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Parametric calculations of service fatigue life of welded T-joints

Miloslav Kepka[a]*, Miloslav Kepka Jr.[a]

[a]*Regional Technological Institute, research center of the Faculty of Mechanical Engineering, University of West Bohemia, Univerzitni 2732/8, 301 00 Pilsen, Czech Republic*

Abstract

The paper describes parametric fatigue life calculations of a simple welded node occurring in agricultural machines. S-N curves were determined experimentally for various materials and welding parameters and design stress spectra were estimated. It was possible to approximately quantify the differences in the fatigue life of individual variants of welded joints and recommend the best solution.

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Keywords: argricultural machinery; welded T-joints; S-N curve; load spectrum; hot-spot stress; permissible maximum stress range.

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1. Introduction

When developing a new machine, the prescribed fatigue criteria must be fulfilled in important structural nodes. These structural nodes are often weldments. S-N curves of welded details are given in standards or they must be determined by statistical evaluation of results of laboratory fatigue tests.

Dynamical loading of machines and vehicles are mostly random processes. To predict fatigue life, these processes must be converted into stress spectra. Then fatigue life calculations can be performed or stress range of harmonic cycling with equivalent fatigue damage can be determined.

The load/stress-time processes can be calculated or measured by strain-gauge technics. It is not always easy to calculate the time courses of service loads well. And the measurement can be realized only when the prototype is ready.

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In the case of some structures, there are regulations according to which the design load/stress spectra can be derived. In many cases, however, it is necessary to estimate the load/stress spectra.

Based on this knowledge, it is possible to perform parametric calculations of fatigue life and look for the most suitable design solutions, or for the required service life to derive the maximum permissible stress ranges of the assessed structural nodes. The article presents the results achieved in cooperation of the university research center with the manufacturer of agricultural machinery, Kepka Jr. (2019). The results are more valid in general, e.g. also for vehicle constructions.

2. S-N curves

Test specimens of real size welded from steel plates with a thickness of 15 mm were tested. Fatigue properties were determined for 9 sets of welded T-joint samples. The individual sets of test specimens differed in several parameters: basic material, additional welding material, preheating, technical execution of the weld. Although each set contained only 4 test samples, the variance of the results was small, so that the mean S-N curves can be considered sufficiently representative. The tests were performed at 4 different load levels and the slope of the S-N curves was determined by regression analysis.

Cyclic fatigue tests of constant load range ΔF were controlled by the applied force F. The stress acting in the critical cross section had a stress ratio $R \doteq 0.1$. The load levels were chosen to cover the wide range of operating loads of considered agricultural machines.

Strain gauges were installed on the test specimens and before the start of the fatigue tests, the stresses were measured as a function of the applied force during static loading. Strain gauges were installed depending on the thickness of the welded plates, so that the hot-spot stresses could be evaluated by extrapolation from the measured values, Hobbacher (2016).

The criterion for completing the test was an increase of the deflection of the test specimen (increase of the displacement of the piston rod of the load cylinder). At such a moment, a macroscopic fatigue crack was already present on the tested specimen. Also, the change of cyclic stresses monitored during the test by means of installed strain gauges made it possible to determine the beginning of the macroscopic crack propagation in the critical cross section of the tested specimen. Fatigue cracks formed and propagated as expected at the fillet weld edge.

The photo of a test specimen in the test stand is in Fig.1. A schematic representation of the location of strain gauges is shown in Fig.2. A photograph of a typical fatigue crack is shown in Fig. 3.

Fig. 1. Test specimen in the test stand.

