THE ANNALS OF "DUNAREA DE JOS" UNIVERSITY OF GALATI.
FASCICLE IX. METALLURGY AND MATERIALS SCIENCE
N^0. 2 – 2007, ISSN 1453 – 083X

EXPERIMENTAL INVESTIGATION OF FATIGUE OF THIN-WALLED WELDED STRUCTURES OF COMMERCIAL VEHICLE FRAMES

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ABSTRACT

The fatigue behavior of bus frame components consisting of thin-walled tube beams joined together by fillet welding has been investigated. Numerical analysis by means of finite elements and experimental stress analysis by means of strain gages explored the failure-critical locations at the weld toe. In addition, a proposal for finite element modeling in particular of the welded area, and evaluation of hot spot stresses to be used for fatigue life calculations of such thin-walled structures has been developed. The calculation results have been verified based on experimentally determined fatigue lives of the components under constant amplitude loading. A satisfactory agreement between experimental and theoretical results has been observed.

KEYWORDS: Fatigue, welds, finite elements, hot spot stress, experimental analysis

1. Introduction

Calculation methods for the investigation of fatigue behavior of welded structures under operational loading are gaining increasing importance in many technical applications, since they contribute in decreasing developmental costs and time. Extensive research activities over the last decade especially in the fields of crane and marine construction led to various calculating procedures, which differ fundamentally in their type of evaluation (based on nominal, local or structural hot spot stresses). Radaj et al. [5] and Maddox [12] give an overview and a systematic survey of the existing methodologies and concepts dealing with fatigue evaluation of welds. Details for numerical analyses by means of finite elements are given in [13]. In addition, fracture mechanics based approaches have been also elaborated [2, 11]. A state of the art has been recently reported by Tovo and Livieri [16] and Fricke [9].

Valuable recommendations for fatigue assessment of welds engineering applications are also given in international guidelines, e.g. the one of the International Institute of Welding (IIW) [9], Eurocode [6], as well as [4] and [1]. However, all these recommendations deal mainly with quite thick structures.

In the automotive sector, there is an increasing interest for computer-aided methods to shorten the development time. In the last years developments on theoretical assessment of welded automotive components with low thicknesses have been achieved in conjunction with the hot spot stress approach, see e.g. Boven-Griffon et al. [3], Fayard et al. [7] and Fermér and Svenson [8]. Own initial experience [14, 15] revealed that fatigue analysis based on hot spot stresses might be capable for handling such thin components.

However, nowadays it still lacks of experimentally verified guidelines for the calculation of fatigue life. Therefore, the assessment of thin-walled welded components under operational loading is still dominated by experimental methods.

Taking new generation bus frame components consisting of thin-walled tube beams with thickness t=2mm joined together by fillet welds as examples, the investigation focuses to:

a) the investigation of the mechanical behavior of the components, in particular of structural stresses acting at the failure critical welds

b) the determination of the fatigue live curves under bend loading

c) the development and assessment of the reliability of a finite element meshing and calculation procedure that can be applied for the fatigue life prediction based on hot spot stresses.

2. Hot spot stress approach

The so-called "structural" stress at the hot spot (HSS), i.e. at the failure-critical point of the weld, is a fictitious stress. In many applications, this point corresponds to the weld toe. The HSS value can be determined using reference points in certain distances from the weld toe by extrapolating the surface stress values measured or calculated at the reference points at the weld toe [10]. The reference points are set dependent on the thickness *t* of the welded components and the extrapolation method used. Depending on the shape of the stress distribution acting perpendicular to the weld toe a linear or quadratic stress extrapolation at the weld toe is recommended as depicted in fig. 1 and 2, respectively.

