FINITE ELEMENT BASED FATIGUE LIFE PREDICTIONS OF LASER OVERLAP WELDS IN AUTOMOTIVE STRUCTURES

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ABSTRACT

A straightforward fracture mechanics and finite element based approach for laser overlap welded thin sheet structures is developed. Sheets and laser welds are modeled with shell elements with a mesh density of about 5 mm. The structural stress at the nodes along the weld is calculated using a commercial finite element software and converted to a stress intensity factor using the approximation $\Delta K \approx 0.58 \Delta\sigma_{\mathrm{inner}} \sqrt{t}$. The corresponding ΔK-N curve was derived from Paris law. Good agreement between the theoretically derived curve and test data for laser welded peel and shear loaded specimens made of different steel grades was found. Finally, it is shown how the proposed procedure can be directly used for automotive structures using the seam weld module in the commercial fatigue software FE-Fatigue.

1 INTRODUCTION

There is an increasing interest in continuous joining in the automotive industry. Laser welds and adhesives are used as a complement to resistance spot welds, to improve car body stiffness as well as fatigue performance compared to spot welds. However, there is a lack of finite element (FE) based fatigue life prediction methods for laser welded automotive structures such as car bodies.

The present paper therefore deals with fatigue assessment of laser welded thin sheet steel. A ΔK-N curve for laser welds is motivated using fracture mechanics, and it is shown how ΔK can be easily calculated with sufficient accuracy using a rather coarse FE mesh. Calculated results are compared with experimental data. Finally, it is shown how the proposed method can be directly used for automotive structures using the seam weld, fatigue life prediction method developed by Fermér and Svensson [1] and implemented in the commercial fatigue software FE-Fatigue [2].

Recent studies on fatigue assessment of aluminum laser welds can be found in Dong *et al.* [3] and Eibl *et al.* [4]. A good summary of earlier work on fatigue of laser welds, primarily for steel specimens, can be found in Radaj and Sonsino [5]. The current work is discussed below, and compared with the relevant literature.

2 FATIGUE DATA FOR LASER WELDED OVERLAP JOINTS

Fatigue test data for a number of laser welded overlap joints was collected [6-8], see Fig. 1. The data analyzed with the method proposed below consists of tensile shear (ts) and coach peel (cp) specimens, schematically shown in Fig. 1a. Most of the data is for specimens including weld starts and stops (s/s) but some data is for continuous (cont) welds across the complete width of the specimen. The data includes materials ranging from mild steel to high strength steels, and the thickness ranges from 0.90 mm to 1.4 mm. The laser weld width was approximately equal to the sheet thickness, or slightly wider, and was not available for all the data.

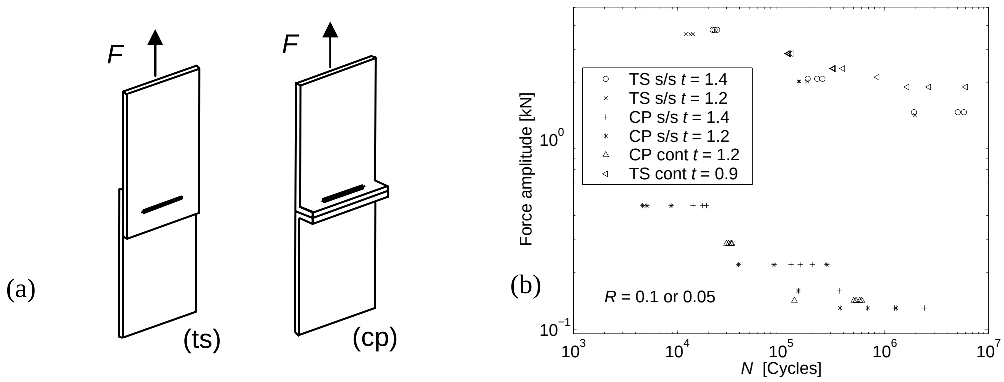

Figure 1: Fatigue data for different laser welded steel specimens: (a) Schematics of shear and peel loaded specimens; (b) Fatigue data for the different specimens in (a).

All tests were carried out under load control with a load ratio $R = F_{\min} / F_{\max} = 0.10$ or 0.05 and the tests were ended at a pre-defined stiffness drop for the specimens corresponding to a visible crack *i.e.* before complete fracture. Failures occurred both in the sheet metal at the weld and through the weld itself for some coach peel specimens.

