ABSTRACT

Fatigue design of welded structures has always been important for construction equipment manufactures. The product development and manufacturing trends are reduction of lead time, cost and LCC. In manufacturing, improved quality assurance system and automated weld processes will reduce scatter and improve the possibilities for lighter structures with improved performance. At present most fatigue analysis is done using the nominal stress method or by structural testing, sometimes with improved concepts as structural stress or effective notch stress. In this thesis methods for fatigue life assessment, with higher accuracy, have been evaluated on frame structures.

The main objectives in this thesis is to investigate the utility of LEFM in fatigue assessment of typical welded structures in construction equipment; to verify the accuracy of LEFM with results from fatigue testing of a complex welded structure and to achieve an better understanding of parameters that influence on crack propagation. The purpose was also to compare different fatigue assessment methods, this has been done to some extent but main part of the work has been on LEFM.

An investigation of the accuracy and efforts in connection with different life prediction methods of welded joints in a complex structure has been done. The investigated structure was a frame to a wheel loader. The life prediction was performed with nominal stress, structural stress, effective notch stress and LEFM. The investigations show a lot of scatter in predicted life for the different methods.

Fatigue analysis and testing of a welded frame has been performed and discussed. The structure contained typical welds for a frame to a wheel loader. A service load spectrum with an overall stress ratio, R, of about -1 was used. The test results were correlated with LEFM including different assumptions of residual stress distributions.

In literature survey information useful in fatigue crack propagation analysis are compiled. The discussed concepts are crack closure, threshold values, crack growth material parameters, mixed mode conditions, variable amplitudes, small cracks and residual stresses.
APPENDED PAPERS

Paper A


Paper B

Byggnevi M., *LEFM analysis and service simulation testing of a welded frame structure*, accepted for publishing, Scandinavium Journal of Metallurgy.

Paper C

Byggnevi M., *Crack growth parameters usefull in fatigue analysis of welded joints in steel*, a literature survey.
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1. INTRODUCTION

The development of the wheel loader started 1954 when the pioneers at Lundbergs Mekaniska and Bolinder-Munktell in Sweden launched their groundbreaking H10 back-end loader, see Fig 1. Quite simply they modified a normal tractor and by locating the loader unit over the big (rear) wheels they opened up opportunities for heavier loads and higher breakout forces. The H10 was an immediate success. It was the first wheel loader in the world with attachment bracket and parallel movement, which means that changing attachments was easier and material handling safer and more efficient. It was the start for Volvo Wheel Loaders and the beginning of a development that includes a long line of technical solutions which were completely impossible to foresee in the middle of the fifties. The productivity of a wheel loader has increased more than 6 times since the beginning.

![Image](image1.png)  
**FIG. 1** a) The first Volvo wheel loader H10. b) A modern L120E wheel loader.

The main load carrying structure in a wheel loader, Fig 2, consists of steel frames, cylinders, linkages, a bucket and wheel axles. Approximately 75% of the weight of a wheel loader consists of steel plates, steel tubes or steel castings welded together. Several of the welded joints are complex, both with regard to geometry and loading directions. During operation the main structure are subjected to a load time history that are more or less unique for different parts in the wheel loader. The intensity in terms of load cycles and load levels varies between type of operation and operators, Samuelsson [1]. The fatigue life of components are then determined by the thoroughness of the load time history and the quality of the welded joints. The economic life for a wheel loader varies from approximately 5000-10000 hours for small loaders and up to the 25000-30000 hours for very large. The technical life for the main structure will be longer than that for the majority of the fleet, but who wants to drive a 15-30 years old vehicle. During 10000 hours of operation the load carrying structures are subjected from 10 to 50 million significant load, torque or pressure ranges on different parts. For a wheel loader the lifting capacity and service life is limited by the capacity of the welded joints this implies high demands on fatigue resistance on load carrying structures.
Fatigue design of welded structure has always been an important task within Volvo Wheel Loaders. The product development and manufacturing trends are reduction of lead time, cost and LCC. New methods for fatigue life assessment, with higher accuracy, have been developed and are ready for implementation at design offices. In manufacturing, improved quality assurance system and automated weld processes will reduce scatter and improve the possibilities for lighter structures with improved performance. The cost reduction potential implied in research and development projects in welded joint technology to further improve the accuracy in fatigue design is therefore great.

