# IMPROVEMENTS IN THE FATIGUE ASSESSMENT OF LARGE WELDED STRUCTURES USING THE NOMINAL STRESS APPROACH

**Guillaume Elbel[a], Michael Karge[b]**

**a** Liebherr-France SAS, Colmar, France/
**b** Liebherr Mining Equipment Newport News Co., USA

**Abstract.** By the fatigue assessment of large welded steel structures such as construction machines structures, the calculation engineer is confronted with a difficulty: the local stress approaches with fictitious notch radius that are very accurate cannot be used on the global structure because of the current computer limitations. Only a nominal stress can be estimated on the whole structure. The accuracy of the current commercial code methods that are using the nominal stress approach is not satisfying for most of the cases. The major problems are the following:
- only one SN-Curve (FAT-class) can be chosen for a weld
- the stress used for the calculation is based on the critical plane concept, not taking into account the direction of the weld (anisotropy of notch effects) and the geometrical weld parameters (e.g. weld throat thickness and penetration)
- choice of the FAT-class when the structural detail is not available in the IIW guideline.

The investigations that have been made in collaboration with LMS Durability development team in the last two years have permitted to elaborate a new nominal stress approach that improves the three issues above. The validation on some weld joints and geometries has shown that this new method allows making a big step forward in the accuracy without affecting the time required for the analysis.

## 1 INTRODUCTION

The Liebherr group has two plants in Colmar, France, one where crawler excavators from 20 to 100 tons are manufactured, the other for mining excavators from 100 to 800 tons. The author is responsible for the fatigue assessment for both plants. To design such machines, a precise fatigue assessment of the different large welded structures is needed. Apart from the difficult question of the load spectrum to be used, the method for the assessment of the seam weld is a critical issue. After an analysis of the methods currently available in the commercial codes, this paper will present a new method based on the nominal stress approach.

## 2 STATE OF THE ART FROM FATIGUE CALCULATION OF SEAM WELDS

The fatigue life of seam welds is mostly governed by the local geometry of the weld. As a consequence, the most accurate method for the fatigue analysis is to model directly these notches with solid elements according for example to the fictitious notch rounding method described in [2] (RxMS). However this method requires a very large amount of nodes, making it not applicable on the entire structure of a construction machine. The only possibility is to use a shell element model.

The methods currently implemented in the commercial fatigue analysis software for the fatigue assessment of seam welds using shell models can be divided into 3 types:

- nominal stress approach according to the Eurocode or the IIW guideline (basic approach in all the software)
- structural stress approach (FE-Safe – Verity [6] and N-Code/Chalmers [4])
- local stress approach (LMS/seam weld [10] and FEMFAT Weld [5])

The local stress approaches do not require a particular modelling of the weld, since the local stresses are not taken directly from the mesh, but are back calculated from the stresses or the line forces with different techniques engaging local fine models.

After having tested the majority of these methods, none of these were satisfying for this application. In spite of having interesting results, the structural stress approaches were rejected, because of the additional shell elements required for the modelling of the weld that would lead to a big amount of additional manual work for the calculation.
The force based approaches from LMS (Seam weld) and from FEMFAT (MSZ/SSZ) both use 2D submodels from the welds (parametric for FEMFAT, with solid elements for LMS). This leads to very conservative results for the seam welds where 3D effects are important (e.g. weld between two bent sheets).

It was decided to further investigate the basic nominal stress approaches in order to increase some of its major accuracy problems.

## 3 IMPROVEMENTS OF THE NOMINAL STRESS APPROACH

The chart from **Figure 1** shows the overview of the new method. Each step will be discussed further in the document. The nominal stresses are the elements stresses from the first row of elements along the weld line.