The test results are shown in Fig. 1b. Note the large difference, one order of magnitude, in load amplitude for the shear and peel loaded specimens. It should also be noted that the thin 0.9 mm shear specimen with a continuous weld falls above the scatter band of the thicker specimens, due to a longer weld and the absence of the start/stop stress concentrations. On the other hand, the continuous peel loaded weld data falls within the scatter band for the peel specimen with the same thickness but with a shorter weld including start/stop. This is not expected, but the data comes from different test series and the specimens are made of different steel grades. However, no material effect could be seen when comparing data for different steels grades.

3 THEORY AND OUTLINE OF THE NUMERICAL APPROACH

The basis for the proposed method is the seam weld method proposed by Fermér and Svensson [1] and the work on spot welds by Henrysson [9,10]. The theoretical work is based on fracture mechanics, described in this chapter, and compared with the test results described above. It is also shown how the method can be directly used in the commercial fatigue software FE-Fatigue [2] which includes an implementation of the seam weld approach by Fermér and Svensson.

The sharp notch between the sheets is assumed to be a crack tip, and an initial equivalent stress intensity factor (SIF), *i.e.* without a fatigue crack, can then be calculated. This SIF is used as the fatigue parameter for the laser weld and adjacent sheets. Approximating the formulas given for overlap welded joints in Radaj and Sonsino [5] gives

$$\Delta K \approx 0.58 \Delta\sigma_{\text{inner}} \sqrt{t} \tag{1}$$

where $\Delta\sigma_{\text{inner}}$ is the structural stress range on the inside of the sheet at the notch root, see Fig. 2. For example, the factor 0.58 is exact for K_{I} for a double cantilever beam loaded under force or bending moment. For K_{II}, the corresponding factor is 0.5 for decomposed stresses [5]. However, the equivalent SIF, K_{eq}, by Erdogan and Sih [11] is often used for overlap welded joints [5]. For pure mode II, $K_{\text{eq}} = 1.15\ K_{\text{II}}$ using the Erdogan and Sih approach. Since 0.5*1.15 also equals 0.58, the above approximation is deemed as satisfactory in this work. Equation (1), is valid for laser welds with weld widths in the order of the sheet thickness or larger, see again Radaj and Sonsino [5]. For example, at Volvo Car Corporation the weld width is chosen to be 90% of the thinnest sheet, or wider, so this approximation can be used in practice when analyzing car body structures.

The structural stress σ_{inner} must now be determined in an effective manner. This is done using the approach for seam welds proposed by Fermér and Svensson [1]. Both the sheets and the laser weld are modeled with CQUAD4 shell elements in the finite element code MSC/NASTRAN, see Fig. 2. The elements next to the laser welds are approximately 5 by 5 mm large and the maximum principal structural stress at the weld line is evaluated using the STRESS(CUBIC) option in MSC/NASTRAN [12]. Stresses are calculated at the nodes of the elements adjoining the weld using a strain gauge technique [12].

A fatigue life curve ΔK-N is then needed for the fatigue life prediction. Consider now, therefore, the Paris law:

$$\mathrm{d}a/\mathrm{d}N = C\,\Delta K^{m}\,. \tag{2}$$

Assume that the initial crack depth is zero and the crack depth at failure N is approximately equal to the sheet thickness t. Assume also, just as for spot welds by Henrysson [9], that the major part of the fatigue life is spent for short crack growth for shear loaded welds and that the SIF does not increase much under bending stresses. The following relation can then be derived by inserting eqn (1) in eqn (2):

$$t/N \approx C\,(0.58\Delta\sigma_{\text{inner}}\sqrt{t}\,)^{m} \tag{3}$$

and rearranged to

$$\Delta K \approx 0.58\Delta\sigma_{\text{inner}}\sqrt{t} \approx C^{-1/m}\left(N/t\right)^{-1/m} \tag{4}$$

if presented as a ΔK-N curve. Normally fatigue life prediction methods for welds are stress-life based and rearranging for use in fatigue packages such as FE-Fatigue [2] one finds the S-N curve

$$\Delta\sigma_{\text{inner}}\,t^{(m-2)/2m} \approx 1.72\,C^{-1/m}N^{-1/m} = 25682N^{-0.3333} \qquad [\text{MPa mm}^{1/6}]. \tag{5}$$

