NUMERICALLY AIDED PREDICTION OF FATIGUE LIFE OF HEADED STUDS UNDER STEEL FAILURE

NUMERISCH BESTIMMTE VORHERSAGE DER ERMÜDUNGSTRAGFÄHIGKEIT VON KOPFBOLZEN BEI STAHLVERSAGEN

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SUMMARY

Fatigue design of fastening systems requires extensive experiments to be carried out for the approval and assessment. With an objective to possibly generalize the fatigue life assessment for fasteners with steel dominated failure, a method for prediction of fatigue life is investigated in this paper. An approach based on stress-life concepts supported by local stress evaluations using finite element analysis is investigated for its potential to predict the fatigue life of headed studs under tension load. The comparison of the predicted fatigue life with the observed test results shows the potential of the approach for fatigue life assessment of fasteners under steel dominated failures.

ZUSAMMENFASSUNG

Die Bemessung der Ermüdungstragfähigkeit von Befestigungssystemen erfordert umfangreiche Versuche für die Zulassung und Bewertung. In diesem Artikel wird eine Methode zur allgemeinen Vorhersage der Ermüdungslebensdauer von Verbindungselemente mit Stahlversagen untersucht. Ein Ansatz, basierend auf einem Spannungs-Lebensdauer-Konzepten, soll die Vorhersage lokaler Spannungen von Kopfbolzen unter Zugbelastung anhand Finite-Elemente-Analysen ermöglichen. Die Gegenüberstellung der numerischen Untersuchungen mit den Versuchsergebnissen zeigt, dass der numerische Ansatz zur Beurteilung der Ermüdungslebensdauer von Befestigungselementen mit Stahlversagen möglich ist.

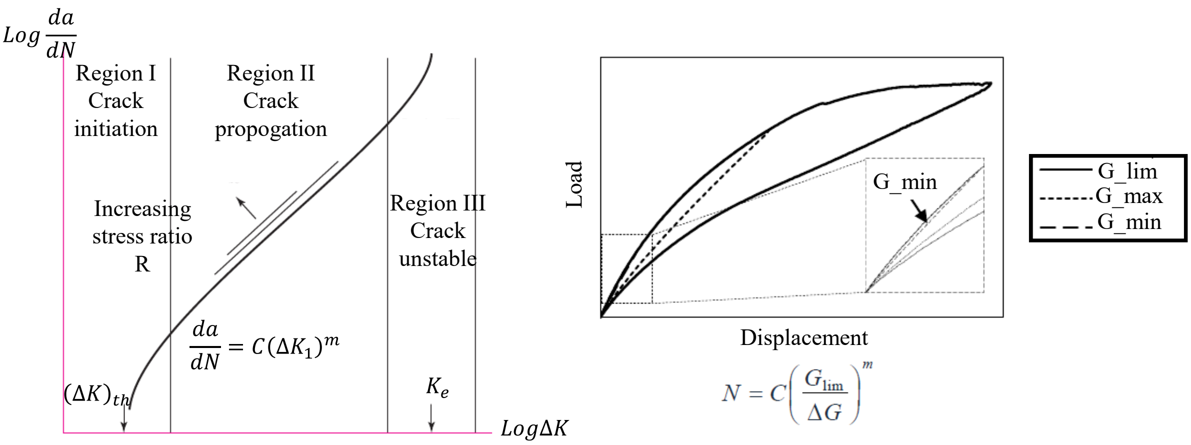
1. INTRODUCTION

Fasteners are invariably used for realizing connections in the construction industry. These components are often subjected to varying load situation through their service life. To this end, the fatigue design of such system is essential to ensure the desired service life. The current state of art design practice for fatigue safety in fasteners has been presented comprehensively in [1], [2]. EN 1992-4 [3] provides European standardized regulations for the design of fastenings in reinforced concrete. In case of cyclic actions, the standard requires an additional verification of the fatigue resistance, which are largely based on laboratory experimentation. Provisions for fatigue design of post-installed anchors are available in EN 1992-4 [3] and EOTA TR 061 [4]. The provisions cover anchors subjected to pulsating tension or shear load and alternating shear load. The products must be approved with an European Technical Assessment (ETA) based on the EAD 330250-00-0601 [5]. The process of fatigue design invariably requires conducting experiments on fastening systems under different load situations.

The research project IGF-20458 N [6] under the umbrella of Industrielle Gemeinschaftsforschung (iGF) was undertaken jointly by Materialprüfungsanstalt (MPA) and Institut für Werkstoffe im Bauwesen (IWB) at Universität Stuttgart for study of fatigue behaviour of fastening systems with a focus on steel as the governing failure mode. The research consisted of a combination of benchmark experiments and numerical evaluations directed towards possible methodology for assessment of fatigue characteristics of fastening systems, which could help generalize, to a reasonable extent, the otherwise system specific fatigue design concepts followed in the fatigue design. This paper presents and demonstrates the fatigue assessment methodology considering headed studs as an example application.