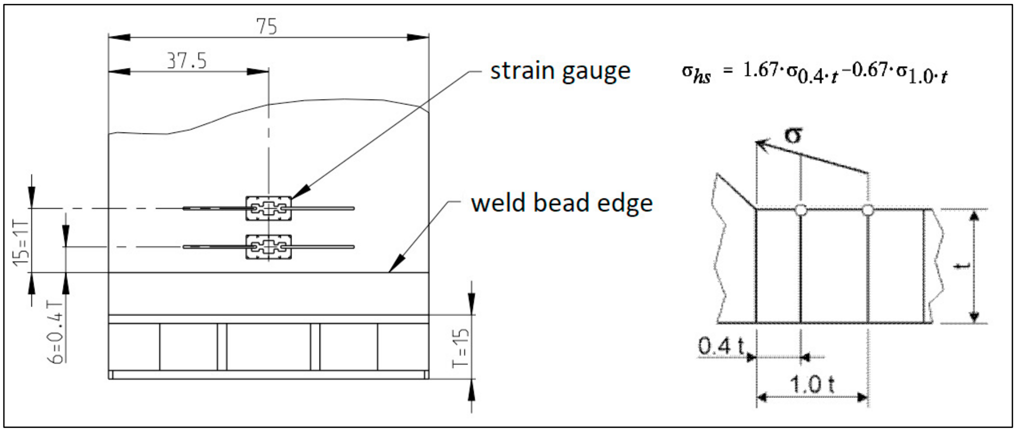

Fig. 2. Location of strain gauges.

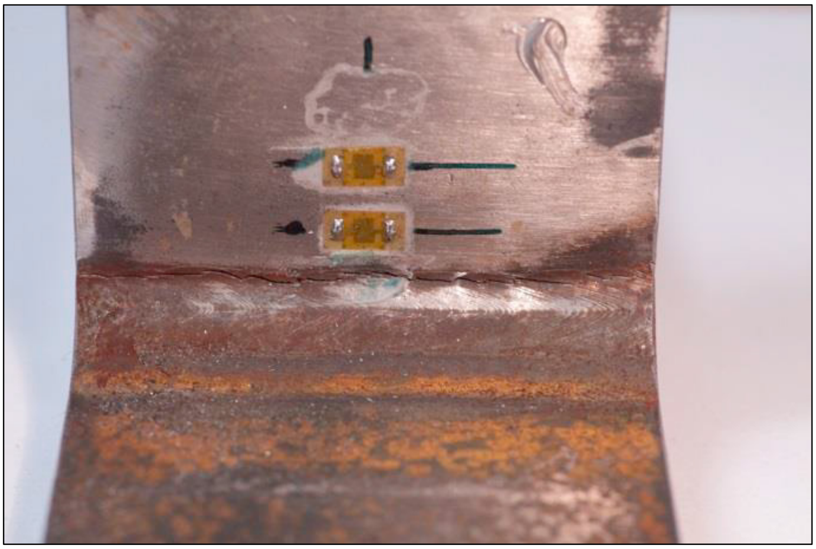

Fig. 3. Typical fatigue crack.

To evaluate the S-N curves, a linear model was chosen. The output of the regression analysis are fatigue curves with a 50% probability of failure. The number of cycles until the occurrence of a macroscopic fatigue crack is expressed as a function of the range of the applied force during the test or, after conversion, as a function of the range of the hot-spot stress.

$$log(N) = q - m \cdot log(\Delta F) \tag{1}$$

$$\log(N) = q_{hs} - m \cdot \log(\Delta\sigma_{hs}) \tag{2}$$

The tests were carried out as contract research for a manufacturer of agricultural machinery and so all specific parameters of the test specimens and the parameters of the evaluated S-N lines cannot be published. However, the mean S-N curves are shown in Fig. 4, where V1 to V9 is the designation of various material and technological variants of test specimens. It can also be stated that the tested materials were: S355J2+N, Alform® 460M and Alform® 700M.

