MULTIAXIAL FATIGUE OF WELDED JOINTS – A METHOD FOR FATIGUE LIFE PREDICTION

Keurrie Cipriano Goes, keurrie.goes@arvinmeritor.com
ArvinMeritor do Brasil Sistemas Automotivos – Commercial Vehicle Systems – Av. João Batista, 825, Osasco, SP, Brasil
Universidade de São Paulo, Escola Politécnica – Av. Mello Moraes, 2231, São Paulo, SP, Brasil

Arnaldo Freitas Camarão, arnaldo.camarao@arvinmeritor.com
ArvinMeritor do Brasil Sistemas Automotivos – Commercial Vehicle Systems – Av. João Batista, 825, Osasco, SP, Brasil

Gilmar Ferreira Batalha, gilmar.batalha@poli.usp.br
Universidade de São Paulo, Escola Politécnica – Av. Mello Moraes, 2231, São Paulo, SP, Brasil

Abstract. *Fillet welded joints are used in numerous engineering applications such as the mobility and power industry, where low cost and flexibility are largely required. The great challenge in welded structures design is to develop the best process and weld configuration capable to sustain multiaxial or combined fatigue service loading. The structural integrity and fatigue strength of these structures depends on the robustness and reliability of the design criteria. The aim of this work is to develop a method for the fatigue life assessment of a welded joint configuration under multiaxial fatigue loading, using experimental and virtual prototypes. The BS7608 weld fatigue design code was used to compute the fatigue life of flange-tube circular welded joint subjectd to combined bending and torsion constant amplitude fatigue loading. A fatigue lab test, with biaxial proportional in-phase bending and torsion loading, was specially designed to calibrate the flange-tube joint FE model. Different approaches exist for the fatigue analysis of welded joints, which can be distinguished by the parameters used for the description of the fatigue life N or fatigue strength. In this work was chosen the structural or hot-spot stress obtained by finite element model (FEM). The obtained stresses were then imported to a fatigue analysis program for fatigue life prediction. The practical use and benefits of this method is discussed. Major challenges associated with this modeling and improvements proposals are finally presented.*

Keywords*: Multiaxial fatigue, Finite Element, Welded Joint, Virtual prototype, fatigue lab test*

1. INTRODUCTION

The welded joint application in general industry is widely used and includes numerous engineering applications such as the mobility and power industry, where low cost and flexibility are largely required.

Welding strongly affects the material by the process of heating and subsequent cooling. Furthermore, a weld is usually far from being perfect, the shape of the weld profile and non-welded root gaps create high stress concentrations with widely varying geometry parameters. In addiction residual stresses and distortions due to the welding process affect the fatigue behavior (Fricke, 2003).

Welded joint subjected to a multiaxial loading is a very complex subject and the fatigue behavior is not only determined by loading features like proportional or non-proportional (Sonsino, 2009). It is necessary to determinate the fatigue life through lab tests. However these are very expensive and in many cases difficult to perform due the large dimensions of the sample. To minimize this problem the virtual fatigue analysis is a helpful tool to assessment the welded joint.

There are different approaches for the fatigue analysis of welded joints, which can be distinguished by the parameters used for the description of the fatigue life N or fatigue strength (Fricke, 2003). The structural or hot-spot stress obtained by finite element model (FEM) was the approach chosen for fatigue analysis in this work.

2. FATIGUE OF WELDED JOINTS

The fatigue behavior of welded joints can be affected due to many parameters. The joint geometry is one of the most important (Branco, 1986) and act as stress raisers (Gustafsson and Saarinen, 2007). U-joint and T-joint are most common classification of welded joints in the literature.

The welded joint can be subjected to uniaxial or multiaxial fatigue. The second one is a very complex subject and can be assessing to some approaches. According to Fricke (2003) there are six fatigue analysis approaches: nominal stress, structural or hot spot stress, notch stress, notch intensity, notch strain and crack propagation. In this work was used hot spot stress approach.