2. FATIGUE LIFE PREDICTION

The fatigue assessment approach [7] based on Paris law and using hysteresis energy dissipation criteria for defining the fatigue damage was proposed to be used at the outset for assessment of fastening systems. Toth et al. [7] proposed an assessment method for fatigue life of fasteners under concrete dominated failure with a mathematical formulation like the Paris law (see Fig. 1). The expression consists of two constants (C and m) which are evaluated based on calibration using two experiment benchmark data points. For an evaluation of the hysteresis energy corresponding to a given cycling range, finite element analysis was proposed to be used as a tool. Once the calibration process and evaluation of the constants m and C is done, the number of cycles to failure for any given level of force cycling can be evaluated based on the corresponding hysteresis areas using the FE analysis.



(a) Paris Law for crack growth **(b) Hysteresis based S-N curve fitting**

Fig. 1: Fatigue concepts (a) Paris law [8] (b) Hysteresis based proposal [7]

The hysteresis-based approach was developed for concrete dominated failure modes. Concrete being a brittle and non-homogeneous material, is characterized by distinct hysteresis behaviour at service loads since occurrence of microcracks is expected and quite normal. The present study is however focussed on steel as the dominant failure mode in the fatigue actions. The cycling ranges correspond to load levels well below the ultimate capacity or yielding capacity of the steel. Thus, on a system level, an expectation of hysteresis behaviour at such load levels without idealising some pre-existing defect crack, is not reasonable.

The micro-plane model [9] used for the simulations [7] is essentially an equation fitted to simulate the nominal stress strain characteristics of the material at the element level. The approach was used to assess the fatigue life for steel dominated situation [10]. To this end benchmark studies from literature on steel component specimens [11] were used. Since no defect cracks were explicitly modelled, the hysteresis loops obtained in the process are attributable to numerical parameters within the micro plane model and its physical correlation with actual defects remains questionable and an open topic. It is perhaps because of this reason that a single prediction equation is not capable for reasonable prediction [10] for all the different geometries. These discrepancies with the originally proposed method called for investigation of possible alternate approach for prediction of fatigue life.

A stress-based approach defining fatigue life expressed by a material S-N curve was found to be reasonable for fatigue studies on components with steel dominated response [10]. The same has been applied for prediction of fatigue life of headed studs in this paper.

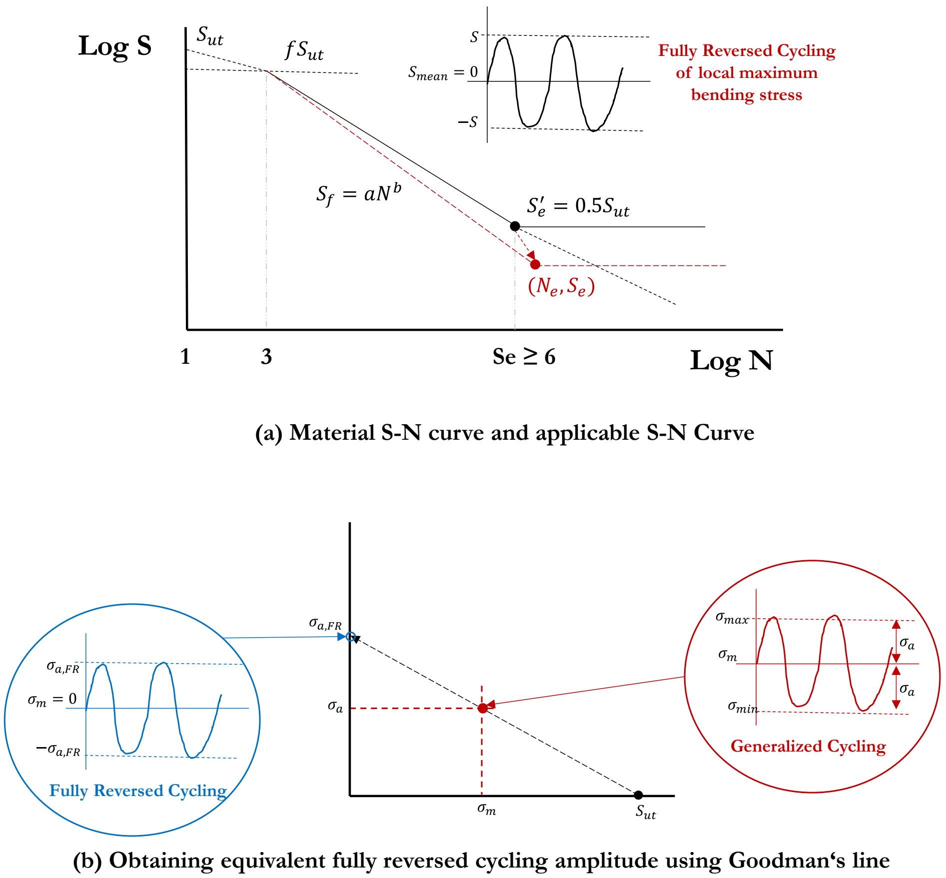


Fig. 2: Stress life concepts for fatigue life (a) S-N curves (b) Goodman's Principle