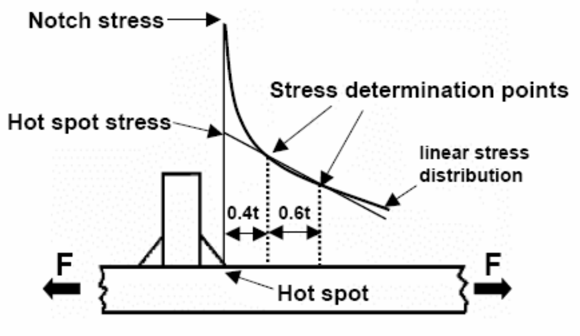

Fig. 1. *Determination of HSS by linear extrapolation*

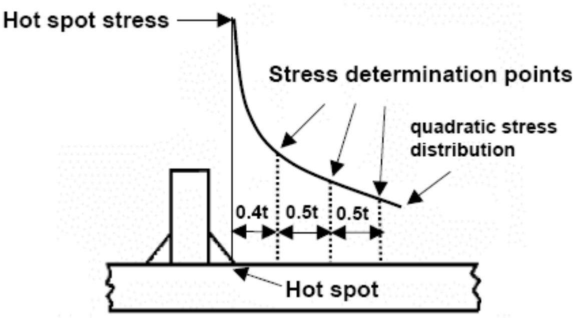

Fig. 2. *Determination of HSS by quadratic extrapolation*

Note that the HSS includes all stress raising effects of the structural detail except the stress concentration due to the local weld profile itself.

3. Specimens and loading

Figure 3 illustrates the geometry of the specimens and the load configuration applied in the present investigation.

Two longitudinal tube beams with dimensions 50x50x2 [mm] are jointed to a vertical tube beam with dimensions 50x50x2 [mm] by fillet welds. The thickness of the weld amounts to 4mm.The ends of the longitudinal beams are fixed while the load is introduced at the one end of the vertical beam.

The specimens were subjected to force-controlled, fully reversed loading with constant amplitudes. Therewith, mainly normal stresses due to bend loading are acting at the weld toes.

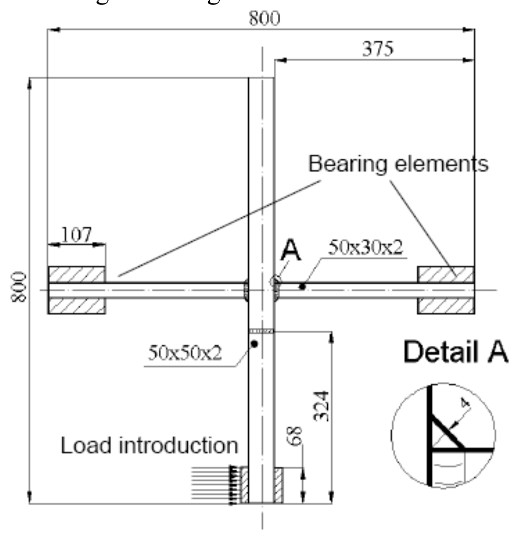

***Fig. 3**. Specimen's geometry and load configuration*

4. Finite element meshing

Figure 4 shows schematically the procedure followed here to model the weld and to calculate the HHS value at the weld toes in the longitudinal and the vertical beam. The origin of this procedure goes back to Fayard et al. [7].

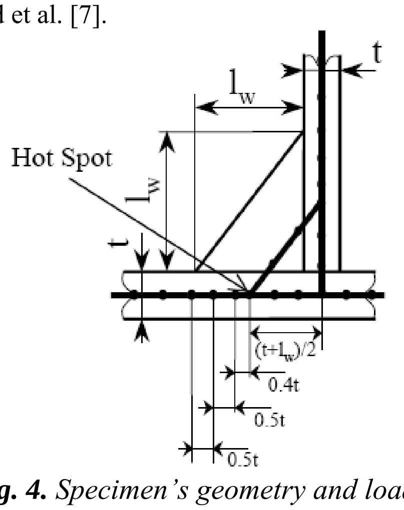

Fig. 4. *Specimen's geometry and load configuration*

The vertical and longitudinal beams of the component are shown in fig. 4. Their thickness amounts to *t*=2mm. The fillet weld triangle is illustrated with side lengths l_w. Two rectangular surfaces consisting of intermediate shell elements have been used to model the beams shown in fig. 4 with bold lines. In accordance with Fayard's et al. [7]

suggestion, the fillet weld itself has been modeled by an additional surface of shell elements, whereby the dimensions of the rectangular sides of the fillet weld triangle amount to $(t+l_w)/2$ on both the longitudinal and the vertical beam, respectively. The stiffness of the shell elements of the fillet weld is assigned to replicate the stiffness of the real weld.