2.1. Multiaxial Fatigue

Most fatigue design data have been obtained under unidirectional axial or bending loads (Niemi, 1995). However, in many applications, engineering components are subjected to combined bending and torsion. Complex stress states very often occur at geometric discontinuities such as notches or joint connections. Fatigue under these conditions, termed multiaxial fatigue (Bannantine at al, 1990).

There are many multiaxial fatigue models proposed in the literature, and the stress-strain approach was chosen for developed this work. The stress-strain approach is based on extensions of static yield theories to fatigue under combined stress. For structural steels, the shear stress amplitude is one of the most important parameters in the formulations of multiaxial fatigue damage models (Reis et al, 2008).

2.2. Hot-spot approach

Hot spot is a term, which is used to refer to the critical point in a structure (Bäckström, 2003). In this approach, the fatigue strength, expressed as an S-N curve, is generally based on strains measured in the specimen near the point of crack initiation (Niemi, 1995).

The structural or hot spot stress is a fictitious value but, to plate or shell structures it corresponds to the sum of membrane and bending stress at the weld toe (Radaj, 1990), which can be determined either by surface extrapolation or inner linearization of the stress (Fricke, 2003), see figure 1 bellow.

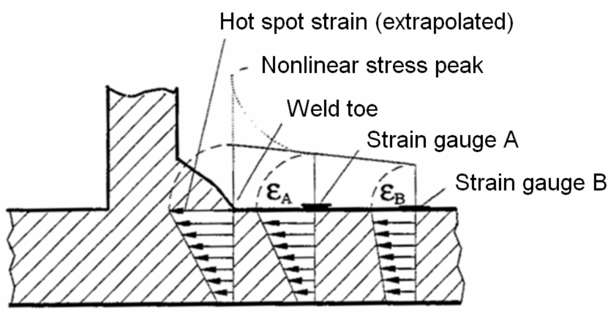

Figure 1. Measurement of the hot spot strain range using linear extrapolation method (Niemi, 1995).

2.3. Fatigue Design Codes

There are some codes to standard the welded joint design. Codes like BS7608 (1993) predicts the fatigue life based on SxN curves, these curves are from several lab test. In this code are used nominal stresses and there is one curve to each welded joint class, based on BS5400 (1980). A general curve is presented in figure 2 and the joint classification in figure 3.

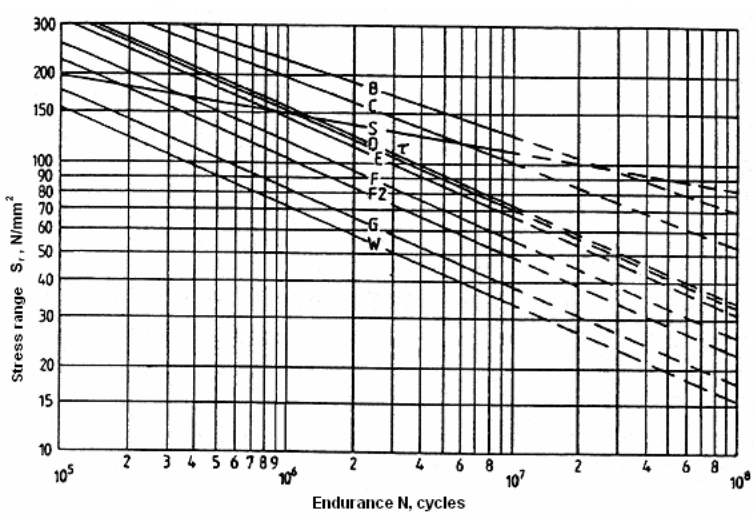

Figure 2. Fatigue life curve to each welded joint class (BS7608, 1993).