2.1 Stress-based fatigue life assessment

The concept of stress life is employed for prediction of fatigue life [8] for metal dominated failures in mechanical as well as aeronautical engineering. The method requires establishing a material S-N relation (of the form: $S = aN^b$, see Fig. 2a) which provides the number of cycles to failure as a function of stress cycling amplitude corresponding to fully reversed loads. Such a relationship is obtained for a material by testing a component specimen under rotating bending test set up. A linear relation between the stress and logarithm of the number of cycles to failure has been observed for metals in the range 10^3 to 10^6 cycles which is known as high cycle fatigue range.

While it is possible to obtain material characterization for each steel material, the practical consideration of the actual system required several empirical assumptions which modify (lower) the endurance limit. Empirical expressions for defining the stress limit $f\ S_{ut}$ corresponding to $N = 10^3$ marking the beginning of the stress life region and the stress limit $S_e{}'$ corresponding to the ideal endurance limit are available. These empirical expressions that define the ideal material S-N curve based on the ultimate tensile strength of the steel are provided in (1).

$$f = \frac{\sigma_F'}{S_{ut}}(2 \cdot 10^3)^b \tag{1}$$

where:

$\sigma_F' = S_{ut} + 345[MPa]$ based on SAE assumption

$b = -\frac{\log(\sigma_F'/S_e')}{\log(2N_e')}$

$S_e' = 0.5S_{ut}$

S_{ut} = material ultimate tensile strength

Using (1), the ideal material S-N curve (solid line in Fig. 1a) can be obtained from S_{ut}. The endurance limit modifying factors (Marin's factors) typically cause a shift of the endurance point of the ideal S-N curve as also schematically shown in Fig. 2a. Thus, if the point (N_e, S_e) corresponding to endurance limit for the practical cases is known, the material characterization of the system can be done. In this study, it is proposed that the point (N_e, S_e) is obtained and calibrated using test data.

The material S-N curve corresponds to fully reversed cycling of stresses. Most practical situations are characterized by load cycling range which are not fully reversed. The Goodman's hypothesis [8] is used for transforming generalized load cycling range of localized max stresses to the equivalent fully reversed localized maximum stress amplitude (see Fig. 2b).

2.2 Approach for fatigue life assessment in EN1993-1-9 [12]

EN1993-1-9 [12] is a design document and uses lower bound quantification of the available experimental fatigue response data for prescribing the related criteria.

Thus, any assessment conducted using the prescribed S-N curves is expected to provide conservative underestimates of the fatigue life. The S-N curves are applicable to certain limited range of geometric configurations and connection situations relevant to the steel construction industries which are subjected to specific loading actions. Thus, the suitability of employment of these curves to fatigue resistance in fastening technology application will require substantial investigation. It is, nevertheless, important to touch on the different analytical methods presented in EN1993-1-9 [12], since the same helps to relate the present development of fatigue assessment with the current state-of-the-art considerations of fatigue in civil engineering.

