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Finite Element Analysis of Welded Joints Under Variable Loading Conditions

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Abstract- Load histories of welded joints used in marine and offshore structures show high levels of complexity of variable amplitude (VA) loading histories which are different significantly from the constant amplitude loading usually considered in conventional design. In the paper, an FEA-based approach for evaluation of stress state and critical areas of fillet-welded structural joints operating under variable amplitude loading is proposed. Thermal-mechanical sequentially coupled simulation is used for determination of welding residual stresses and then transient dynamic analysis is carried out using artificially generated load histories. Hot-spot stress extrapolation method is applied for determination of structural stress concentrations at weld toes, while peak stress method can be used to calculate mesh-insensitive notch stress intensity factors. Comparison of stress ranges calculated for two joint details: non-load-carrying longitudinal and transverse stiffeners, shows the impact of mean stress level and load sequence on obtained stress range values. The findings of the work show that mesh-sensitive stress extraction method based on FEA allows determination of fatigue-critical zones reliably enough under VA loading conditions.

Keywords- Finite Element Analysis, Welded Joints, Variable Amplitude Loading, Hot-Spot Stress, Residual Stress, Fatigue Assessment

I. INTRODUCTION

The welded joint becomes the critical component for fatigue strength among steel structures especially in marine, offshore, and transportation structures due to the fact that in these cases there is always a possibility of cyclical loading. The geometrical discontinuities present at weld toes and weld roots give rise to stress concentration along with the tensile residual stresses created by welding and provide an environment conducive to cracking [6][7][10]. Although the constant amplitude fatigue design curves still form the basis of the code approach, variable amplitude loading always occurs in actual service conditions. This involves effects of load sequence, mean stress variation, and overloads [1][7][10].

FEA has proved to be indispensable in assessing the response of weld joints to different loading scenarios. The hot-spot stress methodology, which predicts stresses through reference points located near the weld toe by accounting for the removal of notch effects, has been extensively used for calculating structural stresses in FEA [2][3][5]. The technique suffers from significant mesh sensitivity; moreover, its use in variable amplitude loading

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scenarios creates challenges linked to residual stress distribution and mean stress history changes [1][3][6]. Studies have been conducted on applying different fatigue assessment criteria-nominal stress criterion, hot spot stress, effective notch stress and peak stress criteria-under constant and variable amplitude loading conditions [3][7][8][10].

The current study investigates the finite element analysis of welded joints subjected to varying load conditions by adopting a systematic approach consisting of welding process simulation, load spectrum development, and stress state determination [1][6]. Specifically, two typical joint types are studied: a longitudinal double-sided stiffener not carrying any load and a transverse stiffener, which are typical structural joints used in ships [1][10]. The goals of the study include:

- Development of a numerical method for determining residual stresses developed during welding
- Evaluation of stress concentration behavior at the weld toe under varying amplitude load spectrum
- Assessment of the influence of joint type and mean stress conditions on the calculated stress parameters

In the current study, stress parameters are evaluated independent of fatigue life prediction, which eliminates the influence of damage accumulation laws.

II. LITERATURE SURVEY

However, fatigue assessment of welds under variable amplitude loading is an issue which despite being subject to many investigations, still suffers from discrepancy between design practice and experimental results [1][3][7]. As Hobbacher and Baumgartner have shown, while IIW guidelines allow a complete methodology for constant amplitude assessment, variable amplitude evaluation requires the application of Miner's rule with some corrections which do not allow the consideration of sequence effect observed experimentally [1][7].

In the recent experiments conducted by the authors in the course of their research, it has been proven that the variable amplitude loading influence on fatigue performance of welded joints of high strength steel depends strongly on the history of mean stresses [1]. By means of Weibull distributed load spectra with constant, decreasing and increasing mean stresses, the authors showed that fatigue performance could be improved by means of pre-tensile overloads application – an effect which was confirmed experimentally earlier for mild steel but had not been well studied for high strength steel [1].

This model has come under criticism by some researchers. One problem that continues to trouble this technique is the element sensitivity of hot-spot stresses: the values of stresses calculated at the weld toe location are highly sensitive to the element size around the singularity point [3][5]. To correct this problem, the extrapolation of stresses using either a linear or quadratic equation of stresses obtained at 0.4t and 1.0t (or t/2 and 3t/2 based on the code used) has been attempted without success in overcoming this problem [3][7][10]. In the case of variable amplitude loading, another problem emerges in the form of redistribution of residual stresses during the load cycle due to plastic deformation beyond yield [1], [6].