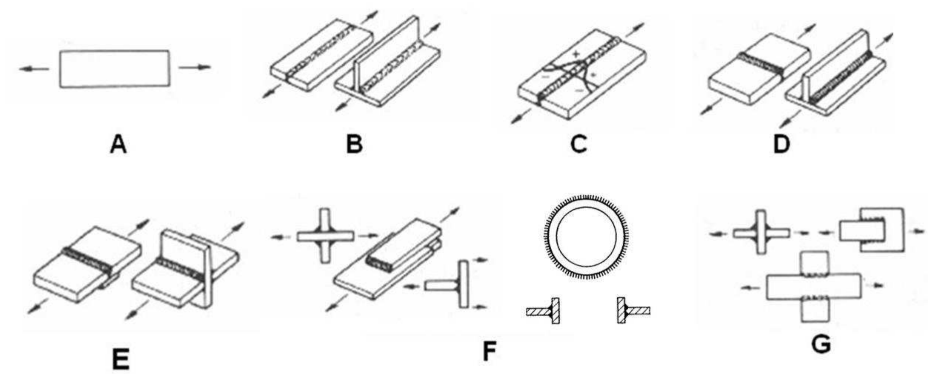

Figure 3. Welded joint types (adapted from BS5400, 1980 and BS7608, 1993).

Recently Sonsino (2009), Bäckström (2003) and Gustafsson and Saarinen (2007), analysed fatigue life under multiaxial load, comparing the lab results with design codes, as Eurocode3, SFS2378 and IIW recommendations. Sonsino and Bäckström studied a tube to plate samples. Circular section was studied by Sonsino and square section by Bäckström. The samples used in this work are a miscellaneous from both circular and square section.

3. METHODOLOGY

In this work the finite element analysis (FEA) was used to assess a welded joint hot spot stress. Two rectangular strain gage rosettes were attached in the hot spot location to calibrate the FE model.

The samples are from an automotive component and the welded joint is located between the axle housing axle and brake flange. The typical chemical composition is showed in table 1.

Table 1. Typical chemical composition of the axle housing material – SAE 1022.

ELEMENTS	C	Si	Mn	P	S	Al	Cu	Nb	V	Cr	Ni	Ti
Composition (%)	0,15	0,30	1,37	0,013	0,006	0,034	0,01	0,027	0,064	0,20	0,02	0,012

The material monotonic properties are described bellow:

- E (Young Modulus) = 210 GPa
- ν (Poisson Ratio) = 0.3
- S_{ut} (Ultimate Tensile Strength) = 530 MPa
- S_y (Yielding) = 350 MPa

3.1. Finite Element Model.

Test specimen consisted of a combined circular to rectangular hollow structural component with a flange-tube welded joint, typically used in automotive axle housings, as indicated in figure 4. The 3D solid model was built on Pro/Engineer CAD software and imported into the Ansys Workbench to generate the finite element mesh and run a linear-elastic analysis. The tube-flange joint was refined to better capture the stress concentration distribution at the toe location (figure 5).

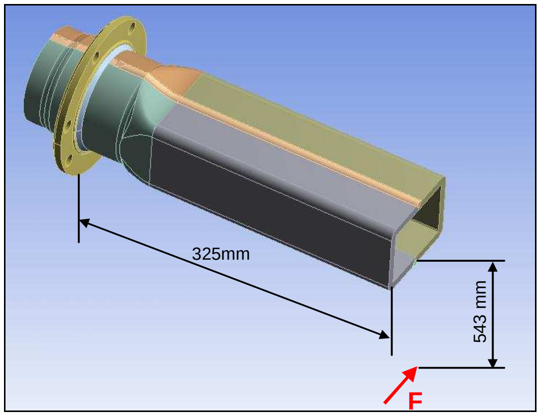

Figure 4. Finite Element boundary condition.