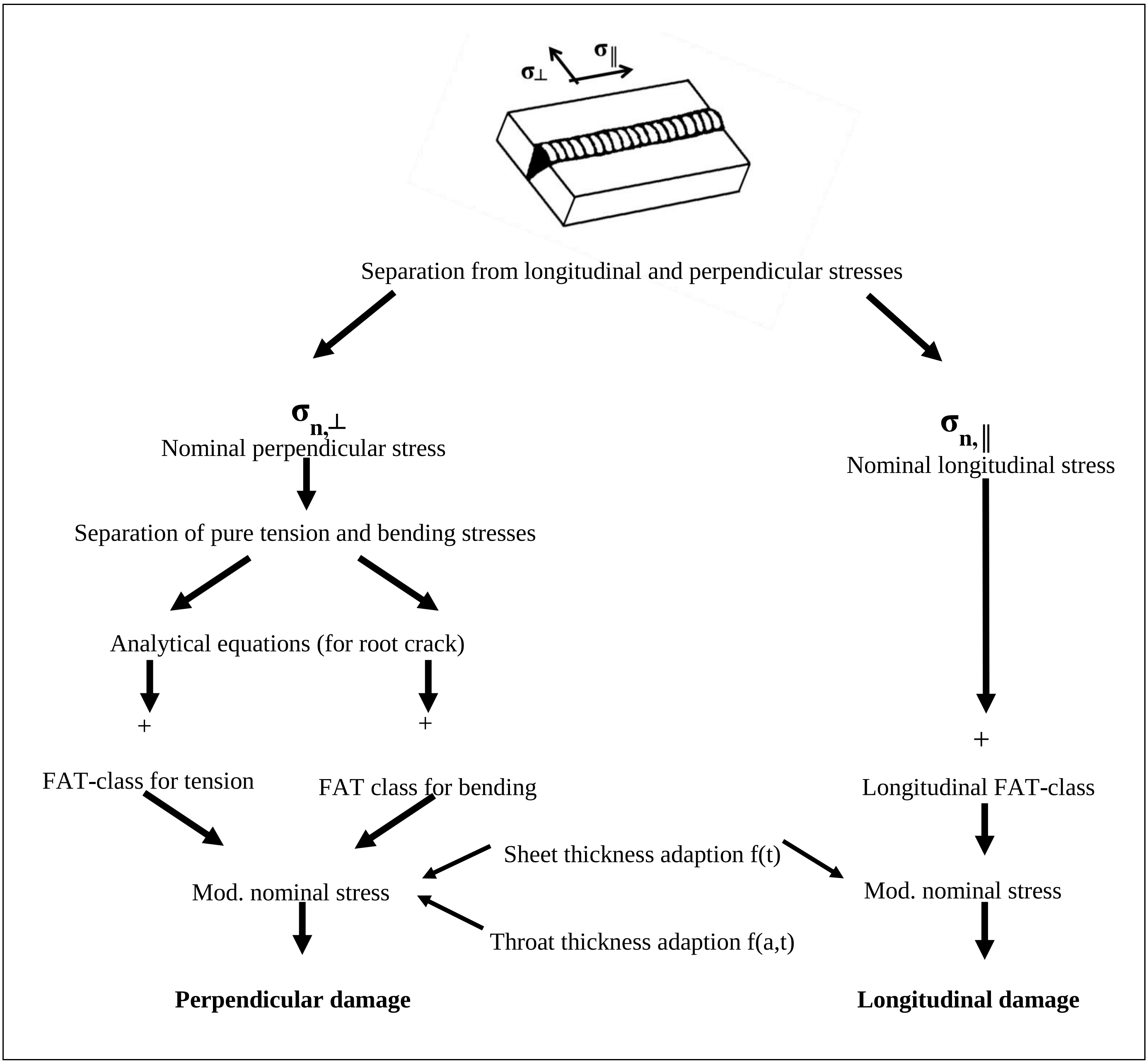



Figure 1: Concept of the improved nominal stress approach [1]

### 3.1 Separation of longitudinal and perpendicular stresses acting on the weld

The majority of the commercial codes use a critical plane approach for the fatigue assessment because of the unknown critical stress direction for multi-axial loads. The problem is that the seam welds have an anisotropic behaviour so that the notch factors in both longitudinal and perpendicular directions are very different. It results that the choice for most of the FAT-classes depends on the load direction (cf. **Figure 2**). The choice has to be done in advance by studying the direction of principal stresses on the FE model. This could be applicable when the load spectrum remains simple (few load cases), as soon as the amount of load cases increase, this process becomes impractical.

