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Practical notes on the evaluation of fatigue life of welded nodes of bus bodyworks

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In order to calculate fatigue service life of structures and their parts operating under cyclic loads, one needs the following data: information on their fatigue strength and information on their service loads. In high-cycle fatigue scenarios, the main input data includes: S-N curve and service stress spectra for major operating modes. This input information must apply to the same (critical) cross-section of the component in question. It is normally found by measurement and testing. S-N curves are constructed from laboratory fatigue test data using statistical evaluation. Service stress spectra are obtained by analysing measured data during operation or so-called design stress spectra are used. Stress spectra are converted to fatigue damage using cumulative damage rules which have been proposed by various authors. Two basic approaches are available for evaluating [1].

Approach A: Using the relevant service stress spectrum and S-N curve parameters, the fatigue damage of a particular component or structural detail cross-section is calculated, and an estimate of its service life is obtained and compared to the desired life. This is the usual procedure.

Approach B: Based on the desired service life, pre-defined S-N curve parameters, and a design stress spectrum, the engineer determines maximum allowable service stress levels for a particular cross-section of a component or structural detail. The procedure is shown in Fig. 1.

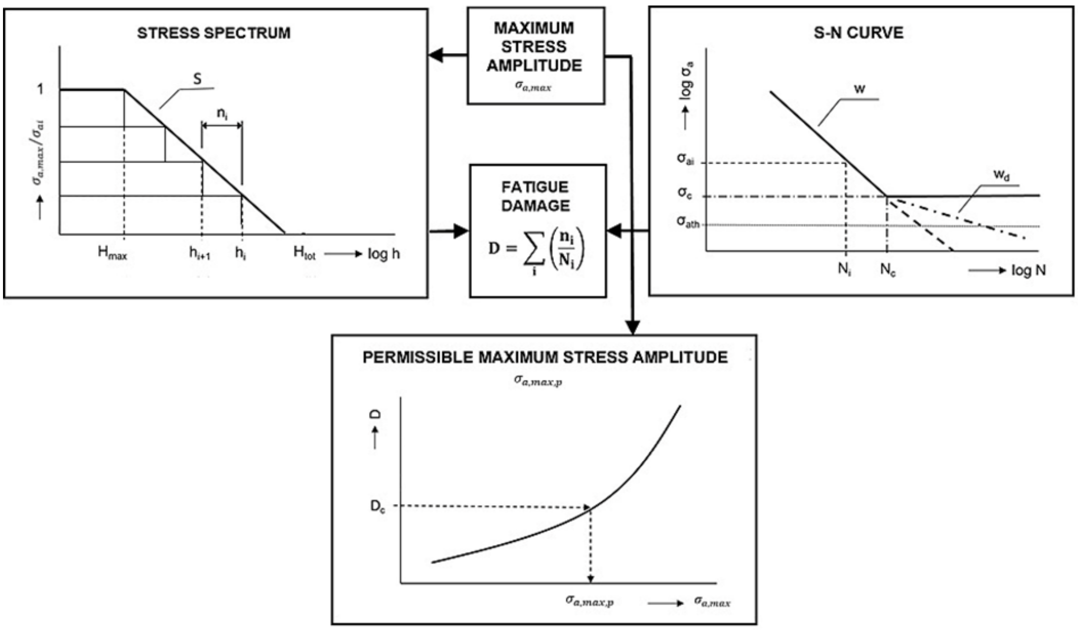

Fig. 1. Procedure to determine the permissible maximum stress amplitude $\sigma_{a,max,p}$

Case study A

The detail of interest was a severely stressed beam joint in the top corner of the door opening in the bus body shown in Fig. 2. The critical cross section was monitored by strain gauge T6.