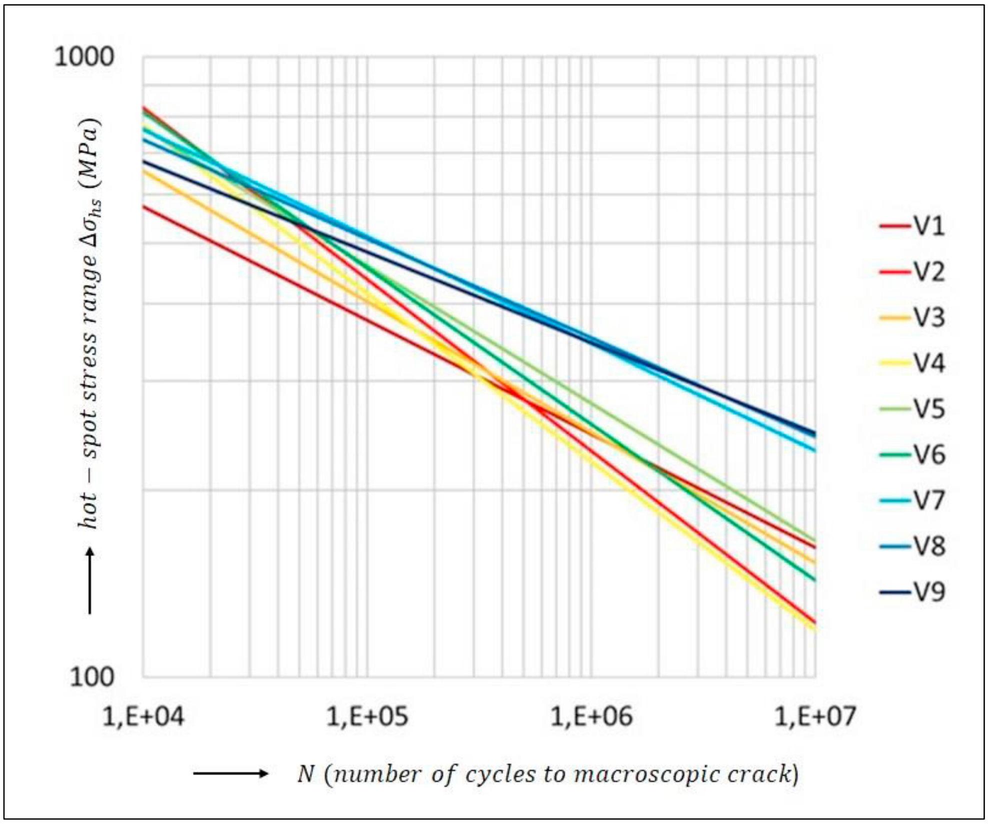

Fig. 4. S-N curves of welded T-joints.

3. Load spectra

Heuler and Klätschke (2005) presented the possibilities of generation and use of standardized load spectra and load–time histories. European standardized load sequences and load time histories mainly concern the aerospace and automotive industries, partly also energy. The rolling stock sector also prescribes what loads must be applied to the bogie frames during their static and fatigue tests.

Standardized load spectra for agricultural machinery components probably do not yet exist. It is not easy to universally estimate the number of cycles over the life of an agricultural machine. On the one hand, the machines differ in their construction and use, and on the other hand, they work in often diverse operating conditions: in fields and are also exposed to stress during transport. The critical (most stressed) areas of the machines can be different at these two main load regimes.

However, parametric evaluation of the results can be performed with generally typified load spectra. Fig. 5. shows schematically a possible process for evaluation of permissible maximum stress range $\Delta\sigma_{max,p}$, Kepka et al. (2018).