At present most fatigue analysis is done using various standards and fatigue design codes. The foundation of such codes rely in some cases on old concepts that do not easily translate to the output from modern computer programs and are also limited to rather simplified structures. Life predictions using SN-curves are widely used, for nominal stress there exist lots of design codes e.g. Swedish regulations for steel structures, BSK99 [2] or Fatigue design of welded joints and components, Hobbacher [3]. In Hobbacher [3] new approaches are introduced as the structural stress, Niemi [4] and notch stress, Radaj [5-6]. Dong et al [7-11] and Poutiainen and Marquis [12] has further developed the structural stress and the possibilities to improve the accuracy of the fatigue design has increased, but for some complex welded structures there is still uncertainty.

Characteristics for a welded joint are that the weld profile is more or less sharp and the weld may contain defects and high residual stresses. This promotes the use of crack propagation procedures to predict the fatigue life. For welds it is assumed that there exists a start crack in situ. Under mode I crack growth the stress intensity range, $\Delta K_I$, is established as crack driving force. For welded joints in complex structures one has to consider the complex conditions which go beyond the validity of the simple Paris law. In reports written the last 30 years one can find lots of parameters that affect the crack growth, such as thresholds, crack closure, mixed mode, residual stresses/relaxation, small cracks and variable amplitudes. For success these factors must be understand and taken into account in the fatigue analysis.

The objectives with this research are to evaluate and improve methodologies for fatigue design of complex welded structures.
2. FATIGUE ASSESSMENT METHODS

There are in principal four kinds of methods which are used in industry for life prediction analysis. There is the Nominal and the Structural stress methods which are said to be global approaches and the Effective notch and the LEFM methods which are so called local approaches. Assessment of these methods can be found in Byggnevi [13], Pettersson [14] and Martinsson [15]. Two important matters to observe in connection with stress methods are, that SN-curves are developed from constant amplitude loading and that as welded welds are assumed to have cracks in situ. This imply for example that the fatigue limit vanish under variable amplitude loading according to the Kitagawa diagram, Spagnoli [16].

Knowledge of initial crack size and stress-rising notches is important for accurate prediction of life and also how they can be affected by improvement methods. For example, if post-weld improvement is used e.g. grinding or TIG-remolding, the sharp transition at weld toe is removed or if hammer peening or ultrasonic impact treatment is used both the transition is improved and compressive residual stresses is induced in the surface. In these cases the slope and fatigue limit of the SN-curves changes, Lihavainen and Marquis [17] suggest a local strain approach in such cases. In design codes this is often treated with an improvement factor for the SN-curve. Besides improvement, the SN-curves can be corrected for plate thickness and stress-ratio. These corrections can also be attributed to the local notch and the conditions at the crack tip. Correction for plate thickness can be explained by an increase in $K_t$ for thicker plates; and in case of bending a weaker decrease of stresses over the crack for thicker plates. Correction for stress-ratio can be attributed to crack closure.

Fatigue cracks start normally from the toe or the root side. In case of manufacturing errors as internal lack of fusion, internal slag and pores the start may be from inside. Failure from the toe side is preferable due to inspection and repair issues. Global methods as nominal- and structural-stress only consider toe failures and the design codes normally assume that the throat thickness end/or penetration is enough to prevent root cracking. The step for eliminate this risk is often to increase the throat thickness and/or machine the plates to get more penetration. This is costly and should not be done unnecessarily. A way out of this is to use a local approach which handle the root side and then optimize throat thickness and penetration depth.