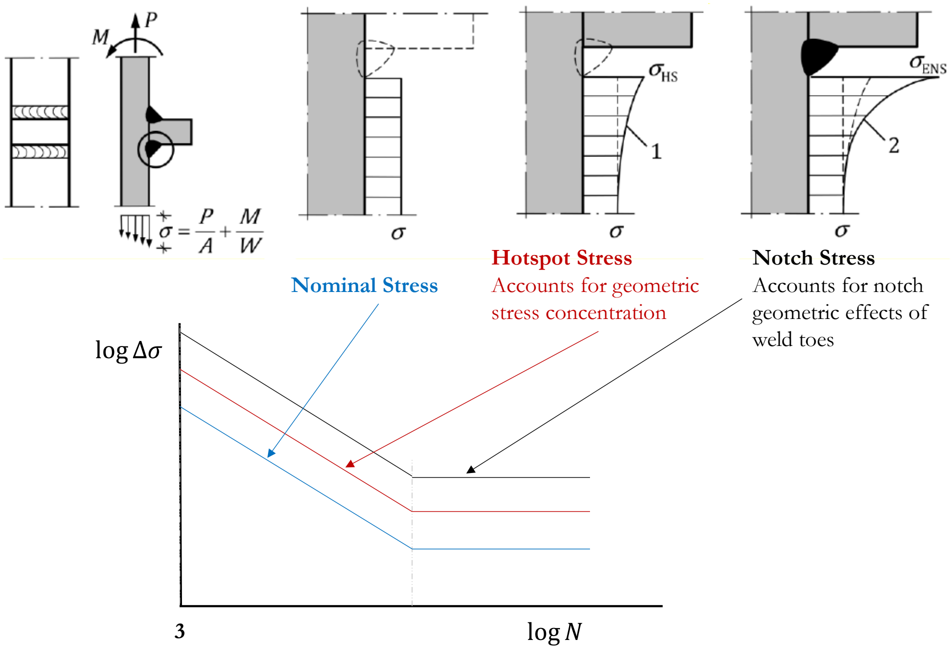


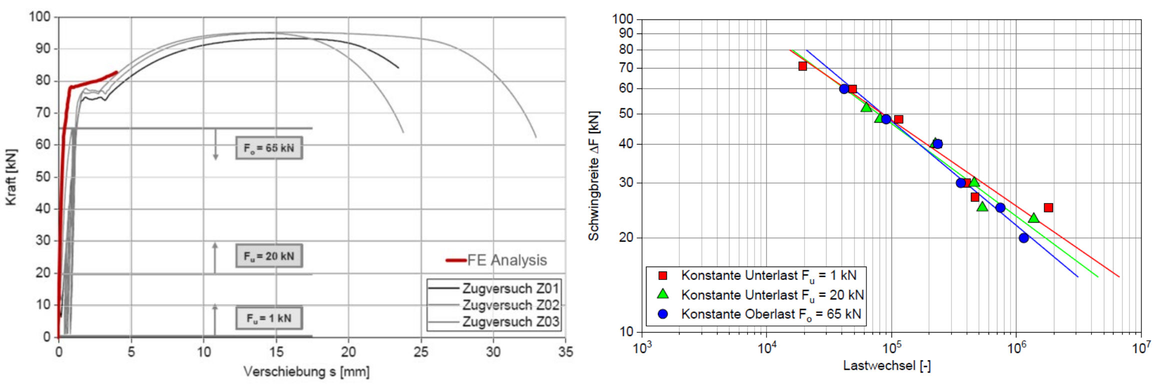
Fig. 3: Methods for stress evaluation and corresponding S-N definition (schematic) [12]

The fatigue life or fatigue resistance in EN1993-1-9 [12] is expressed in terms of S-N curves within the stress life concept. To evaluate the stresses for fatigue verification, three different methods—(i) nominal stress, (ii) hotspot stress and (iii) notch stress—are suggested as shown in Fig. 3. For any given case with specified forces and boundary conditions, typically, nominal stress > hotspot stress > notch stress.

A wide range of structural configuration and loading situations are covered for verification by means of nominal stresses. The prescribed S-N criteria for verification include the possible effects of stress concentrations because of notch and geometric effects in a conservative manner and hence correspond to the lowest stress levels (see Fig. 3). The use of hotspot stresses for evaluation is applicable to relatively lesser number of application cases of geometry and loading. In this case the effects of geometric stress concentration are accounted in the stress evaluation and that of the notch stress concentration is conservatively considered in the S-N criteria.

The use of notch stress method for evaluation of stresses is a relatively recent development and is limited to a few standard cases. For such evaluation all the stress concentration effects are considered in the stress evaluation process, and hence there is no need to introduce related conservatism to the S-N criteria. However, since the structural system and finite element model bears a one-to-many relation, it becomes essential to standardize the approaches for modelling and analysis. To this end, guidelines for design of structural steel systems with the aid of FE analysis are being prepared in EN1993-1-14 [13].

In the present study notch stress method is used for evaluation of stresses. The material characterization of the S-N curve is however obtained with the calibration process based on stress life concepts since no standard S-N curve is available for fastening technology applications. The test data generated on headed studs under tension load [6] from short term tests and fatigue tests under different cycling load ranges (see Fig. 4) is used to demonstrate the potential of the fatigue life prediction algorithm to assess the failure in comparison to the test observation.