In any case the user has to make a decision for the one or the other direction (along the seam weld direction or transverse). The difference in the FAT-class is so significant that for safety reasons, the most conservative FAT-class is frequently chosen. This produces very conservative results in most of the cases. In some cases, it has been observed that two separate cracks can appear in the same area of a part in two different directions (cf. **Figure 3**). This information is very important in the design stage because the strategy that will be adopted to increase the fatigue strength of the seam weld will be different for both cases.

The only way to deal with this issue is to make two separate calculations, which is the first step of the new approach. The longitudinal stress component, combined with a longitudinal FAT-class will allow calculating the longitudinal damage, and perpendicular stress, combined with a perpendicular FAT-class will allow calculating the perpendicular damage.

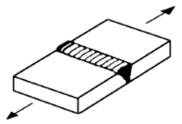
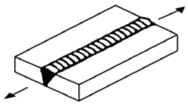
| | | | | |
|---|---|---|---|---|
| 216 |  | Transverse butt welds welded from one side without backing bar, full penetration<br>root controlled by NDT<br>no NDT | 71<br>36 | 28<br>12 |
| 313 |  | Longitudinal butt weld, without stop/start positions, NDT<br>with stop/start positions | 125<br>90 | 50<br>36 |

Figure 2: Structural details regarding the load direction [2]

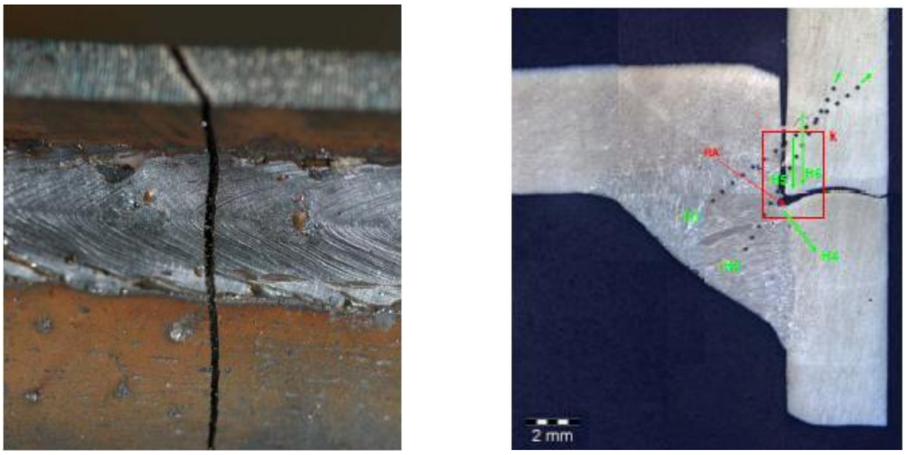



Figure 3: Cracks due to longitudinal stress (left) and to perpendicular stress (right) on the same area of one part [3]

### 3.2 Separation of bending and tension

#### *3.2.1 Different FAT classes for tension and bending*

The academic example from **Figure 4** shows clearly why this separation has to be done. For both cases, the nominal stress in the welded sheet is equal to 1 MPa, but the difference in the local stress is huge (factor 5). This difference is due to the additional bending in the throat because of the asymmetric behaviour of the weld regarding the tension load case.