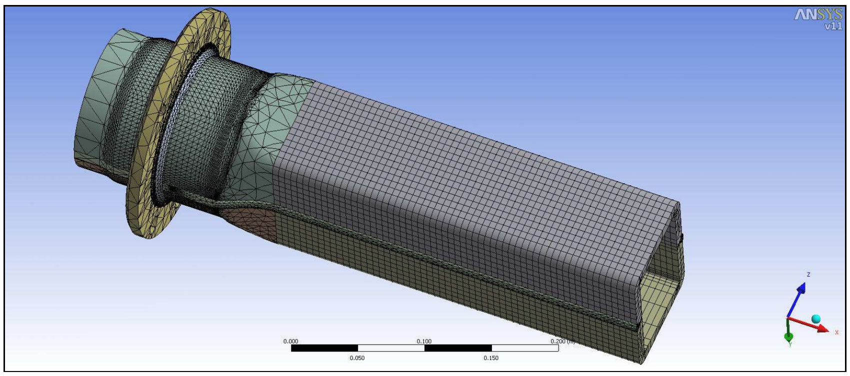

Figure 5. Finite Element Mesh.

The Finite Elements types and boundary conditions are described bellow:

- Elements - Table 2 shows the Solid Elements types used.

Table 2. Element Types Summary

Generic Element Type Name	ANSYS Name	Description
10 Node Quadratic Tetrahedron	Solid187	10 Node Tetrahedral Structural Solid
20 Node Quadratic Hexahedron	Solid186	20 Node Structural Solid
20 Node Quadratic Wedge	Solid186	20 Node Structural Solid

- Boundary Conditions:
  - Remote Force: 20,000N as indicated on figure 4.
  - Constraint: Clamped at the holes location.

3.2. Stress Analysis Calibration

A test rig was built to calibrate the FE model. The test set up consisted of one hydraulic linear actuator, one lever arm, the specimen and fixtures. See Figures 6 and 7 (dimensions in mm).

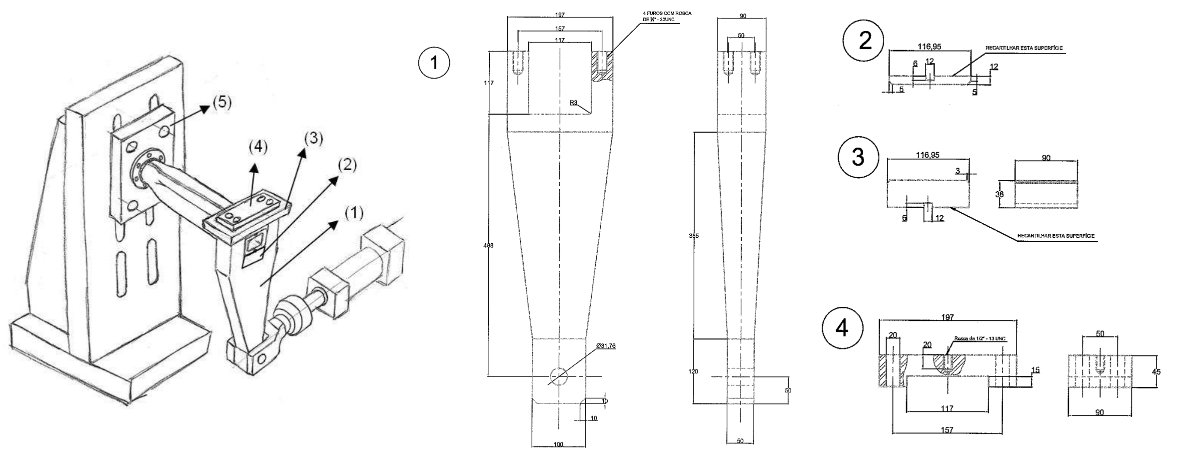

Figure 6. Test rig set up and fixtures sketches used to apply the combined in-phase bending and torsion loads.