Differing from Fayard's initial suggestion, the finite element mesh has been created to explore nodal stresses at the distances of $0.4t$, $0.9t$ and $1.4t$ from the weld toe. These distances correspond to the principal recommendation of the IIW guideline [10] when a fine mesh with quadratic surface stress extrapolation is to be applied.

Figure 5 shows the finite element mesh detail of the welded area used for the theoretical analysis.

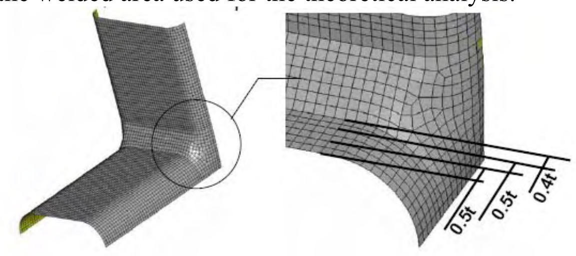

Fig. 5. *Finite element mesh detail of the weld*

The stress values at the reference points $0.4t$, $0.9t$ and $1.4t$ from the weld toe will be used to calculate the HSS values at the weld toe using Equation (1) [10]:

$$HSS = 2.52 \cdot \sigma_{0.4t} - 2.24 \cdot \sigma_{0.9t} + 0.72 \cdot \sigma_{1.4t} \quad (1)$$

5. Test rig

Figure 6 shows the test rig used for the experimental investigation. Note that the adjustment of the specimen in the test rig is rotated by an angle of 90° in comparison to the illustration shown in fig. 3.

Fig. 6. *Test rig*

A servo-hydraulic actuator introduces the load into the end of the vertical beam. The longitudinal beams are beard to the test rig traverse and the table using two bearing elements. The bearing elements are designed to compensate possible misalignments between the vertical and the longitudinal arms due to residual stresses induced by the weld-heat as well as possible deviations of the real geometrical dimensions of the beams from the nominal ones.

Three batches of specimens with equal dimensions of the beams and the welds but made up of three different constructive steels have been tested, named as T1, T2 and T3. However, the steels provide similar mechanical behavior and fatigue properties so that no influence is expecting due to the different steel material.

The specimens were tested under force-controlled, fully reversed cyclic loading (force ratio R_F=-1) with constant amplitudes vs. time. Thereby, various force amplitudes were applied in order to determine secured knowledge of the component's Woehler curves. The specimens were tested in the as-welded condition, at room temperature with a frequency of 4 Hz.

6. Results

Fatigue cracks were initiated at the weld toe very near to the edges of the beams, where the highest stresses arise, during the applied force-time sequences.

The cracks propagated along the weld toe perpendicular to the direction of the normal stresses. Thereby, both weld toes, the one in the vertical and the one in the longitudinal beam, have been found out to be failure-critical. The initiation of fatigue cracks with lengths of approximately 3mm to 4mm at the surface of the components has been defined as failure criterion.

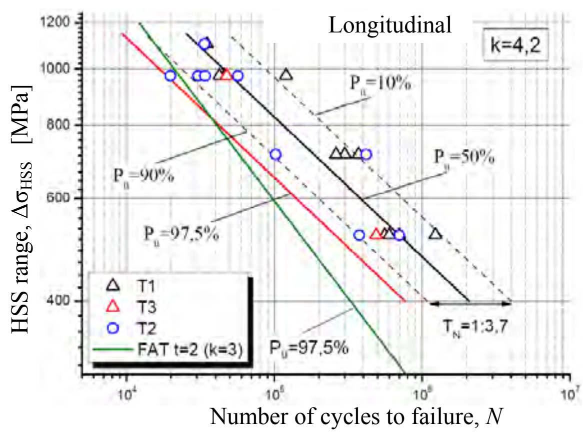

Fig. 7. *Fatigue life results for failure at the longitudinal beam*

A crack length of this size causes a reduction of the component’s stiffness of approximately 5%, which can be measured reliably by the electronic devices of the test rig. Figures 7 and 8 contain the experimentally determined fatigue life results plotted vs. the range of the HSS, $\Delta\sigma_{HSS}$, calculated by means of finite elements for failure detected in the longitudinal and the vertical beam, respectively.