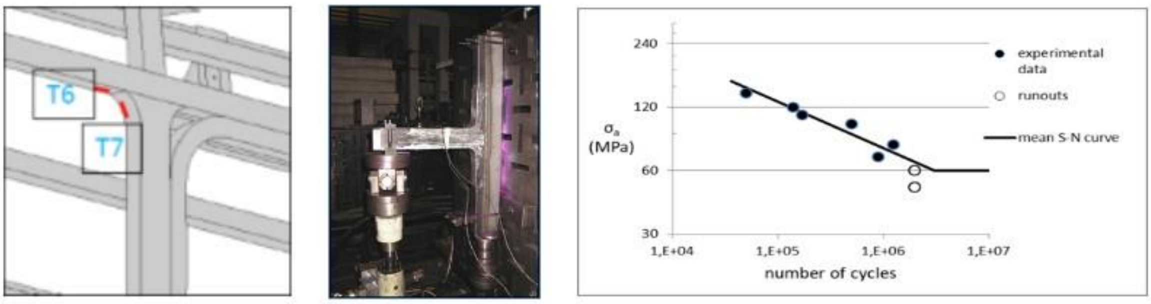

Fig. 2. Detail of interest, laboratory fatigue test and S-N curve

The test specimens were made from thin-walled welded closed profiles, which had 70×50 mm cross-section and 2 mm wall thickness and were made of S235JR steel. The critical cross-section of the joint was subjected to reverse bending load (the cycle stress ratio was $R = -1$).

The limit state was defined by the instant at which a macroscopic fatigue crack forms (1 to 2 mm). In all cases, fatigue cracks initiated in the transition zone of the fillet weld.

Statistical evaluation of the fatigue test data yielded the parameters of the mean S-N curve for the structural detail in the form

$$log\,(N) = 14.54 - 4.53 \cdot log\,(\sigma_a)\ ;\ \sigma_c = 60 \text{ MPa}.$$

During testing, the stresses acting on the critical cross-section were measured by strain gauges attached approximately 5 mm from the toe of the fillet weld. The measured values by strain gauges T6 can therefore be referred to as the equivalent structural stress.

In this case, the service stress-time histories were measured for a city bus riding on an irregular surface along a city route whose total length was $L_m \approx 40$ km. In a similar manner to representative urban traffic, the stress spectra on the test polygon were evaluated. The test polygon offers sections, tracks and roads with various longitudinal road profile and different surface quality. The measurement was repeated tree times with empty vehicle and three times with fully loaded vehicle. Total length of the measured route was $L_m \approx 35.5$ km. The signals were analysed in the frequency domain, and insignificant high frequencies were eliminated before using the rain-flow technique. In high-cycle fatigue of welded structures, the mean stress of the cycle does not play a major role. Therefore, only the one-parameter stress spectra $\sigma_{ai} - n_i$ were used for subsequent calculations.

Mostly the fatigue damage D is calculated using the linear cumulative damage rule. According to this rule, the limit state with respect to fatigue is reached (i.e. the fatigue life of the structural part is exhausted) when the following condition is met

$$D = \sum_i \frac{n_i}{N_i} = D_c,$$

where D is the fatigue damage caused by the stress spectrum imposed, n_i is number of cycles applied at the i-th level of stress with the amplitude σ_{ai}, N_i is limit life under identical loading (the number of cycles derived from the S-N curve for the part in question at the amplitude σ_{ai}) and D_{lim} is limit value of fatigue damage.

Various rules apply various boundary conditions to fatigue damage calculation. A schematic representation of these boundary conditions is shown in Fig. 3.

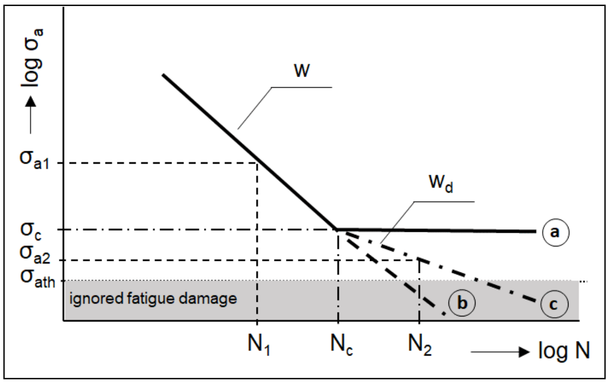

Fig. 3. Boundary conditions for calculating cumulative fatigue damage:
a - Palmgren-Miner original, b - Palmgren-Miner elementar, c – Haibach

In the present case, the Haibach-modified version of the Palmgren-Miner rule was chosen for calculating fatigue damage. The limit number of cycles Ni was determined as follows

- $\sigma_{ai} \geq \sigma_c$: $$N_i = N_c \cdot \left(\frac{\sigma_c}{\sigma_{ai}}\right)^w,$$

- $\sigma_{\text{ath}} < \sigma_{ai} < \sigma_c$: $$N_i = N_c \cdot \left(\frac{\sigma_c}{\sigma_{ai}}\right)^{wd}.$$

Haibach recommends the exponent for the lower part of the S-N curve to be set as $w_d = 2w - 1$. In this study, the value was $w_d = 8$. The threshold stress amplitude for taking the fatigue damaging into account was given as $\sigma_{ath} = 0.5 \cdot \sigma_c$ in the present case. The limit value of fatigue damage was taken as $D_{lim} = 0.5$.