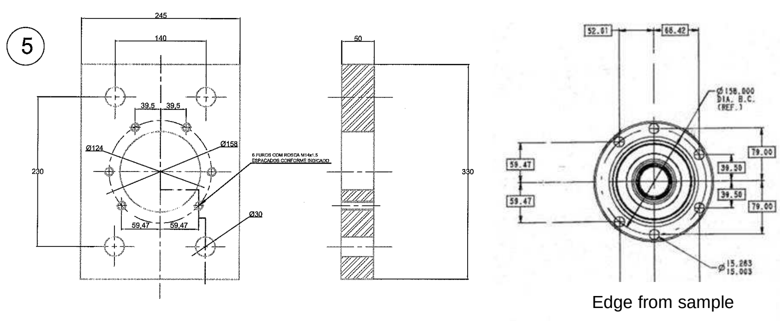

Figure 7. Test fixture plate to attach the sample.

The hot spot stress was obtained through two strain gage Kyowa rectangular rosettes KFG-2-120-D17-11 attached to the flange-tube at the high stress critical area. The rosette location was defined based on FE model stress distribution and was disposed at 7mm from weld toe approximately, in lower side and in direction of corner line. The both rosette were in the opposite side from the sample. The HBM MGCPlus data acquisition system was used to capture the strains on each direction. The strain gage rosette installation is showed in figure 8.

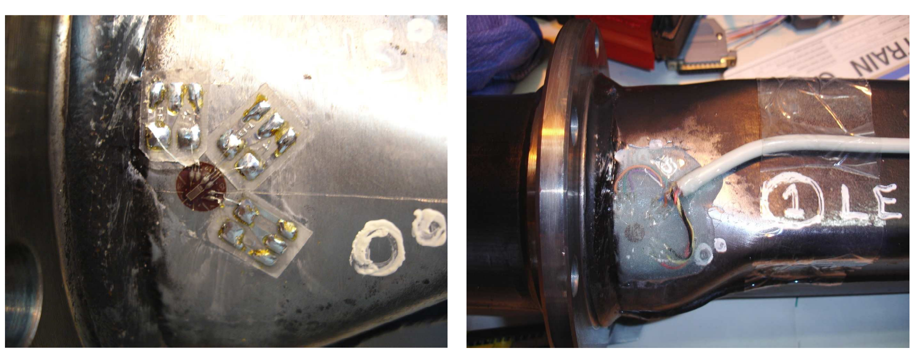

Figure 8. Strain gage rectangular rosette.

The test equipment consisted of one hydraulic actuator (± 100kN) which was controlled by the MTS control system 407. Figure 9 shows the equipment and test set up used.

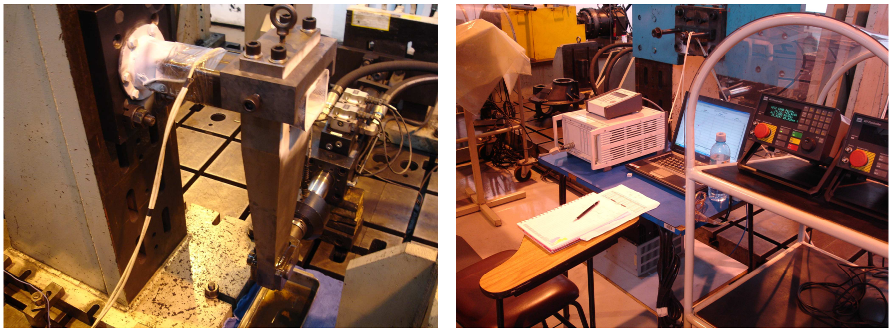

Figure 9. Test equipment – Servo-hydraulic actuator and Strain Gage Data Acquisition Systems.

The strain gage rosette calibration curve was determined applying incremental loads with the linear hydraulic actuator up to 20 kN. The strain gage response of each channel (0º, 45º and 90º) was recorded and plot in a Strain-Load graph (Figure 10). Both rosette presented the same result in calibration curve.