From the discussions above it can be concluded that accurate life predictions require detailed information of the quality of the weld, i.e. weld geometry and defects. The only methods that explicitly can model these quality parameters is LEFM and if necessary completed with a local strain approach, see e.g. Fuchs [18] or Socie and Marquis [19], for initiate a crack. However, in this thesis only welds which have initial crack (defects) is considered.
2.1. Nominal stress

Nominal stress ref [2,3,20,21] is the oldest and most popular method used in fatigue analysis. The idea is to calculate a stress component, nominal stress, which would cause the same damage on your particular welded joint as it would cause on a reference joint. These reference joints are tabled in design codes. Two main difficulties arise, first, how to choose the associated reference joints, and second, how to calculate the nominal stresses.

2.2. Structural stress

The structural stress is an improved nominal stress method. The structural stress includes all stress raising effects except non-linear stresses caused by local notches in the weld profile. Under the assumption of a standardizing local notch, only a single SN-curve is needed. Because of only bending and tension is concerned the stress distribution through thickness is linear. Several assessment methods for structural stress exist. Niemi [4] suggested the use of surface stress or strains in the vicinity of the weld toe. Two or three points are used for extrapolation of structural stress at the weld toe.

Another method for calculation of structural stress is proposed by Dong et al [7-11]. In an arbitrary distance in front of the weld toe the section forces are calculated using a summation of the through thickness stresses, $\sigma, \tau$. Equilibrium taken in the toe section then gives the structural stress. Dong has also constructed a master SN-curve to be used with his method. By correcting the structural stress for thickness effects and for effects due to the relative composition of membrane and bending stress he has collapsed a large amount of published SN-curves to a single master curve.

Recently Poutiainen and Marquis [12] have proposed a structural stress definition for load carrying fillet welds. The advantage is that the method can account for the weld size and the plate thickness. The proposed structural stress is composed of the stress in the weld and the nominal stress.

2.3. Effective notch stress

Effective notch stress is the calculated maximum principal stress in a fictitious notch. The fictitious notch radius is calculated from $\rho_f = \rho + s\rho^*$, where $\rho$ is the actual notch radius, $s$ is a constraint factor and $\rho^*$ is the microstructural length. By considering the worst case of zero notch radius, $\rho = 0$, combined with $\rho^* = 0.4mm$ for low strength cast steel and $s=2.5$ for plane strain the fictitious radius become 1 mm. The calculated effective notch stress is then equal to $\sigma_{eff-notch} = K_f \sigma_{min.al}$ where $K_f$ is the fatigue notch factor. For correlate the effective notch stress with fatigue strength a large amount of fatigue tested welded joints was analysed with a ficticious radius of 1 mm. The remarkable result from the analysis was that the fatigue strength can be expressd by a single SN-curve, $320MPa, N = 2 \cdot 10^6$, at $R=0$ and 50% failure probability. In Hobbacher [3] fatigue strength for effective notch stress method is $225MPa, N = 2 \cdot 10^6$, at $R=0$ and 2,3% failure probability. A comprehensive review of the effective notch stress method can be found in Radaj [5-6] and in Sonsino et al [22].
2.4. Fracture mechanics

For fatigue of welds the physically proper description is crack propagation. For welds it is assumed that there exists a crack in the critical location. The size of this crack varies from 0.05 - 0.2 mm as an average size for LEFM analysis, in some cases an undercut can be regarded as a crack then the size can be 10 times larger. In fillet weld a defect parallel to parent metal, a cold lap, may occur the initial mode II crack will rapidly kink into mode I crack growth, Martinsson [23].

The conventional approach in LEFM use only one crack tip driving force that is \( \Delta K \). The crack growth rate, in region II Fig. 3, is then calculated using a power law, eq. (1). For describing crack growth in all regions I, II and III, there is numbers of equations. For fatigue calculations of welded joints, which are assumed to have an initial defect, only crack growth in region II is considered in this thesis. As a lower limit for crack growth, in constant amplitude loading, a threshold value, \( \Delta K_{th} \) can be used.

\[
\frac{da}{dN} = C \Delta K^n
\]  

(1)

FIG. 3 Fatigue crack growth in metal.