Finally the crack growth data is needed in eqns (4) and (5). The crack propagation data for welds recommended by Hobbacher [13] was used in the current study: C = 9.5e-12 and m = 3 (units in $\text{MPa}\sqrt{\text{m}}$ and m). These are characteristic values, *i.e.* conservative, upper-bound 95% values for the crack propagation rate. The threshold value for crack propagation given by Hobbacher [13] is ΔK_{th} = 6 – 4.56R $\text{MPa}\sqrt{\text{m}}$. The derived ΔK-N curve, eqn (4), and ΔK_{th} are shown in Fig. 3. The results from detailed three-dimensional, fracture mechanics, finite element analyses of laser overlap welds by Wang [14] are also included in the same figure. The cyclic J-integral by Wang [14] was converted to stress intensity factor ΔK assuming plain strain. All results in Fig. 3 are discussed below.

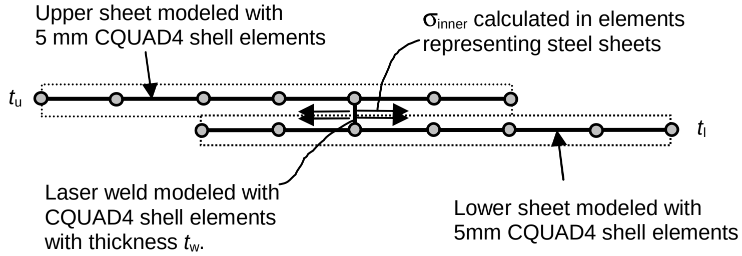

Figure 2: FE representation of laser weld joints and location for evaluation of structural stress.

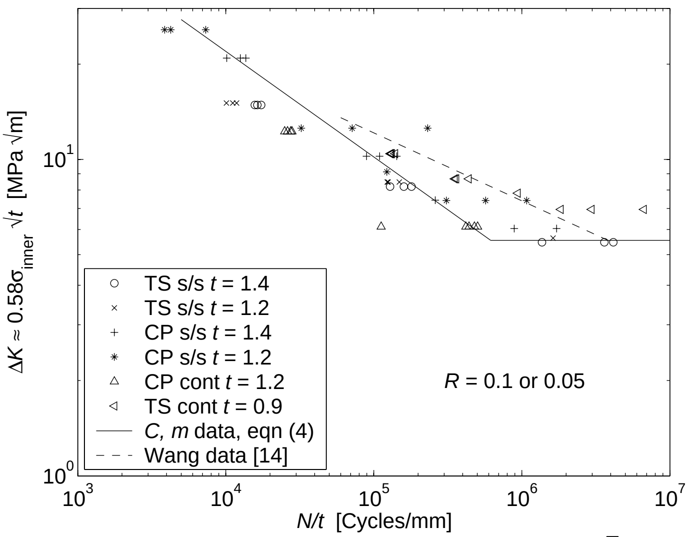

Figure 3: SIF-life results for test results in Fig. 1: $\Delta K \approx 0.58\Delta\sigma_{\text{inner}}\sqrt{t}$ data, derived fatigue life curve using 95% crack growth data by Hobbacher [13], and fatigue data by Wang [14].

In Fig. 4, the stress-based version, the *S-N* curve given in eqn (5) for direct input into the commercial software FE-Fatigue, is shown. The fatigue parameter plotted on the y-axis is now $\Delta\sigma t^{(m-2)/2m}$ assuming $m = 3$. These results are also discussed below.

4 DISCUSSION OF RESULTS AND FUTURE WORK

Figure 3 shows how fatigue data for different weld patterns, load cases, thicknesses and steels can be collapsed into a single curve with good accuracy, despite all the simplifications in the analyses. As mentioned above, the method is valid for weld widths equal to or larger than the sheet thickness. For smaller welds, the structural stress in the laser weld element needs to be analyzed as well, see Radaj and Sonsino [5], and Eibl *et al.* [4].

The fatigue data is in very good agreement with the theoretical ΔK-N curve in Fig. 3 for long fatigue lives. The theoretical curve is slightly above some of the test results due to the assumption of a constant ΔK during the crack growth to failure, and the structural stress might be somewhat underestimated using a 5 mm mesh. Under peel loading, the stress increases 10% with 3 mm element size and decreases 5 % for 7 mm element size for a weld with start/stop. Results using 5 mm as element size are judged as sufficient for structural analyses, especially when considering the work on seam welds by Fermér and Svensson [1].