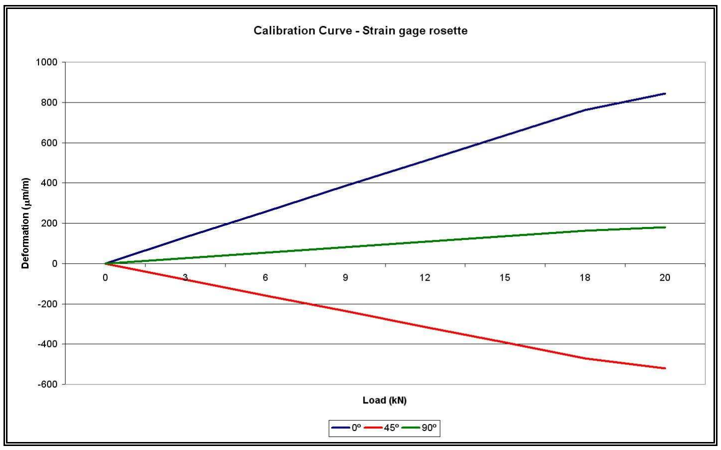

Figure 10. Strain gage rosette calibration curve.

3.3. Fatigue Life Prediction

To FE-Fatigue software was used to predict the fatigue life, by importing the finite element results (.rst file) from Ansys. The user needs to define the properly fatigue life curve from FE-Fatigue database or input a specific curve. In this work the BS7608 (1993) type "F" weld joint configuration was selected in the FE-Fatigue software, similar to the Goes et al (2008) that better fits to the flange-tube weld configuration in this study.

The FE-Fatigue predicted life using the BS7608 database was compared with analytical calculation using the classical Stress-Life equations from BS7608 code as indicated below:

$$NS_r^{\,m} = C_d \tag{1}$$

$$Log(C_d) = Log(C_o) - d * \sigma \tag{2}$$

Where:
N = Predicted number of cycles to failure
S_r = Stress range per cycle
C_0 = Constant related with the mean SxN curve (50% of failure probability)
σ = The standard deviation of log (N)
d = Number of standards deviation below the mean S x N curve
m = The inverse slope of log (S_r) versus log (N) curve.

The class F Stress-Life curve from FE-Fatigue database is showed in figure 11.

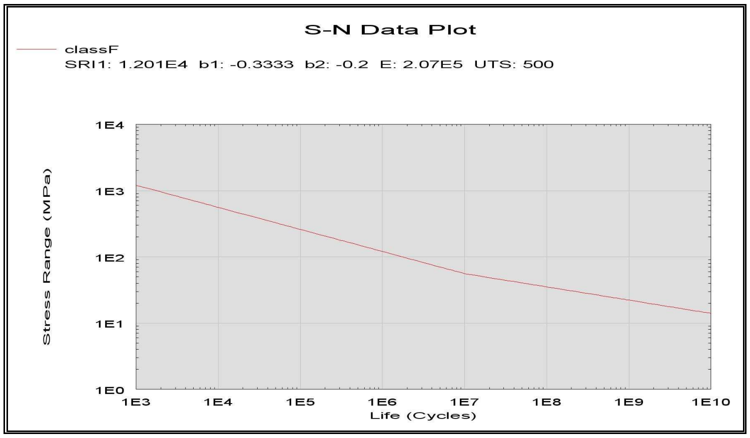

Figure 11. Class F (Stress-Life) S-N curve.

4. RESULTS & DISCUSSION

The Maximum Principal Stress distribution from FEA is showed in figure 12.

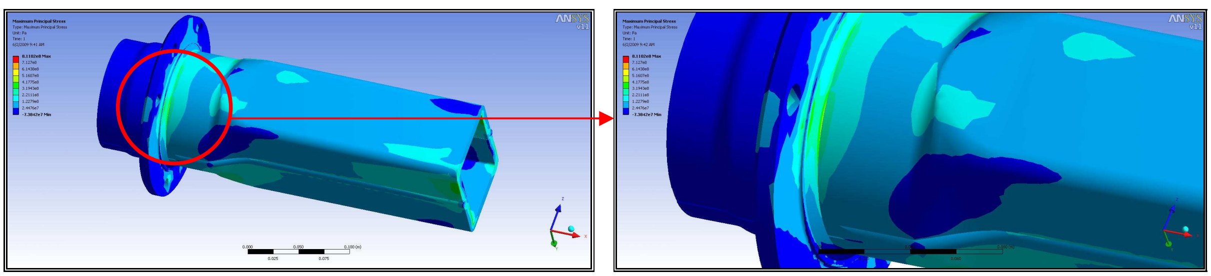

Figure 12. Maximum Principal Stress (MPa) – FEA.