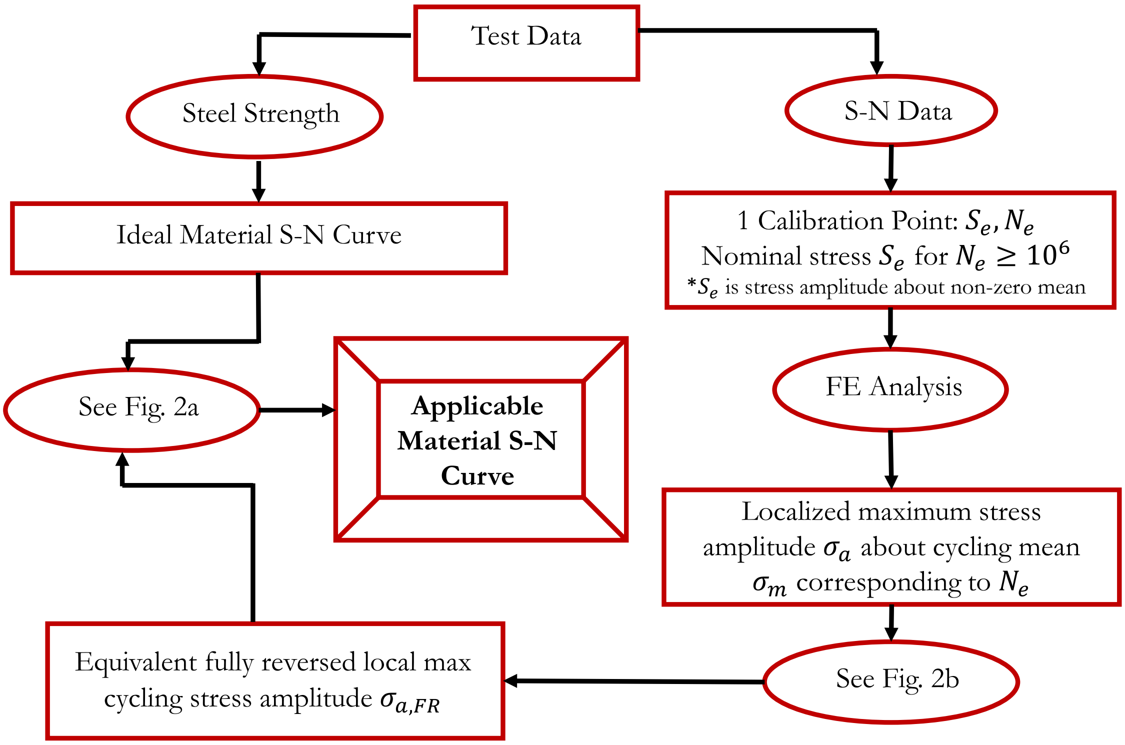
(a) Static response: FE vs test

(b) Fatigue Life (test)

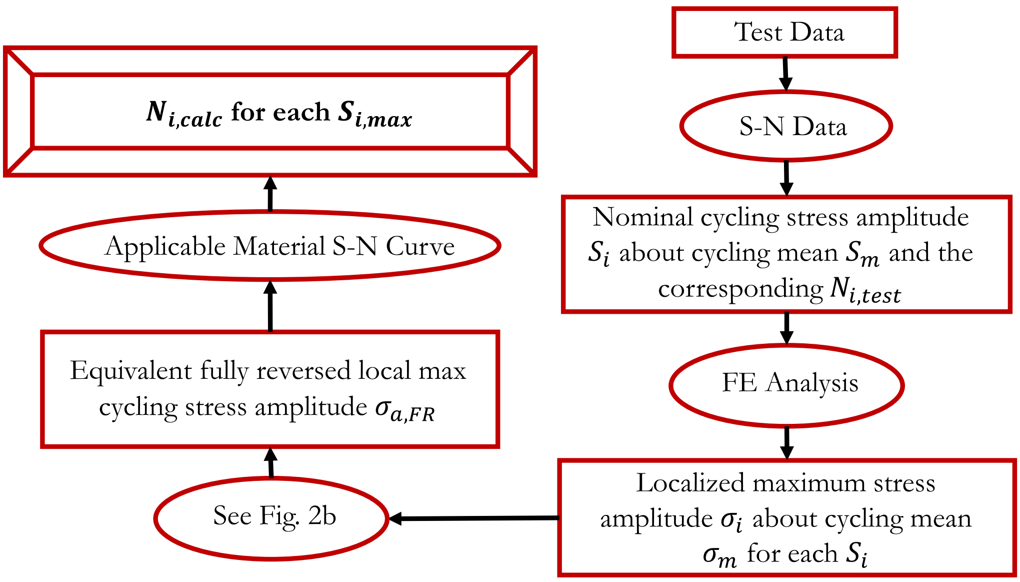
Fig. 4: Test data on headed studs [6] (a) static test in comparison with FE (b) fatigue life

3. FATIGUE LIFE ASSESSMENT OF HEADED STUDS

In the notch stress method, FE analysis is required to establish the correlation between the applied force and localized maximum stresses in the regions of stress concentration vulnerable to fatigue failure.



(a) Procedure for obtaining calibration point for general cycling case



(b) Procedure for prediction of number of cycles to failure for each test case

Fig. 5: Proposed fatigue life assessment algorithm

To this end, the tested system of headed stud welded to the surface plate and embedded in concrete was modelled and analysed using ANSYS [14]. The nonlinearity of concrete and steel was modelled using geo-mechanical model and multilinear model respectively. The weld geometry for connection between the plate and stud was considered in the modelling, since the same is critical w.r.t stress concentration. At the outset, the FE analysis approach was validated using the short term (reference) test data. A comparable load displacement behaviour (see Fig. 4) and failure pattern relative to the test was observed in the analysis [10].