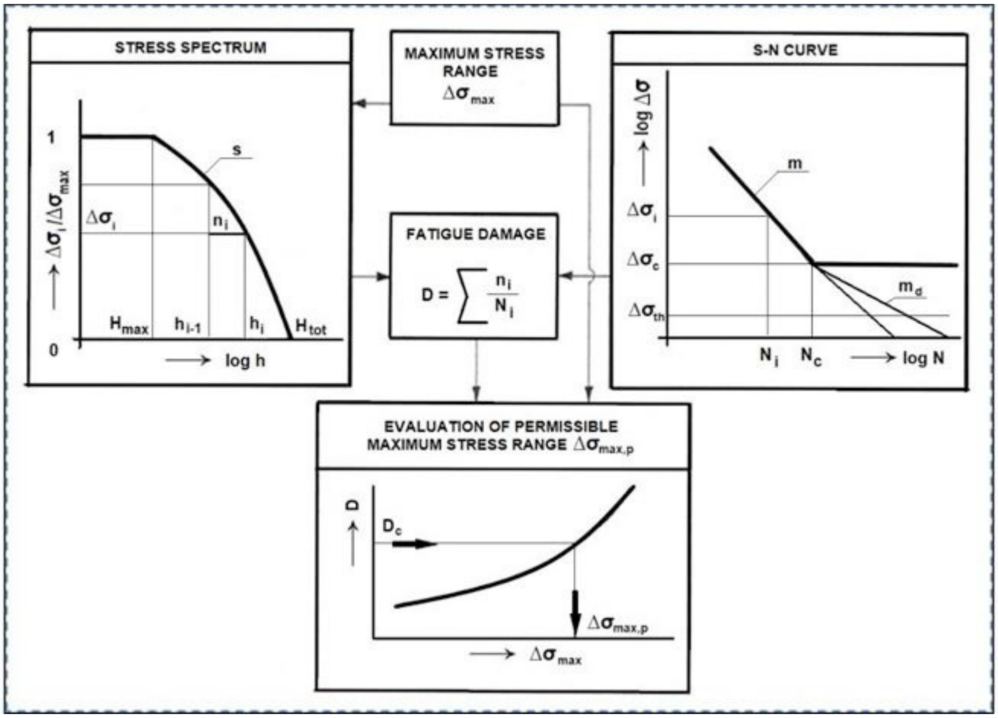

Fig. 5. Evaluation of permissible maximum stress range $\Delta\sigma_{max,p}$ of design stress spectrum.

The process of determining the maximum permissible value $\Delta\sigma_{max,p}$ for safe life approach is based on the concept of linear accumulation of fatigue damage. The input data to the fatigue damage calculation are: S-N curve of the assessed structural node and stress spectrum in its critical cross-section. The stress spectrum represents a random loading process over the required service life.

To apply this procedure S-N curve for welded T-joint version V1 was evaluated:

$$\log(N) = 19{,}09 - 5{,}47 \cdot \log(\Delta\sigma_{hs}) \tag{3}$$

S-N curve for welded T-joint version V7 was considered as an alternative:

$$\log(N) = 20{,}70 - 5{,}80 \cdot \log(\Delta\sigma_{hs}) \tag{4}$$

The design stress spectra were generated using the relative coordinates $\Delta\sigma_{hs,i}$ /$\Delta\sigma_{hs,max}$ and the equation proposed by Ruzicka et al. (1987):

$$h_i = H_{tot} \cdot \left(\frac{H_{max}}{H_{tot}}\right)^{\left(\frac{\Delta\sigma_{hs,i}}{\Delta\sigma_{hs,max}}\right)^{s}} \tag{5}$$

$\Delta\sigma_{hs,max}$ - maximum hot-spot stress range in the spectrum;
H_{max} - number of cycles with $\Delta\sigma_{max}$ range in the spectrum;
H_{tot} - total number of cycles in the spectrum;
s - shape parameter of the spectrum;
h_i - cumulative frequency of cycles with an amplitude of $\Delta\sigma_{hs,i}$.

In parametric calculations two values s = 1 (on road conditions) and s = 2 (in field conditions) were considered. The expected number of loading cycles for the life of a machine was considered H_{tot} = $1{\cdot}10^7$ cycles. The occurrence of the load cycle with the maximum stress range $\Delta\sigma_{hs,max}$ was considered H_{max} = 100, 1000 and 10000 cycles inside the spectrum. Fatigue damage was calculated using the Palmgren-Miner damage rule (without an endurance limit).