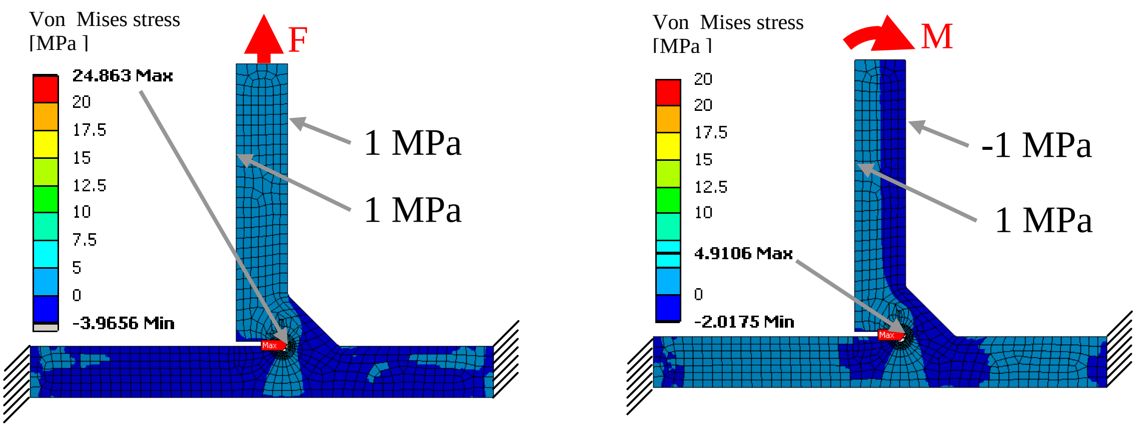



Figure 4 : FEM calculation results of a single sided fillet weld subjected to tension and bending applied to the welded sheet [1]

The separation of the nominal stress to nominal tension and bending stress is easily done for a shell element, by adding the Top and Bottom stresses for the tension stress, and subtracting them for the bending ones (equations (1) to (3)).

$$\sigma_{tension} = \frac{\sigma_{Top} + \sigma_{Bottom}}{2} \tag{1}$$

$$\sigma_{bending,Top} = \frac{\sigma_{Top} - \sigma_{Bottom}}{2} \tag{2}$$

$$\sigma_{bending,Bottom} = \frac{\sigma_{Bottom} - \sigma_{Top}}{2} \tag{3}$$

For the case of cracks in the weld throat, the nominal stress in the sheet has to be converted into nominal stress in the throat. For that purpose, analytical equations have been derived according to the theory of plates [1]. These equations allow taking into account important weld parameters such as the weld throat and the penetrations. Equations (4) and (5) are valid for single sided fillet welds.

$$\sigma_{n,tension,root} = \sigma_{n,tension} + \sigma_{n,bending} = \sigma_{n,tension,sheet} \cdot \left( \frac{t}{\sqrt{2} \cdot a} + \frac{6 \cdot \left( \frac{a}{2} + \frac{\sqrt{2} \cdot t}{2} \right) \cdot t}{\sqrt{2} \cdot a^2} \right) \tag{4}$$

$$\sigma_{n,bending,root} = \sigma_{n,bending,sheet} \cdot \left( \frac{t}{a} \right)^2 \tag{5}$$

### *3.2.2 The modified nominal stress*

Since tension and bending perpendicular to the weld line are both affecting the same crack initiation sites (transversal notches, weld toes and roots), the stresses can be added, taking into account that the notch factors (or FAT-classes) are different. As a convention, the fatigue calculation is done with the tension FAT-class, so that the bending component has to be modified as shown in equation (6):

$$\sigma_{n,\mathrm{mod}} = \sigma_{n,tension} + \frac{FAT_{tension}}{FAT_{bending}} \sigma_{n,bending} \tag{6}$$

## 3.3 Modification of the FAT-class to different parameters

### *3.3.1 Sheet thickness adaption*

The sheet thickness has an important influence on the local stress. The IIW guideline [2] gives a formula to take that effect for sheet thicknesses above 25 mm into consideration. For thinner sheet thicknesses it is recommended that the beneficial factor is verified by component tests.
The local stress approach with the fictitious notch radius contains naturally the sheet thickness influence [1] and all the test results with sheets thinner than 25 mm that have been analysed so far show that this adaption is important to be done otherwise the results are too conservative.

### *3.3.2 Throat thickness adaption*

It has been shown with the study of several solid models of single sided fillet welds [1], that the notch stress depends of the throat thickness. This adaption is not explicitly mentioned in [2], but the guideline only refers to standard fillet welds, where the throat thickness is equal to t/√2. Since the throat thickness can clearly differ from this value, it was decided to take this effect into account.
The **Figure 5** shows the result of this analysis.