The process chart for calibration of the material S-N curve and prediction of fatigue life for any general case of load cycling is presented in Fig. 5. Step by step process for fatigue life prediction of headed studs is explained here:

Process for obtaining calibrated material curve:

Step 1: The material S-N curve is defined in term of the cycling amplitude of fully reversed localized maximum stresses. The point on the material S-N curve corresponding to $N = 10^3$ cycles is evaluated based on the steel strength data from the component tests as explained above in Fig. 2a and (1).

Step 2: One test data point is required for fixing the point corresponding to cycles to failure of the order of 10^6. The point S_e corresponding to $N_e \approx 10^6$ corresponding to generalized loading needs two independent parameters for its characterisation. These can be either minimum and maximum cycling stress levels or stress amplitude and cycling mean.

Step 3: The minimum and maximum stress (or force) levels corresponding to the point S_e are representation of nominal stress. The corresponding minimum localized maximum stress and maximum localized maximum stress are evaluated using the results of FE analysis. This process is schematically shown in Fig. 6. The minimum force F_{min} and the maximum force F_{max} defining the cycling range corresponding to the selected calibration point are taken. From the localized maximum stress versus force chart obtaining in the FE analysis, the localized maximum stress cycling parameters (stress amplitude σ_a and mean level σ_m) corresponding to the calibration point are obtained, and the calibration point is expressed on a σ_a v/s σ_m chart. This process is repeated for all the points corresponding to different series in Fig. 4b. The resulting graph is shown in Fig. 6.

Step 4: For the calibration point, the Goodman's line is used for obtaining the corresponding fully reversed cycling stress amplitude as shown in Fig. 2b and

Fig. 6. A straight line starting from the ultimate tensile strength on the σ_m (x) axis through the calibration point and intersecting the σ_a (y) axis is constructed. The ordinate of the point of intersection on the σ_a (y) axis provides the equivalent fully reversed cycling amplitude corresponding to the calibration point.

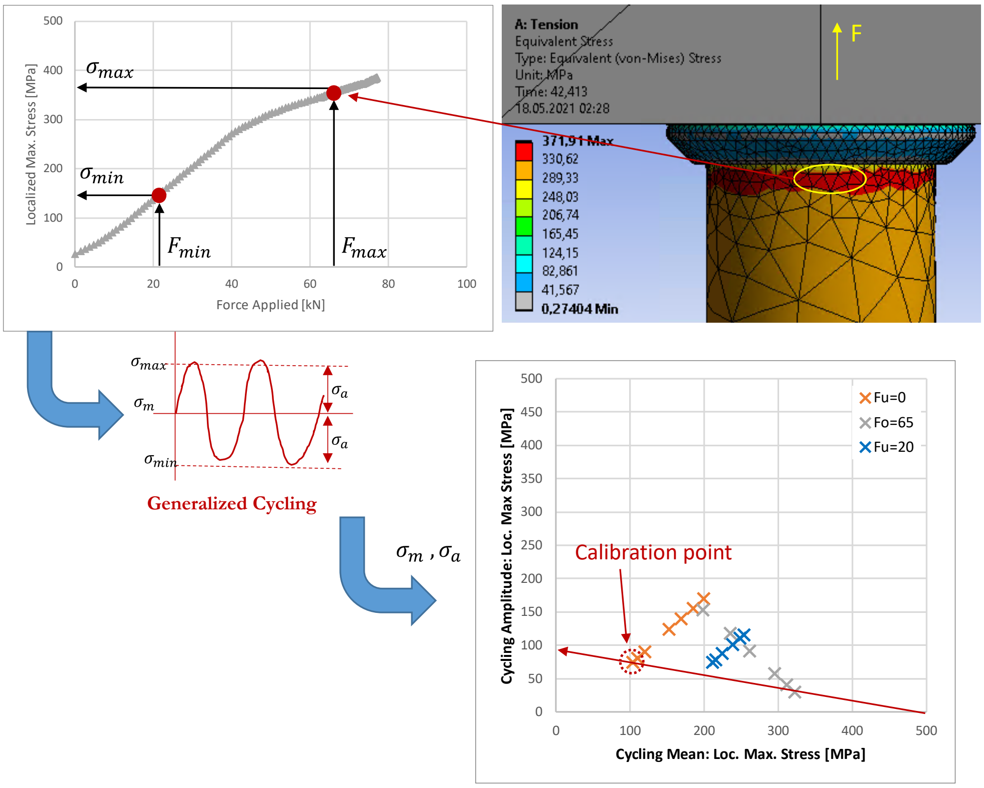


Fig. 6: Static output from FE analysis necessary for the fatigue prediction process

Step 5: Thus, the point with stress value of $f \cdot S_{ut}$ for $N = 10^3$ and localized maximum fully reversed stress for the calibration point S_e with its corresponding number of cycles to failure from test N_e completely define the S-N curve. This is schematically shown for the present example in Fig. 7.

