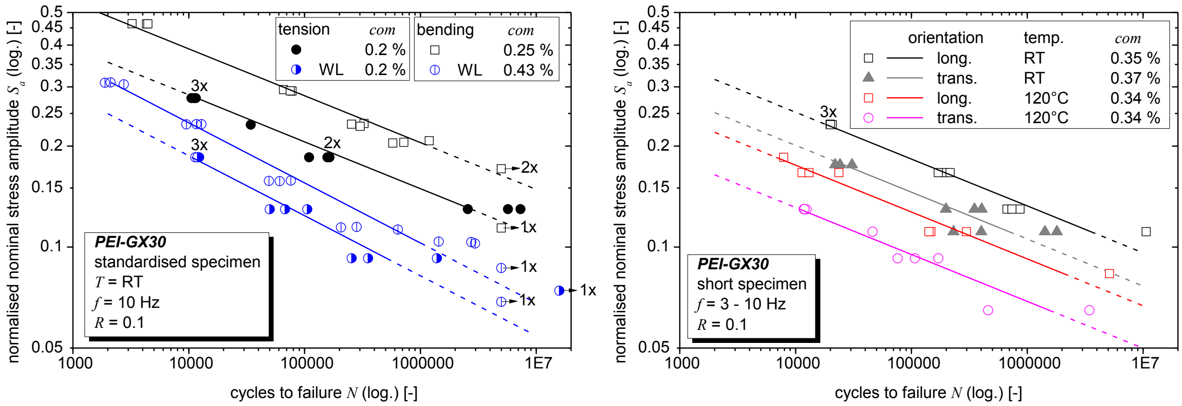

Figure 5. Results of fatigue tests on standardised (left) and short (right) dog bone specimens

3. Modelling

For calculation of local S/N-curves material models in form of mathematical formulations describing fatigue strength regarding the considered influences are necessary. Based on these models local fatigue strength σ_a is calculated according to Equ. 1 where $\sigma_a(\alpha)$ is the orientation dependent fatigue strength at e.g. $N = 10^6$ cycles to failure and S corresponds to the safety factor. $\sigma_a(\alpha)$ is calculated by using the material model for anisotropic fatigue strengths (cf. Fig. 6 on the top left) and the procedure described in [5, 11]. The *f*-values are exemplary influence factors for fatigue like stress gradient f_{Sg}, mean stress f_{Ms}, statistical influence f_{St} and the A'-values are plastic-relevant influences such as moisture A_M', temperature A_T', ageing A_A' and so on.

$$\sigma_a = \frac{\sigma_a(\alpha)}{S} \cdot f_{Sg} \cdot f_{Ms} \cdot f_{St} \cdot A_M' \cdot A_T' \cdot A_A' \ldots \qquad (1)$$

Because of different contents of moisture (*com*) in specimens at the time of testing the material properties are converted to dry condition for deducing material models by using the model shown in Fig. 6 on the bottom left. This model for influence of content of moisture is determined by quasi-static tension tests (cf. Fig. 4) and points representing fatigue tests which are not presented in this paper. It is shown that Young´s modulus is almost independent of content of moisture while strength values are dropping significantly with increase of content of moisture.