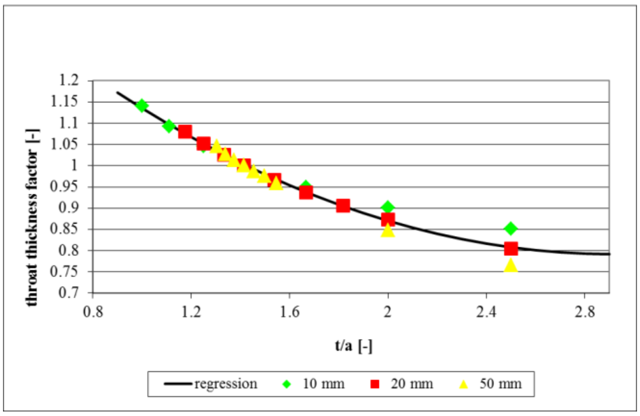



Figure 5: Throat thickness adaption of the FAT class for a single sided fillet weld [1]

### *3.3.3 Misalignment for butt joints*

Another parameter that can be taken into account in the method is the misalignment of the neutral axis of the sheets for butt joints. This misalignment has a great influence on the fatigue life of those seam welds because of the additional bending moment created by tension. A standard fabrication tolerance is already included in the FAT-class (e.g. 10% for detail 213 [2]) but the additional misalignment due to sheets with different thicknesses welded on one edge has to be taken into account. This misalignment is not modelled in the shell elements model in order to avoid very small elements in this area. Therefore, an analysis has been conducted on several solid models with changing the sheet thickness and the excentricity between both sheets in order to find the regression curves shown on **Figure 6**. The tension FAT-class has to be divided by the relative notch factor.

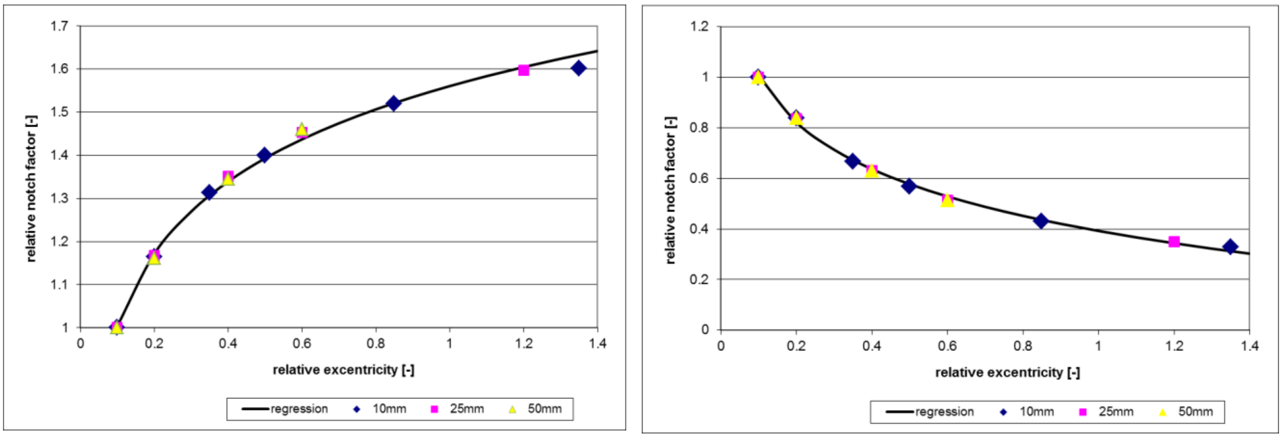



Figure 6 : Adaption of the FAT-class to the misalignment on the side of the misalignment (left) and on the other side (right)

## 3.4 Determination of the FAT-class for details that are not in the IIW catalogue

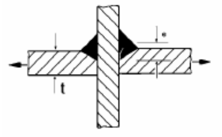
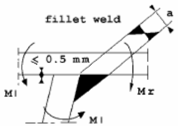
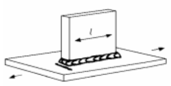
For such cases, the local stress approach is used directly on a small solid element model in order to determine the notch factor $\beta_k$. The new FAT-class is then obtained with equation (4):

$$FAT_n = \frac{FAT_{local}}{\beta_k} \tag{4}$$

With $FAT_{local}$=225 MPa for a fictitious notch radius of 1mm [2].

In order to validate this approach, it has been applied to details from the IIW catalogue by using a standard seam weld geometry and 25mm sheet thickness. The results can be seen on **Table I**. The difference between the calculated FAT-class and the one in the catalogue is not bigger than 10%.