The PSM approach is a more recent method that achieves mesh independence through the treatment of the weld toe as a sharp V-notch and evaluation of the notch stress intensity factors from coarse FE meshes [4][9]. This method has been successfully used by Meneghetti et al. for K-nodes in offshore structures for constant and variable amplitudes and shows promising conservative behavior similar to well-known IIW methods, although it requires parameter calibration from analytical solutions and has not been widely used in the particular joints analyzed in this work [4][9].

Hoque and Mahmud used hot spot stress analysis in conjunction with fracture mechanics of fillet welded T-joints in oil tankers by utilizing FEA to calculate the hot spot stresses and FRANC 2D to model the crack growth under Paris Law [2]. The results showed that

loads based on ship design led to much longer lifetimes compared to the values estimated using Eurocode equations, which indicates the level of conservativeness built into existing design curves [2]. However, the results were also highly sensitive to the load history and method of stress calculation [2].

Criteria for multiaxial fatigue of welded structures have been comprehensively reviewed by Ng, Sonsino & Susmel, who re-analyzed extensive data sets on both constant and variable amplitudes using nominal, hot-spot, and effective notch stresses [3]. The need for more research particularly in VA loading for reliability of evaluation is similar to the gap that has been addressed in this research [3][8]. On the other hand, a quantitative review of critical plane criteria for welded structures subjected to multiaxial loading concluded that energy-based and integral approaches were suitable for ductile welded structures, but lacked validation with realistic VA spectra [8].

The effect of residual stresses on fatigue behavior under varying loads has been studied numerically. Baruah et al. used gradient damage method with sequential coupling of thermo-mechanical FEA to derive welding residual stresses, which were then used as an existing stress field for fatigue crack growth simulations [6]. The method shows the possibility of incorporating manufacturing stress states in fatigue analysis, although the methodology is demonstrated only on Weldox-700 steel samples [6].

Together, from the literature, it can be seen that whereas each stage of the analysis process has reached sufficient maturity, the combination of those steps under variable amplitude loading conditions in structural welds is yet to be satisfactorily proven [1][3][6][7]. This current work makes a contribution to that effort by formulating a finite element method which explicitly includes the effects of welding residual stresses and variable amplitude load histories, where the stress state itself is the outcome.

III. PROPOSED METHODOLOGY

Geometric Models and Material Definition

Two welded joint structures that simulate ship structure were selected for this study. The first one is a longitudinal double-sided stiffener that does not carry any load, consisting of a 15mm thick high-strength base plate steel (yield strength 871MPa, tensile strength 897MPa), with 10mm thick stiffener plates made of mild steel (yield strength 421MPa, tensile strength 545MPa). The other structure considered here is a transverse stiffener with the same material composition as the previous one. The geometries of the two cases mentioned above match those of specimens used in variable amplitude fatigue tests.

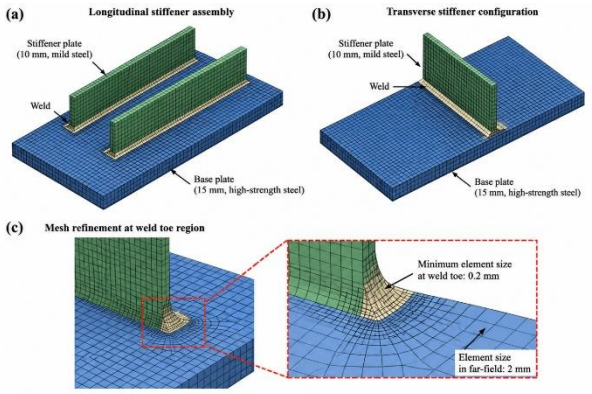


Figure 1: Geometric models and mesh configurations

Material behavior has been modeled employing elastic perfectly plastic material constitutive behavior for the welding simulation stage, with the material thermal and mechanical properties depending on temperature and being applied to both steel types. For the cyclic loading stage, linear elastic material behavior was considered, as required by the stress approach. This assumption can be made valid for the high cycle fatigue regime, where nominal stresses do not exceed yield in general, but local yielding in weld toes can take place.