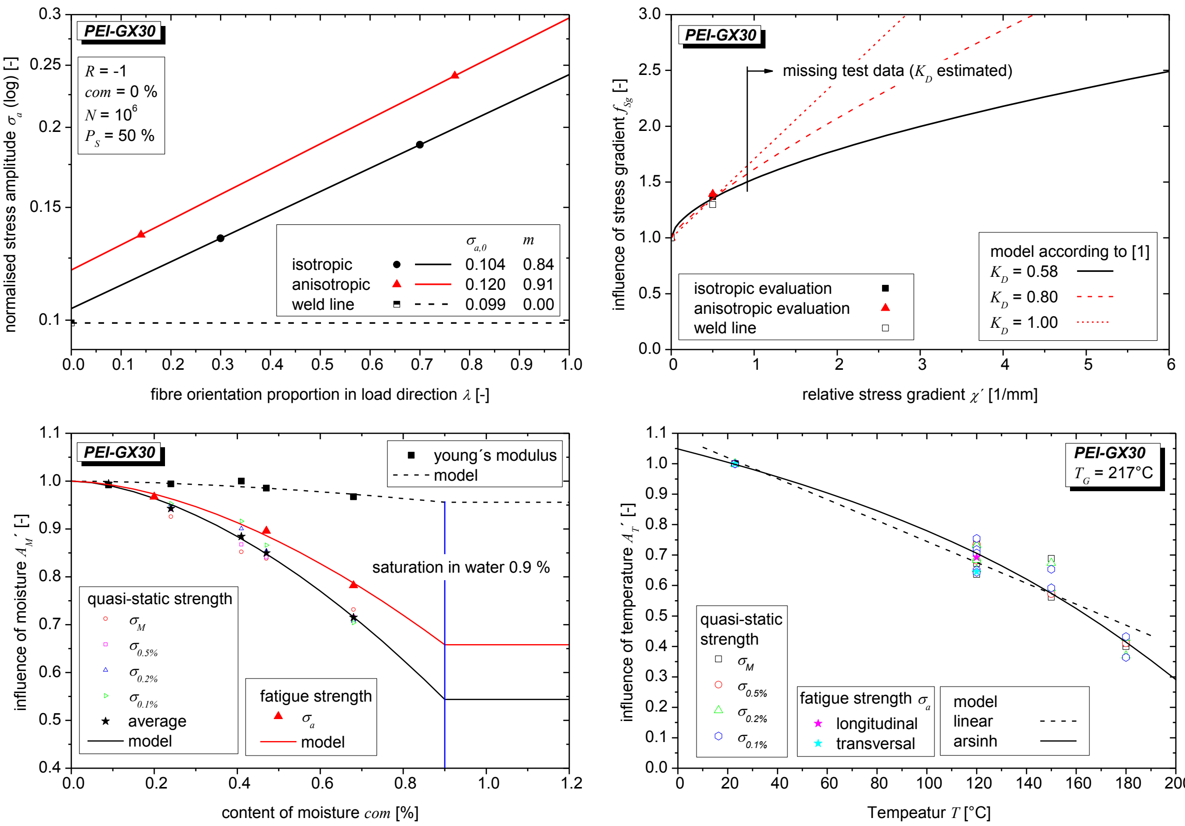

Figure 6. Mathematical models characterising anisotropic fatigue strength (top left), local effect of stress concentrations (top right), influence of moisture (bottom left) and elevated temperature (bottom right)

The influence of fibre orientation and weld line is characterised by using the model shown in Fig. 6 top left. For fatigue strength calculation of the weld lines an orientation independent value from S/N-curve for tension in Fig. 5 left, converted to a stress ratio of $R = -1$ is used. The orthotropic fatigue strengths of unimpaired material behaviour are calculated by a linear correlation between fatigue strength σ_a which was evaluated by performing tests at stress ratio of $R = -1$ (not shown in this paper) and fibre orientation proportion λ in single logarithmic scale according to [3, 5]. This model is evaluated in two different ways. Isotropic by using

nominal stresses assigned to average fibre orientation of test specimen and anisotropic by using realistic local stresses and local fibre orientation on positions of failure. The local stresses are calculated by finite element simulation considering anisotropic material behaviour and characteristic layer structure in the specimen. As shown the evaluation with the local point of view estimates higher endurable fatigue strengths of about 20 %.
To characterise the local support effect of stress concentrations (cf. Fig. 6 top right) which is significant for fibre reinforced thermoplastics [8, 9, 10], results from tension and bending fatigue tests (cf. Fig. 5 left) are used according to [1]. The exponent K_D which describes the flattening of the model is estimated on the basis of results from [8] and [10]. The variation of this exponent ($K_D = 0.58$, 0.8 and 1.0) should demonstrate the uncertainty of the model in the area of high relative stress gradients χ' if test results are not available for the material.
The influence of loading at elevated temperature on the strength properties of the material is shown in Fig. 6 on the bottom right. This behaviour shows that evaluated strength properties of the material (quasi-static and fatigue) are influenced by temperature in almost the same manner.

4. Validation

In the validation process of the method the closed simulation chain was applied to a lens holder from Zizala Lichtsysteme GmbH. The moulding simulation was performed with the software tool Cadmould®. Anisotropic elasticity as well as fibre orientation tensors for each finite element were mapped to an Abaqus® mesh by using the software tool Converse®. The anisotropic structure analysis with Abaqus® was realised for two fictitious load cases. The first load case is a tension load, so that inside of the lens holder two critical positions are appearing as shown in Fig. 7 left exemplarily. The second load case is a compression load, so that critical positions are appearing on the outside of the lens holder similar to the first load case. Fatigue life calculation was performed with the software tool Femfat® with the dry as moulded data set and a stress ratio of $R = 0.1$. The considered influences are mean stress, stress gradient and fibre orientation at room temperature.