Process for prediction of number of cycles to failure using material curve:

Step 6: For the prediction process, the stress cycling parameters for all other points other than the calibration point (the prediction points in the present case) from test data in Fig. 4b are expressed on σ_a v/s σ_m chart in Fig. 6 in Step3. The goal of fatigue life prediction is to determine the number of cycles to failure for each of the prediction points.

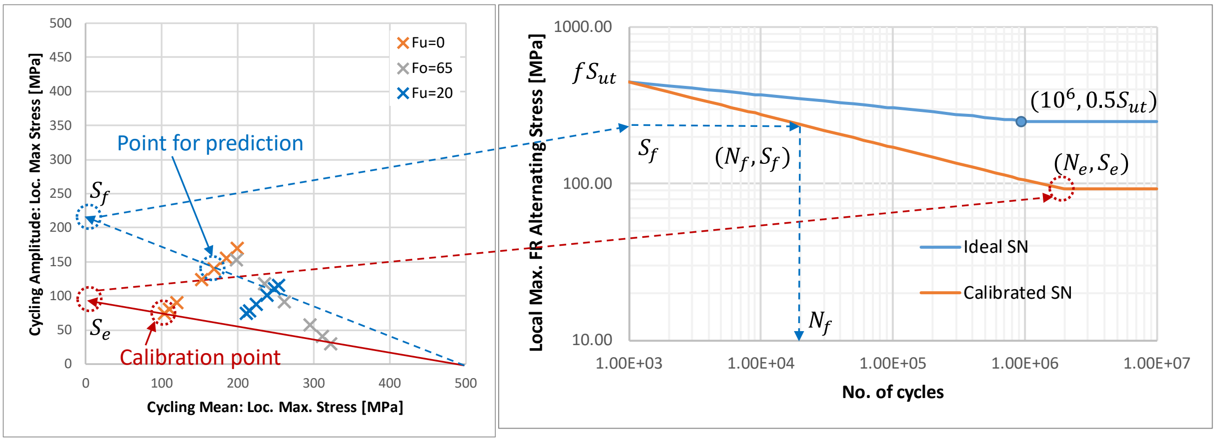


Fig. 7: Procedure of the prediction of fatigue life

Step 7: For each prediction point the Goodman's line is used for evaluating the equivalent fully reversed cycling amplitude S_f as shown in Fig. 7.

Step 8: The material S-N curve is used to obtain the predicted number of cycles to failure N_f corresponding to each of the prediction point as schematically shown in Fig. 7.

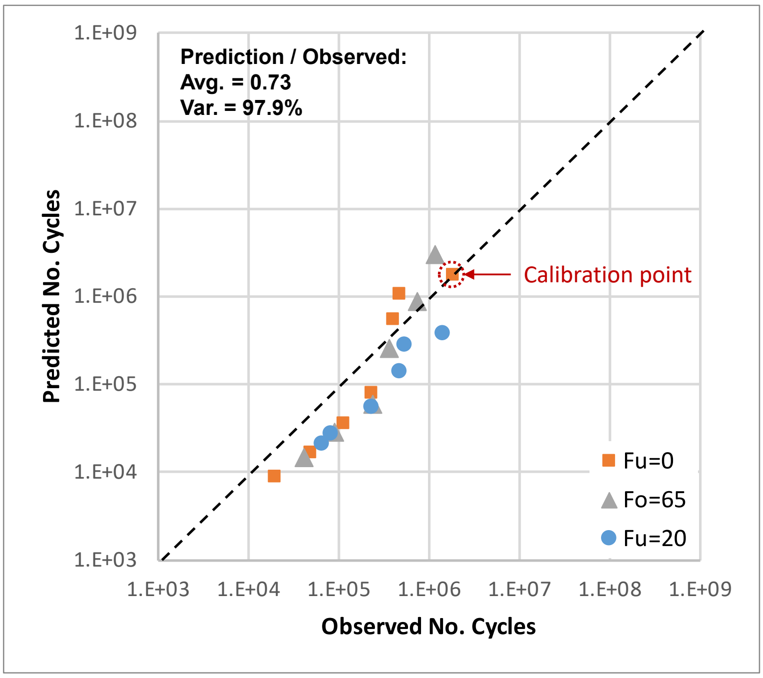


Fig. 8: Comparison of predicted number of cycles to failure with that observed in the test

Using the process described above, a comparison of the predicted number of cycles and the observed number of cycles is shown in Fig. 8. The calibration point lies exactly on the 45° line. It is noted here that the X and Y axis are logarithmic and hence each gridline represents an order of 10 times. The average prediction to observed ratio for this example was found to be 0.73 with a variation of 97.9% as indicated. It is noted that the coefficient of variation is quite high. This is reasonable and within the scatter range for fatigue life prediction where the range of prediction (fatigue life) varies from 10^3 to 10^7. It can be concluded that a reasonable prediction of the fatigue life could be reached using the stress-life based methodology.