The stress results from FEA were imported into the FE-Fatigue software to predict the fatigue life in the Virtual Model. Class F material S-N curve was selected from BS7608 (1993), inside the software database. The fatigue life result based on the Maximum Principal Stress is showed in figure 13.

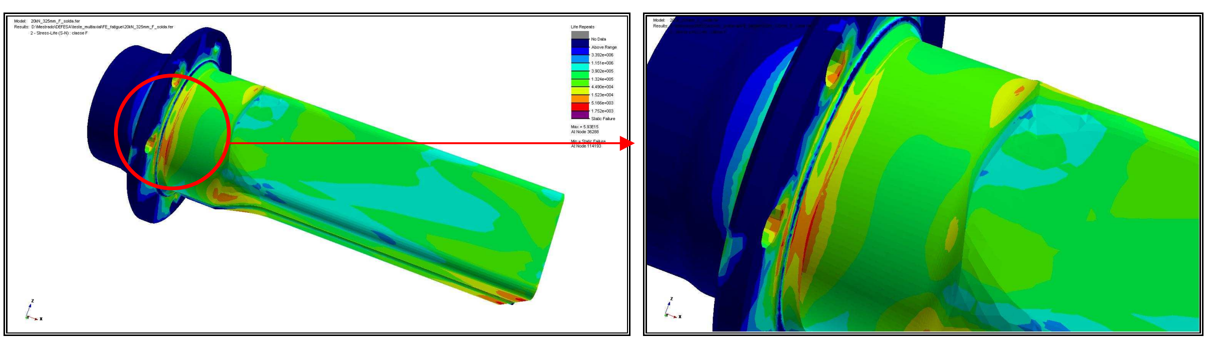

Figure 13. Fatigue Life based on Maximum Principal Stress - BS7608 (1993) class F curve.

Table 3 summarizes the stress level results obtained and table 4 the fatigue life at the hot spot location.

It is observed a very good correlation between the finite element model and the experimental results from the calibration test.

Table 3. Stress level results.

Stress Analysis (MPa)	Nominal	Hot Spot	Lab test
Maximum Principal Stress	215MPa	360MPa	330MPa
Equivalent Stress	186MPa	320MPa	340MPa

Table 4. Fatigue life at Hot Spot Stress (in cycles).

Stress Analysis (MPa)	Class F (FE-Fatigue)	Class F (Analytical)
Maximum Principal Stress	33,000	37,000

5. CONCLUSION

The FEA model was able to reproduce with a reasonable accuracy the test sample stiffness and predict the hot spot stress at the critical location close to the weld toe. The Fatigue Life prediction obtained on the virtual model also had a good correlation when comparing to BS 7608 analytical calculation. These results could validate both the finite element model and BS7608 type “F” S-N curve of the Fatigue software. Next step is to complete the fatigue lab test to calibrate the predicted life from the virtual model. This will require a number of test samples to conduct S-N sensitive study by comparing the fatigue life predicted in the virtual model with the test sample results. Weld typical imperfections, geometry discontinuities, residual stresses, deleterious microstructures in the heat affect zone (HAZ), internal defects, not included on the FEA model would be considered by the corrections of the S-N calibrated curve, develop on the test lab through the sensitivity study above mentioned. Also the comparison with other fatigue design codes like Eurocode IIW recommendations and ASME is required to define the better approach according to the loading case, base material properties and weld configuration. The local strain approach is another important study to compute the initiation life based on low cycle fatigue concept, which could be very useful and conservative when weld design codes are not available or cannot accurate predict the fatigue life of the weld configuration investigated.

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