For validation of material models dry as moulded lens holders were fixed on a servo hydraulic test rig as shown in Fig. 7 right and tested cyclically using the defined fictitious load cases with a stress ratio of $R = 0.1$. The test frequency was 5 Hz. Because of the thin design no hysteretic heating occurred.

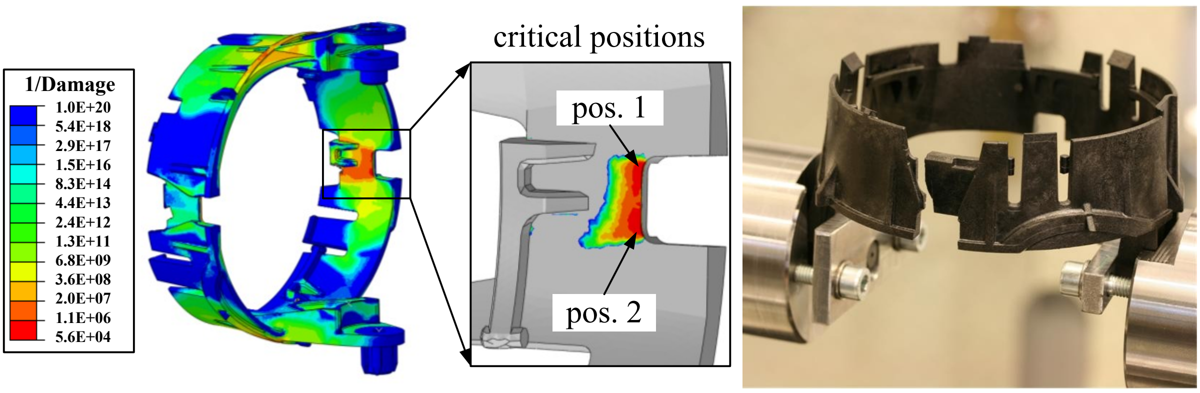

Figure 7. Exemplary representation of fatigue life distribution on the lens holder calculated for the load case one (left) and failure of the tested lens holder on a servohydraulic test rig (right)

As shown in Fig. 7 the position of failure could be estimated very well by the simulation method. If the calculated local S/N-curves of two respective critical positions are compared with results from the fatigue tests the accuracy of the method can be demonstrated (cf. Fig. 8). The slopes of calculated S/N-curves are similar to the test results. Furthermore by using the anisotropic evaluated material model which implements fibre orientation (cf. Fig. 6 top left) the results are better than the ones using the model with standard evaluation by nominal stresses. Generally the method gives conservative results with deviation factors along the stress axis of 1.6 for load case one and 1.2 for load case two.

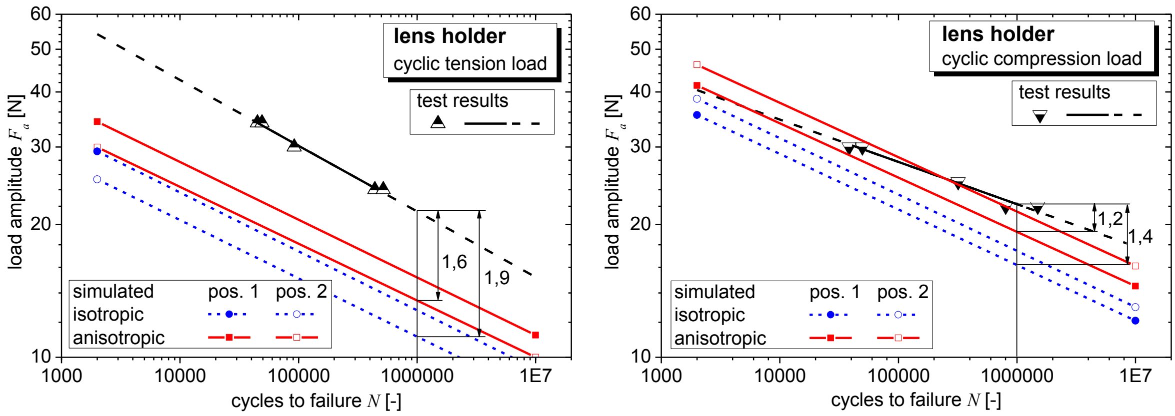

Figure 8. Comparison of calculated local S/N-curves in the critical positions one and two with real test data from load case one (left) and load case two (right) using the isotropic and anisotropic evaluated material model

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