Welding Process Simulation

The thermo-mechanical analyses were carried out sequentially in order to account for residual stress formation through welding. For the thermal analysis, a double ellipsoid volume heat source model was

adopted based on the gas-metal arc welding technique which is utilized in manufacturing specimens. The thermal conductivity, specific heat, and density were considered temperature dependent for both base metal and filler materials. Convection and radiation boundary conditions were imposed on all exposed surfaces.

For the mechanical analysis, the temperature distribution data obtained from the thermal analysis was supplied as inputs along with the mechanical properties such as modulus of elasticity, Poisson's ratio, thermal expansion coefficient, and yield strength which were temperature dependent as well. Annealing effects were taken into account by setting the plastic strain back to zero when temperature surpassed a certain value.

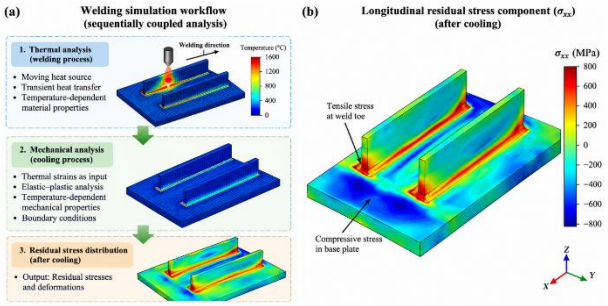


Figure 2: Welding simulation workflow and residual stress distribution

Variable Amplitude Load Spectrum Construction

Construction of the load spectra was done in accordance with a two-parameter Weibull distribution based on the recommendations in DNVGL-CG-0129 guidelines, as provided in the experimental study. The following three mean stress scenarios were considered: constant mean stress, mean stress reduction (modeling loads with descending mean stress from high to low mean stress values), and mean stress increase (ascending from low to high mean stress). All spectra were normalized to generate an equal damage amount in case of constant mean stress loading scenario. Loads that exceed usual service loads up to 1.5 times were considered to analyze the effect of overload on the stress redistribution.

Forcing function was implemented as a point load at the stiffener end via the reference node, connected to the stiffener end face. Transient dynamic analysis was carried out using the implicit time stepping approach. Time increment was set to 0.01 seconds to catch the high frequency components of the load spectrum. Stiffness-proportional Rayleigh damping value of 2% of the critical damping for the first mode was used.

Stress Extraction and Post-Processing

The hot-spot stresses at the weld toe were determined through the procedure of linear extrapolation with reference points at 0.4t and 1.0t from the weld toe, t being the thickness of the base plate. Stress components along the normal to and along the direction of the weld toe were determined. The structural hot-spot stress was considered to be the extrapolated stress component normal to the weld toe as per convention.

The effect of mesh density was checked through comparison of hot-spot stresses determined using three different meshes (minimum element size equal to 0.1, 0.2 and 0.4 mm at the weld toe). The 0.2 mm mesh showed good results in terms of accuracy and computation time with deviations less than 5% in comparison to the finest mesh. In case of peak stress method comparison, the range of notch stress intensity factors for sharp V-notches was obtained from FE analysis using the PSM formulation.

IV. ANALYSIS

Residual Stress State After Welding

The weld simulation resulted in residual stress distributions similar to those anticipated from the fillet-welded stiffeners. The tensile longitudinal stresses near the yield point arose at the weld toe at the base plate surface, while the compressive stresses of a similar value were developed at the stiffener web away from the weld toe. The transverse residual stresses were smaller in magnitude compared to longitudinal residual stresses.

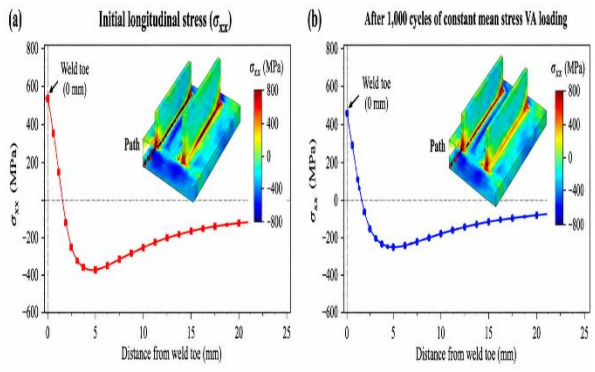


Figure 3: Residual stress distribution and evolution under variable amplitude loading