Table I : Results from the comparison between the IIW catalogue and the R1MS method [1]

| IIW-No. | Detail | IIW FAT-class | Calculated FAT-class with R1MS |
|---|---|---|---|
| 213 |  | 80 MPa | 79 MPa |
| 416 |  | 71 MPa | 67 MPa |
| 515 |   | 71 MPa | 65 MPa |
| 521 |  | 71 MPa | 64 MPa |

## 4 VALIDATION OF THE METHOD

### 4.1 The “trumpet”

It is a trumpet-like box with longitudinal single sided fillet welds, subjected to bending [3]. 7 different specimens have been tested until cracks appeared. The two types of cracks that have been observed are those described in **Figure 3** and **Figure 7**.

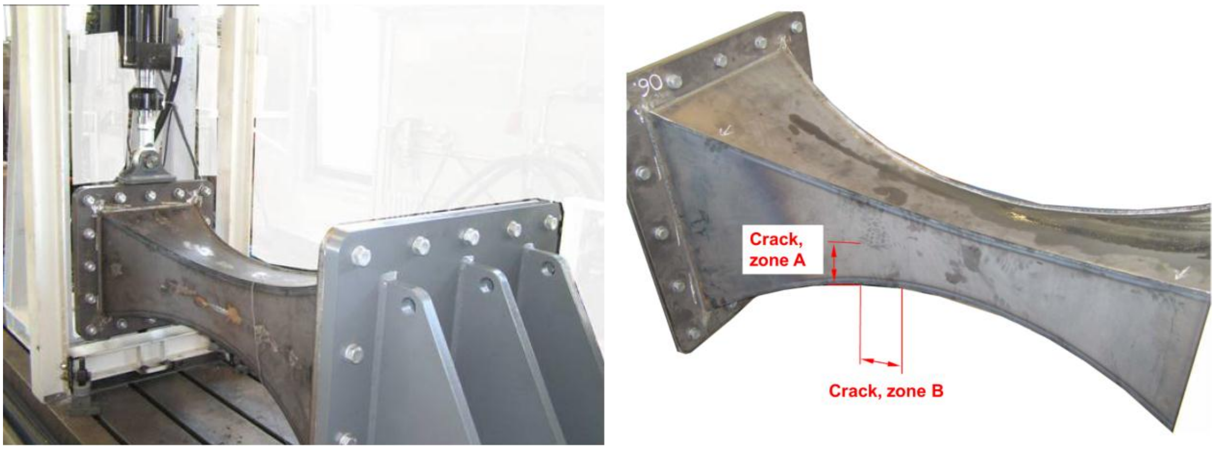



Figure 7: The "trumpet" sample

The results from the fatigue calculation with the improvements described above are shown in **Table II**. The two lines highlighted in yellow are those where the two cracks appeared, almost at the same time (depending on the samples). As it is shown, the new method is precise enough to localise the 2 cracks in the base sheet and to explain why both cracks appeared almost at the same time, since the damage in both zones have very similar values, close to the theoretical expected value of 1. The comparison with the direct local stress approach (with a fictitious notch radius of 0.3mm) is very good as well, at least for the base sheet.

Table II : results from the fatigue calculation of the "trumpet" at the time when the cracks appeared [8]

| | | New method | Local stress approach R0,3MS |
|---|---|---|---|
| **perpendicular FAT-class (MPa)** | | **63/71** | **320 [9]** |
| **longitudinal FAT-class (MPa)** | | **100** | - * |
| **perpendicular damage at the root (-) Zone A** | **base sheet** | **1,13** | **1,33** |
| | **welded sheet** | 1,07 | 0,27 |
| **longitudinal damage (-) Zone B** | **base sheet** | **1,08** | - * |
| | **welded sheet** | 0,58 | - * |

** local stress approach not applicable*

### 4.2 Combination of all the available test results

The **Figure 8** shows the damage values with the new approach for different fatigue tests at the time when the crack appeared. Some of the cases (1 to 3, **Figure 8**) are related to tests where several specimens have been used.
In the other cases only one big specimen has been tested, where multiple crack types and locations were recorded. Positions 6 to 12 come from a variable amplitude test, and therefore, the theoretical damage value is reduced to 0.5 [2]. Except for position 3 which will be discussed in the following section, all the results are satisfying, the damage value is always at least equal to the theoretical value and not bigger than 3 times this value, which looks reasonable compared to the average scatter for seam weld fatigue tests.