The computational estimate of service fatigue life (in kilometre run) is obtained from equation

$$L = (D_{lim} / D) \cdot L_m .$$

Table 1 provides predicted fatigue life for the service stress spectra and the spectra measured on the test polygon. The ratio of these predicted fatigue life is an estimation of the acceleration (shortening) of the driving fatigue test that could be achieved on the test polygon compared to normal vehicle operation.

Table 1. Estimation of acceleration factor of driving fatigue test

Empty vehicle	Real operation	Testing ground	Acceleration
L [km]	3,178,000	203,000	15.7

Loaded vehicle	Real operation	Testing ground	Acceleration
L [km]	4,309,000	337,000	12.8

Case study B

The structural nodes with and without reinforcement were tested and two materials (low carbon steel and stainless steel) were considered in this study, see schematic pictures of nodes A, B and C in Fig. 4. Statistical evaluation of the fatigue test data yielded the parameters of the S-N curve. The scatter of fatigue properties of assessed construction nodes was considered by British Standard BS 7608. In the present case, the Haibach-modified version of the Palmgren-Miner rule was chosen for calculating fatigue damage again. The maximum permissible stress amplitudes $\sigma_{a,max,p}$ were determined by the approach schematically shown in Fig. 1 and compared with the values calculated, Fig. 5.

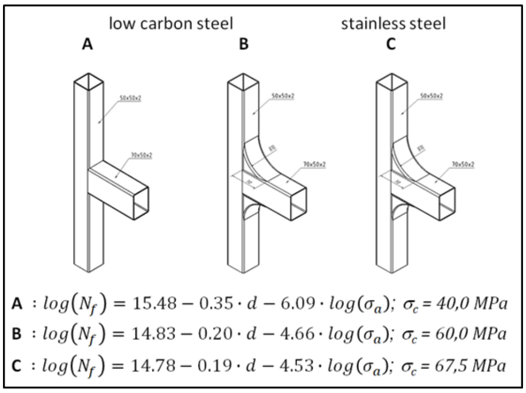

Fig. 4. Bodywork structural nodes and S-N curves

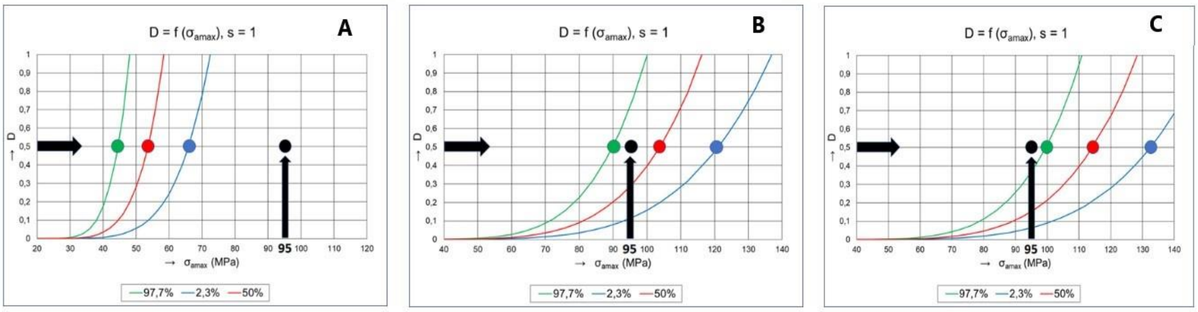

Fig. 5. Maximum calculated stress amplitude (black) and permissible values

Based on the case study, it is possible to formulate a clear conclusion. The structural node A does not absolutely meet the required service life. Even the structural node B does not achieve the required service fatigue life with sufficient reliability. Only the structural node C could be recommended because it meets the required service fatigue life with the usual design reliability (survival probability higher than 97.7%).

Acknowledgements

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References

[1] Kepka jr., M., Degradation of mechanical properties of cyclically loaded materials and structural nodes, dissertation thesis, University of West Bohemia, Faculty of Mechanical Engineering, Pilsen, 2021.