4. Maximum permissible values

The fatigue damage functions ($D = f(\Delta\sigma_{hs,max})$ were evaluated for 2 types of design stress spectra (with shape parameter s=1 and s=2) and for 2 considered S-N curves (V1 an V7). For the critical damage value D_c the maximum permissible stress ranges $\Delta\sigma_{hs,max,p}$ can be deduced from the functions plotted in Fig. 6 and Fig. 7. If these value $\Delta\sigma_{hs,max,p}$ is not exceeded, the fatigue life for a given stress spectrum should be guaranteed.

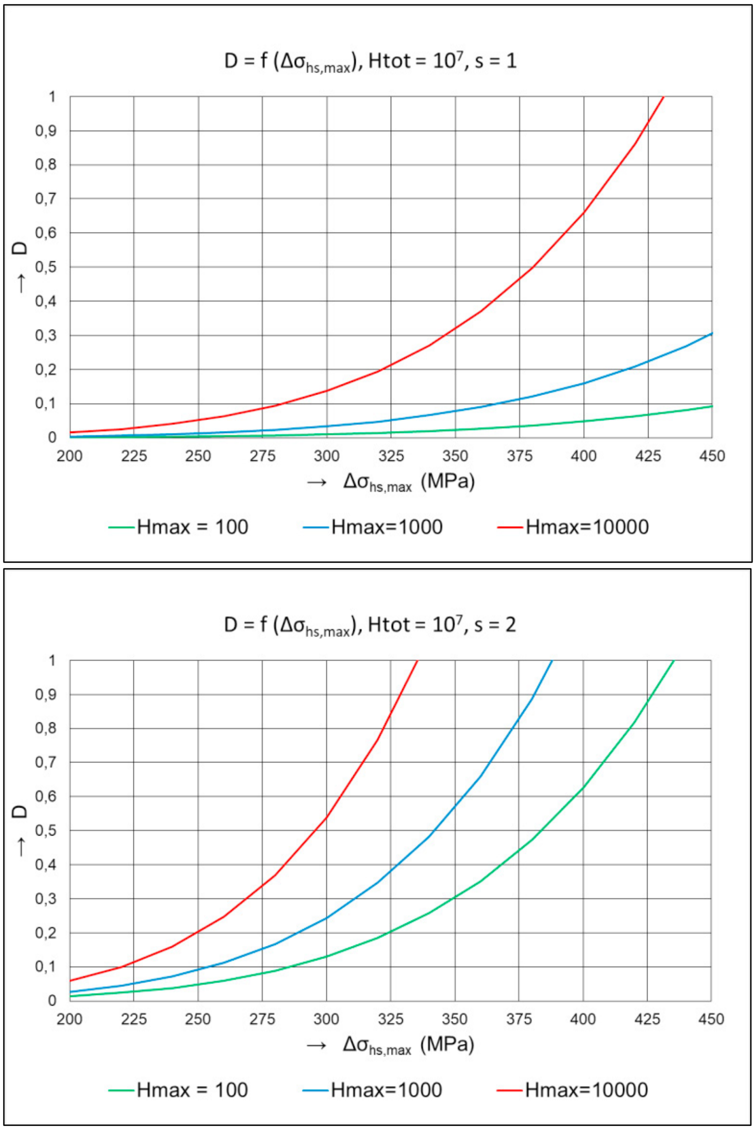

Fig. 6. Welded T-joint V1: functions for evaluation of maximum permissible stress range $\Delta\sigma_{hs,max,p}$.