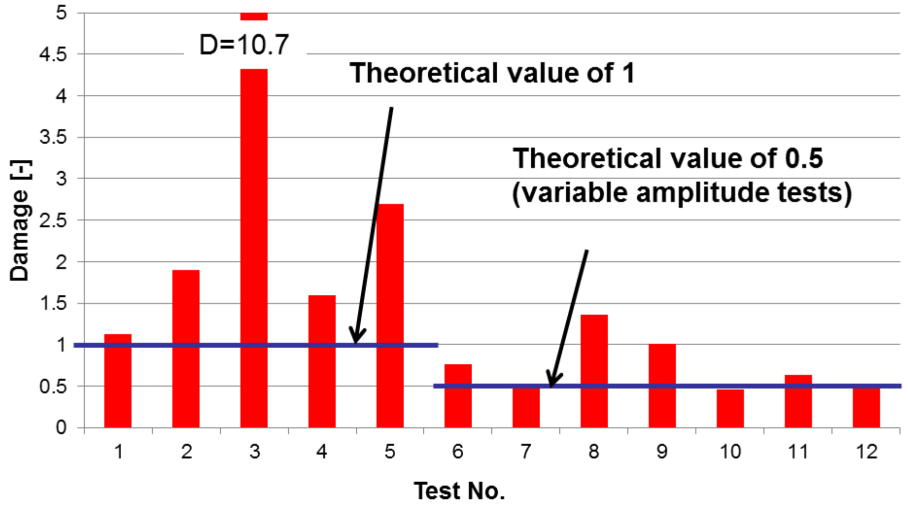



Figure 8 : Overview of all the available results

## 5 LIMITATIONS

The position 3 from **Figure 8** corresponds to the results of the calculation for the sample shown at Figure **9** and **Figure 10**, which has been tested by Prof. Fricke [7]. Table **III** shows the result of the calculation with the new approach and those with the R1MS method. The results from the new approach are more than 10 times too conservative. In this case, this is due to the small radius at the location of the crack, which makes equations (1) and (2) invalid because 3D effects are not taken into account in the simple 2D plate model.
This is actually the main limitation of the suggested approach.

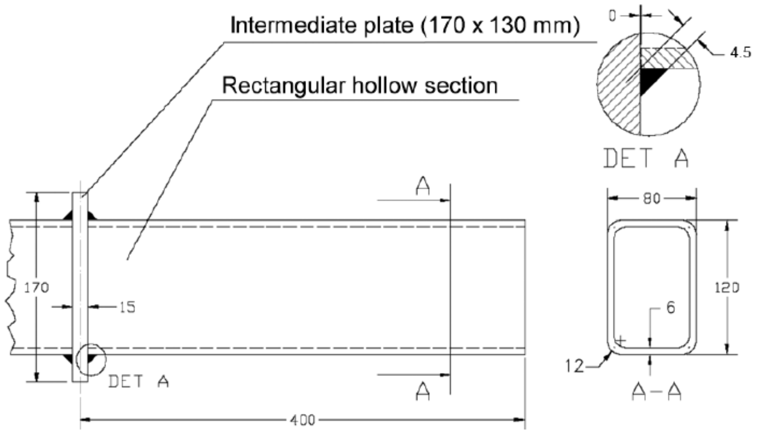



Figure 9: the sample from Fricke [7]