Eq. (1) is valid under mode I crack growth under constant amplitude loading. Further the constant \( C \) is valid for a certain R-ratio, often \( R = 0 \). Using eq. (1) as a general rule in fatigue \( \Delta K \) must be corrected due to some phenomena. These phenomena are stress-ratio (R) effects, retardation/acceleration due to overloads/underloads, small cracks, and effects of environment. All this effects are of many researches attributed to crack closure Elber [24]. In addition one has to consider residual stresses. In eq. (1) \( \Delta K \) is assumed to be \( \Delta K_I \), but in general there is mixed mode conditions at the crack tip, therefore some authors have suggested the use of an equivalent value \( \Delta K_{equ} \), that combine all modes.
3. FATIGUE TESTING AND LEFM ANALYSIS

Fatigue testing of complex welded structures with variable amplitude may contain behavior not appearing in constant amplitude testing of simple structures. Relaxation or introduction of residual stresses and no fatigue limit is typical events in variable amplitude testing. In case of local multiaxial loading mixed mode behavior is evident and increases the analysis complexity. Nevertheless such testing must be performed and the result shall be correlated with some fatigue assessment method. The best method to use for correlate fatigue test of complex structures is LEFM. It can be used for predict possibly crack paths and for tracing the actual crack in a fatigue test.

In constant amplitude testing of small specimen’s assessment of the test results is simple and SN-curves are easily developed. For variable amplitude and especially for complex structures SN-curves are normally only valid for the actual type of loading conditions (Stress ratio, irregularity factor and shape of load histograms). Variable amplitude testing takes longer time and requires larger loading capacity than constant amplitude but normally the scatter due to testing conditions are smaller.

One common problem in connection with testing of complex structures is that failure may occur at several locations and it can be difficult to repair for further testing. Very often, especially in closed sections a repaired weld will fail soon again due to several reasons as locally high residual stresses, unfavourable root side and no complete removal of the origin fatigue crack. In the testing described in Paper B it was not possible to repair any of the frames after failure at the second critical location. The reason for that was that the frames have to be reinforced with additional steel plates which affect the stress distribution.

Another problem is that fracture criteria can be difficult to define in structural fatigue testing. For a simple specimen fracture occurred when the object brakes in to two parts. In a complex structure there are possibilities for redundance so the failure criteria can be subjective. The first failure on the frame tested in Paper B was a trough thickness crack and welldefined. At the second location for fatigue failure the test was stop when crack have grown 8 to 10 cm although the structure was still functioning.

3.1. Analysis of a frame

A rearframe, Fig. 4a, to a Volvo wheel loader have been analysed using different fatigue assessment methods, see Paper A. In this paper also the difference between computed and measured strains was analysed and differencies up to 30 % was observed. Similar results are also presented by Pettersson (14), such differencies affect the accuracy of life predictions and this is a general problem in mechanical industry.

To verify the fatigue life of some of the analysed positions in the frame, fatigue testing of a simplified frame Fig. 4b with similar welds has been performed, see Paper B.

The test frame (beam) was designed with three locations where fatigue cracks are expected. Three test objects were manufactured and the beams were produced in a
Volvo production plant using the ordinary production process. The length of the frame was 3 meter and the thickness of the web and flanges are 10 to 25 mm.

For pure mode I crack LEFM correlate well with the test for large root-cracks. For mode (I+III) cracks correlation with LEFM was possible only if a suitable residual stress field was chosen.

In the fatigue test reported in Paper B there where mainly two areas of high uncertainty which affect the possibilities to achieve good accuracy on predicted life. Firstly the residual stress field and its relaxation and secondly the mixed mode complexity. Residual stress is possible to incorporate in the analysis when measurements are available. Mixed mode complexity on the other hand has to be solved. And the main problem to solve is the mode I+III crack growth. In paper C residual stresses and mixed mode influence are discussed.