For shorter lives in Fig. 3, the accuracy is not as good as for longer lives. This is probably due to the loading under load control in the tests and how the fatigue test data in terms of measured experimental elastic-plastic force is converted to ΔK, also assuming elastic conditions for shorter lives in this work, as normally done for joints. This has been investigated and discussed for spot welds by Fermér *et al.* [15] and to some extent also discussed by Henrysson [10]. The current data falls somewhat below the results by Wang [14], which probably can be explained by the rather coarse mesh used here as compared to fully three-dimensional fracture mechanics analyses by Wang.

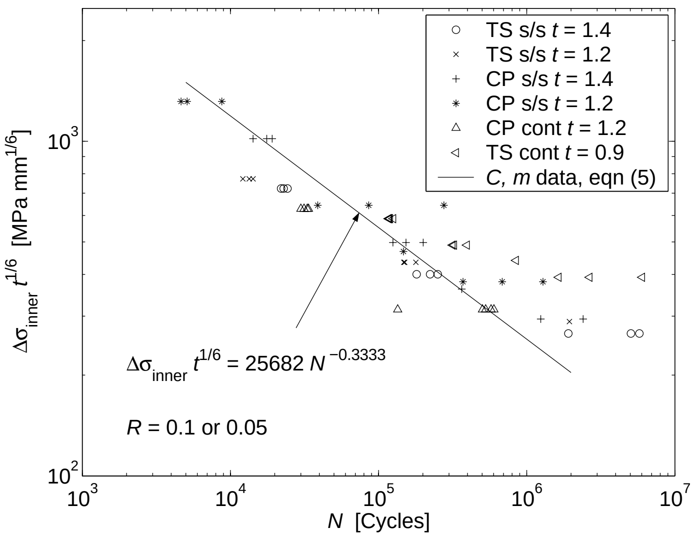

Figure 4: Stress-life results for test results in Fig. 1: $\Delta\sigma t^{(m-2)/2m}$ data, and derived fatigue life curve for input to stress-based, fatigue life prediction software FE-Fatigue [2].

In Fig. 4, the stress-life version of the current method, eqn (5), is shown. This is very similar to the work by Dong *et al.* [3] although derived in somewhat different ways. The factor 1.72 in eqn (5) is replaced by a crack propagation integral for seam welds by Dong and co-workers. Since calculated FE stresses can be easily multiplied with a constant factor in the commercial software FE-Fatigue, the parameter $\Delta\sigma t^{(m-2)/2m}$ can easily be used, and eqn (5) can be directly used as a first approximation *S-N* curve for laser welded structures.

The current work shows promising results. However, more work is needed on variable amplitude loading of laser welds to establish design recommendations. Very little work has been published so far, see for example Sonsino *et al.* [16]. In addition, fatigue data for joints between thin sheets is very often generated for $R = 0$ in order to avoid buckling for shear loads and sheet contact for peel loads. Most automotive components are, however, loaded with a load ratio closer to -1. Finally, both the current work and the work by Dong *et al.* only include specimens with equal thickness for the two sheets. Specimens with unequal thickness need to be addressed with the simplifications made for structural analyses. See Radaj and Sonsino [5] for a discussion of ΔK calculations from structural stress for unequal sheet thickness. Work on loading at $R = -1$, unequal sheet thickness and variable amplitude loading is currently planned and started at Volvo Cars.

5 CONCLUSIONS

Fracture mechanics was used to motivate a finite element based, fatigue life prediction approach for laser overlap, welded, thin sheet structures. The structural stress at the nodes along the weld was calculated using the commercial finite element software MSC/NASTRAN. Both the sheets and laser welds were modeled with shell elements with the element length along the welds set to about 5 mm, which is judged to give accurate enough results. The stress was then converted to a stress intensity factor using the approximation $\Delta K \approx 0.58\Delta\sigma_{inner}\sqrt{t}$. The corresponding ΔK-N curve was derived from Paris law using the same assumptions as for spot welds.

Good agreement between the theoretically derived curve and test data for laser welded peel and shear loaded specimens made of different steel grades was found. It was also shown how the proposed procedure can be directly used for automotive structures, using an available commercial fatigue software for seam welded thin sheet structures. A first approximation for an *S-N* curve was established. Finally, the results were discussed in relation to published literature and indications for future work were given.

6 ACKNOWLEDGEMENTS

Comments by Dr. Mikael Fermér at Volvo Car Corporation are greatly acknowledged.

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