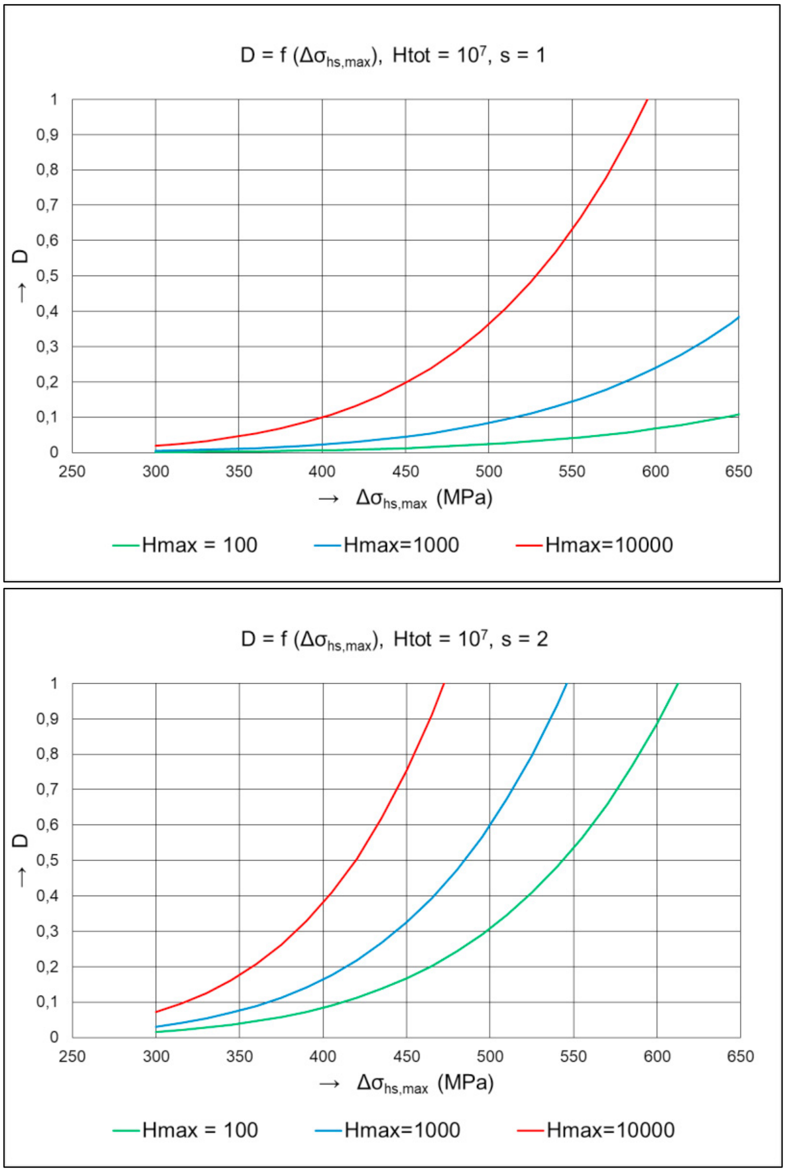

Fig. 7. Welded T-joint V7: functions for evaluation of maximum permissible stress range $\Delta\sigma_{hs,max,p}$.

Estimates of permissible stress ranges $\Delta\sigma_{hs,max,p}$ are influenced by the choice of the critical value of fatigue damage D_c. According to the original version of the Palmgren-Miner rule D_c = 1, but D_c can be within the wide range and non-conservative. This problem can be partially solved by recommending a value of D_c = 0.5. The most correct solution is to calibrate this value D_c based on a properly designed and correctly implemented experimental program (relative Palmgren-Miner). Of course, it is not possible to allow such stress cycles whose maxima are close to the yield strength of the material.

The above findings and conclusions are valid for the presented case study, for the used test specimens and for the predominantly acting uniaxial stress. The study provides a quantitative estimate of how the fatigue strength of welds can change with some different parameters such as: base material, additional welding material, preheating, technical design of the weld.

When dimensioning a specific structure, it is necessary to take into account other possible aspects (e.g. by considering partial safety factors), such as: scatter of material properties, random service loading or aggressiveness of the operating environment (corrosion), etc.

5. Conclusions

Using parametric calculations with welded T-joints made of steels with different strengths, a procedure for determining the maximum allowable stress fluctuations was demonstrated. When applying this procedure, the required service life of machine or vehicle structures with this type of structural detail can be guaranteed. The maximum stress ranges occurring in real operation must be calculated at the design stage, later they can be determined by measuring with a prototype machine or vehicle.

Acknowledgements

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