3.2. Analysis of a fillet weld in mode III

Recently the author has evaluated a mode III fatigue test of a fillet weld, Fig 5. It was a torsional test of a circumferential fillet weld. The crack started from the root in all cases. The LEFM results shown in Fig 6 is calculated using the the suggested parameters in Tjernberg [25], \( C = 7.3 \cdot 10^{-15} \) and \( m = 5 \). Life is calculated using Paris law without any corrections. As seen in Fig. 6b the correlation is good.
3.3. Analysis of defects in production components

A relatively common weld defect is locally lack of fusion. And a common question is if that could be accepted for a small number of components. During the last years LEFM have been used in Volvo Wheel Loaders for relative calculation of stress intensity to understand the seriousness of the lack of fusion defects. Other defects that exist and can be analysed are internal slag and pores. Fig. 7 shows a detail of a repaired component containing root defects, lack of fusion and pores; the example is extreme but illustrative. An increase in failure rate for the component was observed in field and it was decided to repair all of them whether or not they have failed. Using LEFM, life for the repaired component was compared with life for the original design. The analysis show that life for the repaired component was enough and the failures have also stopped in field. Of course the accuracy in the analysis is questionable, but still, the only method that can handle this kind of problem is the LEFM approach.
4. DISCUSSION

Most of the stress based methods used in fatigue assessments are just applicable to the toe side of the weld. The introduction of different weld improvement methods and hence introduction of higher stresses in the welds moves often the critical location to the root. The demands for effective methods handling root side are therefore great. Two methods for the root side exist, effective notch stress and LEFM. The physical correct method to use is LEFM and that is also the only method that handles redundancy, e.g. Martinsson [15]. Especially in assessment of fatigue testing of complex structures, LEFM is the best method to use for that it can track the actual crack path. The usefulness of LEFM is also verified in several failure investigations at Volvo Wheel loader AB during the latest year done by the author.

One motif not to use LEFM is that the method is regarded to be very time consuming. With modern computers and programs, modelling of cracks and computing of stress intensity is not difficult, not even in 3D. The real problem is the lack in knowledge in LEFM at the design departments in mechanical industries. To improve the situation it is necessary to educate engineers, and the way to do this is to have expertise in developing and manufacturing of loaded welded structures. These aspects legitimize that kind of applied science which is presented in this thesis.

5. CONCLUSIONS

- For Mode I crack it is possible to correlate fatigue life with LEFM on a complex welded structure with large initial defects, i.e. root-defects.

- The different equations for calculation of crack growth under mixed modes (I+III) applied in this thesis show large differences.

- The scatter in life between different life assessments methods applied on a complex structure is large.

- It is shown that LEFM can be used as an efficient method in design departments and calculations can be done using standard 3D FE modeling tools.

6. FUTURE RESEARCH

- Methods for handling residual stresses and relaxation must be developed.

- Crack propagation laws for mixed modes (I+III) must be improved.

- An alternative method for calculation of stress intensity, i.e. the J-integral, should be examined.
7. SUMMARY OF APPENDED PAPERS

**Paper A** compare different methods for assessment of welded joints in a complex structure based on FEM. The investigated structure is a frame to a wheel loader and in the investigation a global FE-model and a number of different sub-models are used. The paper also contains comparisons between computed and measured strains for verification of the FE-model. The life prediction is performed with nominal stress, geometric stress, effective notch stress and LEFM. The investigations show a lot of scatter in predicted life. The paper also discusses the working efforts and practical aspects using the different methods.

In **Paper B** the results from fatigue analysis and testing of a welded frame is discussed. The structure contains some typical welds, which can be found on a frame to a Volvo wheel loader. Actually the welds are similar to the one examined in paper A. The test was carried out with a service load spectrum with an overall stress ratio, R, of about -1. The fatigue cracks started from the root of the welds in all cases. The test results were correlated with linear elastic fracture mechanics (LEFM) including different assumptions of residual stress distributions.

**Paper C** is a literature survey and compiles information useful in fatigue crack propagation analysis. The main focus is on crack propagation in welded steel but many of the concepts presented apply to other material as well. Some recommendations of best practice for engineers are also given. This survey is restricted to linear elastic fracture mechanics and small scale yielding. Basic fracture mechanics are presented followed by the concept of **crack closure**, **threshold values**, **crack growth material parameters**, **mixed mode**, **variable amplitudes**, **small cracks** and **residual stresses**.

8. REFERENCE