The prediction algorithm presented in this paper is based on a single test data calibration point and the material strength characteristics. The calibration process can be rather crude in the light of extensive variation associated with fatigue life data. Despite these odds, the prediction methodology is observed to provide reasonable estimation of fatigue life in the present example.

4. CONCLUDING REMARKS

The following concluding remarks result from this paper:

- The hysteresis energy dissipation dependent prediction methodology based on Paris law was found to be irrational for the present study. The method was borrowed from investigations with concrete dominated behaviour of fasteners under fatigue. For steel dominated behaviour, hysteresis loops for service level loads make sense only when the defect crack is explicitly modelled in the analysis. The microplane law used in the preliminary studies did provide hysteresis characteristics at service loads. However, the absence of modelling of defect cracks indicates that the hysteresis loops are mere numerical and their realistic correlation with the actual behaviour remains questionable.
- A stress life concept for evaluation of fatigue life of steel dominated failure situation was explored for prediction of fatigue life of headed studs under tensile actions.
- For the case of headed studs under tension load, the entire process of calibration of the material S-N curve and use of the same for fatigue life prediction was explained. FE analysis was used as a tool to generate the inputs necessary for the prediction algorithm.

- The modelling approach and fatigue life prediction algorithm were able to simulate the test observations in a reasonably realistic manner for headed studs subjected to tension loads.

ACKNOWLEDGEMENT

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REFERENCES

[1] FRÖHLICH. T., LOTZE. D.: *Fatigue of fastenings - Investigations on the effect of static load level*, Otto-Graf-Journal, vol. 18, 2019

[2] TOTH, M.: *Fatigue behaviour of fasteners: Numerical and experimental investigations on the concrete cone failure mode*. PhD. Thesis, Institute of Construction Materials, University of Stuttgart, 2020

[3] EN:1992-4, *Eurocode 2 - Design of concrete structures - Part 4: Design of fastenings for use in concrete*. British Standard Institutions (BSI), 2018

[4] TR-061, *Design method for fasteners in concrete under fatigue cyclic loading*. Technical Report, European Organization for Technical Assessment, 2020

[5] EAD 330250-00-0601, *Post installed fasteners in concrete under fatigue loading*. European Assessment Document, European Organization for Technical Approvals, 2018. Accessed: Oct. 23, 2023

[6] LOTZE, D., FROEHLICH, T., HOFMANN, J., MAHADIK, V.: *Ermüdungsverhalten von mechanischen Befestigungen in Beton bei überlagerter statischer Beanspruchung*. Schlussbericht, IGF-Vorhaben Nr. 20458 N, 2021

[7] TOTH, M., OZBOLT, J., FUCHS, W., HOFMANN, J.: *Fatigue behaviour of fasteners in case of concrete failure: Numerical and Experimental Investigations*, fib Symposium on Performance-based Approaches for Concrete Structures, 21-23 November 2016, Cape TownAt: Cape Town, 2016

[8] BUDYNAS, R.G., NISBETT, J.K.: *Shigley's mechanical engineering design (9th edition)*. Mc Graw Hill, 2011

[9] OZBOLT, J., LI, Y., KOZAR, I.: *Microplane model for concrete with relaxed kinematic constraint*, International Journal of Solids and Structures, vol. 38, no. 16, pp. 2683–2711, 2001

[10] MAHADIK, V, HOFMANN, J.: *Assessment of Fatigue Life of Fastening Systems using FE Analysis*. Report No. IR/21-001-R0/VM, Institute of Construction Materials (IWB), University of Stuttgart, Germany, 2021

[11] SUSMEL, L., TAYLOR, D.: *A novel formulation of the theory of critical distances to estimate lifetime of notched components in the medium-cycle fatigue regime*, Fatigue Fracture Engineering Materials Structures, vol. 30, pp. 567–581, 2007

[12] EN:1993-1-9, *Eurocode 3 - design of steel structures - part1-9: Fatigue (final draft CEN/TC 250/SC 3 N 3268)*. European Committee for Standardisation, 2020

[13] EN:1993-1-14, *Eurocode 3 - Design of steel structures - Part1-14: Design assisted by finite element analysis (Draft CEN/TC 250 Version April 2021)*. European Committee for Standardisation, 2021.

[14] ANSYS®, *Academic Research Mechanical, Release 22.2*. 2022