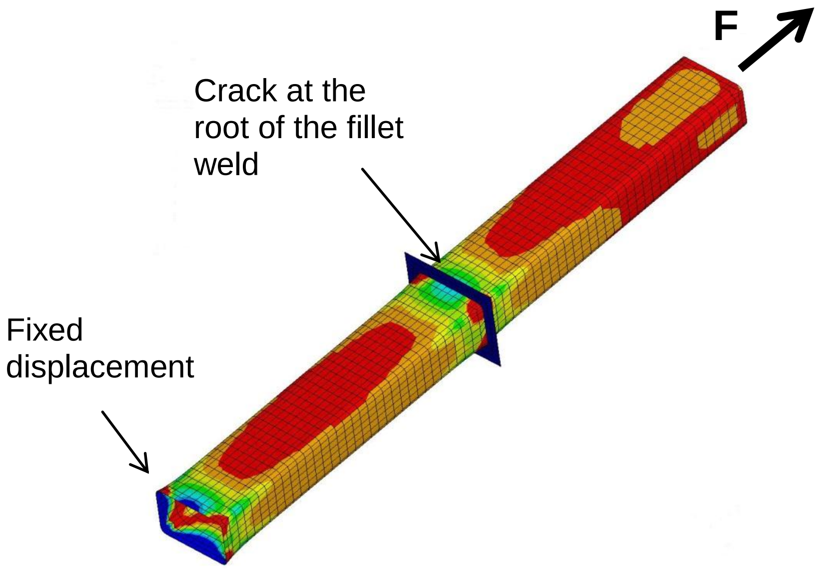



Figure 10: Boundary conditions and loading with Von Mises stresses plot on the FE-Shell model

Table III : Results of the fatigue calculation

| | **new method** | **R1MS** |
|---|---|---|
| **Damage** | D = 10.7 | D = 0.9 |

## 6 CONCLUSION

The study of that paper has shown that there is a high potential to improve the accuracy in a fatigue calculation of large welded structures without increasing the time needed for the analysis. In fact, since the method is based on the nominal stress a simple shell element model can be used for the structure.
The majority of the improvements were made according to the recommendations of the IIW guideline.

The main limitation of proposed method is related to condition where geometry of structure is sensitive to 3D effect and is noticeable, which makes the equations for transferring the nominal stress in the sheet material to the nominal stress in the throat, being invalid.

In those cases, a local solid element submodel according to the fictitious notch rounding method is needed. The new method is always conservative in those areas and allows localising the critical areas where a more detailed analysis has to be done.
The next steps will be:

- investigation, of the limitations, in order to define rules to be able to know when the results are valid or not
- application of the method to other seam welds (overlap joints, cruciform joints)
- implementation of the method in a software

## 7 REFERENCES

[1] Karge M.: Methode zur Berechnung der Schädigung von Schweissnähten mobiler Arbeitsmaschinen (Method for the fatigue assessment of the seam welds from mobile construction, machines), Diploma Thesis, Technische Universität Dresden, 2011
[2] Hobbacher A.: Recommendations for Fatigue design of welded joints and components, International Institute of Welding, June 2008
[3] Issler L.: Schwingfestigkeitsversuche an Kastenprofilen aus Baustahl S 355 für Liebherr-Hydraulikbagger (fatigue testing from box profiles of steel S 355 for Liebherr-Hydraulikbagger), STZ Bauteilfestigkeit und -sicherheit, Werkstoff- und Fügetechnik (BWF), Fachhochschule Esslingen, October 2008
[4] ICE Flow: DesignLife theory guide 5.0, nCode International Ltd., 2008
[5] Hofwimmer K., Gaier C., Dannbauer H., Zhang S., Weisner R., Eppler R., Hempel H.: Force Based Fatigue Assessment of Weldings, ATZautotechnology Vol. 8, April 2008
[6] Dong P., Hong J.K.: The master S-N curve approach to fatigue evaluation of welded structures, OMAE 2004-51324
[7] Fricke W.: Guideline for the Fatigue Assessment by notch stress analysis for welded structures, IIW-Doc. XIII-2240-08/XV-1289-08, June 2008
[8] Karge M.: Improvements in the fatigue assessment of large welded structures using the nominal stress approach, Liebherr fatigue and simulation meeting, Ehingen, June 2011
[9] Sonsino C.M., Kaßner M., Fricke W.:Stand von Bemessungskonzepten zur schwingfesten Auslegung von Schweißverbindungen (status from the fatigue assessment of weld connections), Festigkeit geschweißter Bauteile, DVS conference in Braunschweig, May 2009
[10] Koettgen V.B., Zingsheim F., Hack M., Speckert M.: A New Approach for Numerical Fatigue Life Prediction of Parts or Systems with Seam Welds, SAE Technical Papers, 2003