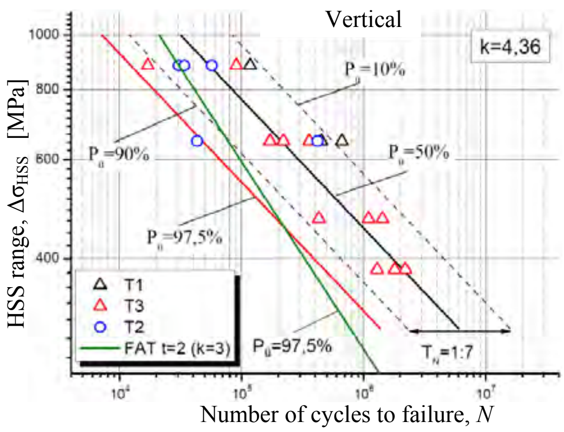

Fig. 8. *Fatigue life results for failure at the vertical beam*

The different marker symbols in fig. 7 and 8 stand for the different specimen batches. The Woehler lines for the various probabilities of survival $P_Ü$ have been determined by means of regression analysis of the corresponding results.

The characteristic scatter band T_N can be derived from the Woehler curves for the probabilities of survival of 10% and 90%. It is defined as

$$T_N = \frac{N_{P=10\%}}{N_{P=90\%}}. \quad (2)$$

It amounts to T_N=1:3,7 for the cases with failure at the longitudinal beam, and T_N=1:7 for those with failure at the vertical beam.

The slopes of the Woehler curves for the two failure cases do not deviate significantly from each other. They amount to k=4.2 (failure at the longitudinal beam) and k=4.36 (failure at the vertical beam). These k-values are slightly higher than the one reported in the IIW-guideline (k=3).

Furthermore, a general comparison of the fatigue life results determined according to the procedure described in section 4 with the hot spot stress-life curves suggested by the IIW-guideline [10] is shown in fig. 7 and 8 for the two failure cases, respectively. The latter are to be used for the design of fillet welds in an as-welded condition if no experimental results are available.

They are based on several fatigue tests and assigned with a probability of survival of 90% within a confidence belt of 75%, which results in an overall probability of survival of $P_Ü$=97.5%.

To determine the Woehler curves according to the IIW guideline, the so-called FAT value for this weld configuration, i.e. the HSS range at a lifetime of 2000000 cycles, has been used as reference value. The reference FAT value for the weld configuration under investigation amounts to FAT=100 MPa. This value considers wall thicknesses of approximately 25mm and stress ratios of R>0.5. Therewith, the benign thinness effect due to the reduced thickness of the beams investigated here (t=2mm) has been taken into account explicitly, using the correction thickness factor reported in the IIW guideline. Finally, an additional correction factor due to the acting stress ratio R_σ=R_F=-1 has been considered. To determine fatigue lives at lower N-values, IIW recommends a unique Woehler curve slope of k=3 for all types of welds.

In both failure cases noticed in the present investigation, a satisfactory agreement between the Woehler curves determined according to the IIW guideline and the corresponding ones determined by the presented calculation procedure for the probability of survival 97.5% can be observed.

7. Conclusions

The fatigue behavior of thin-walled, fillet-welded components made from various ductile steels used for bus frames have been investigated theoretically and experimentally under fully reversed constant amplitude cyclic loading. The following remarks are made in conclusion:

The test results identified the weld toes at the edges of the horizontal arm to be the failure critical locations. Few specimens failed at the corresponding weld toe of the vertical arm. The finite element analysis unraveled the locations, which were identified experimentally as failure-critical.

A finite element meshing procedure according to Fayard’s et al. proposal for weld modeling by means of shell elements in conjunction with the recommendations of the IIW guideline has been applied. In addition, a quadratic surface stress extrapolation at the hot spot of the modeled weld has been proposed.

The HSS-Woehler curves determined by the suggested calculation procedure have been found out to be in satisfactory agreement with the corresponding ones determined according to the IIW guideline. These results confirm the accuracy and efficiency of the so-calculated hot spot stresses for fatigue design of thin-walled components such as the ones investigated here.

Though the experimental database used here for the verification of the calculation procedure is certainly narrow for generalizations, the results encourage to apply and verify this procedure to thin-walled structures such as the one investigated.

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