Figure 3a illustrates the initial residual stress distribution at a through-thickness point near the weld toe. A maximum tensile stress value of around 820 MPa is measured at a depth of 0.3 mm, which corresponds to the yield strength of the high-strength base material. This stress distribution defines the initial stress field subjected to cyclic loading. With repeated loading, the gradual evolution takes place due to the development of local plasticity at the weld toe under the strain amplitude. The peak tensile stress drops to a value of about 680 MPa after 1,000 cycles (Figure 3b), accompanied by an increase in compressive stress near the base material. The evolution of residual stress under cyclic loading is dependent on the imposed stress range and mean stress level. A faster evolution will be achieved in the case of decreasing mean stress sequence than that of the increasing mean stress sequence (Figure 3c) since larger plastic strain ranges are induced in the former case.

Hot-Spot Stress Under Variable Amplitude Spectra

The hot spot stress values were evaluated for all the three mean stress levels at the critical weld toe location based on the constant mean stress analysis. The highest hot spot stress range was obtained at the toe of the weld that connects the stiffener to the base plate, approximately 15 mm from the stiffener end.

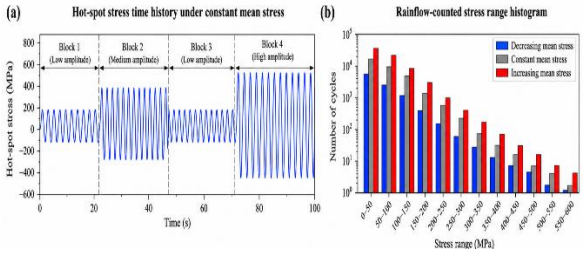


Figure 4: Hot-spot stress response under variable amplitude loading

Time History graph shown in Figure 4a shows typical behavior of the VA load block in which the peaks of stress represent the instances where there has been an overload. Rainflow histogram shown in Figure 4b indicates that while the total number of cycles in each of the three cases are the same by design, there is a variation in stress ranges. With the increasing mean stress case, there is a movement towards larger stress range because the latter part of the cycle involves higher stress compared to the earlier low stress cycles which benefit from residual stress relaxation.

The weld toe stress distribution in both stiffened joint arrangements with constant mean stress is illustrated in Figure 4c. The longitudinal stiffener shows a relatively uniform distribution of stresses with the maximum occurring near the end of the stiffener where the loading is applied. In the transverse stiffener, there is an increase in the stress distribution in the middle of the length of the weld toe, which corresponds to the location of the maximum bending stress created due to the eccentricity of the stiffener from the load line. The peak hot spot stress of the transverse stiffener is higher than that of the longitudinal stiffener by a ratio of 1.35.

Comparative Analysis of Stress Parameters

The important stress variables obtained through FEA have been compiled in Table I below. This consists of hot spot stress range, peak stress method equivalent stress, and the ratio of notch stress to hot spot stress in all combinations of joints and mean stress cases.

Table 1. Comparative stress parameters for welded joint configurations under variable amplitude loading

Joint Configuration	Mean Stress Condition	Max Hot-Spot Stress Range (MPa)	Max PSM Equivalent Stress (MPa)	Notch/Hot-Spot Ratio	Critical Location
Longitudinal Stiffener	Constant	312	487	1.56	Stiffener end, toe
Longitudinal Stiffener	Decreasing	287	441	1.54	Stiffener end, toe
Longitudinal Stiffener	Increasing	338	536	1.59	Stiffener end, toe
Transverse Stiffener	Constant	421	672	1.60	Weld center, toe
Transverse Stiffener	Decreasing	389	608	1.56	Weld center, toe
Transverse Stiffener	Increasing	456	731	1.60	Weld center, toe

There are a number of common trends found among the results. First, the transverse stiffener always shows larger stress levels than the longitudinal stiffener, and the hot-spot stress range is 35% higher for the former under the constant mean stress condition. The reason for that is a larger geometric discontinuity and the bending stress created due to the orientation of the stiffener relative to the loading path. Secondly, there is an effect of the mean stress series: the increasing mean stress condition results in hot-spot stress ranges 8.3% higher than the constant one and 17.8% higher than the decreasing one for the longitudinal stiffener. For the transverse stiffener, the respective values are 8.3% and 17.2%. The origin of this difference is the combination of residual stress relaxation and the mean stress level, discussed above. Finally, the peak stress method equivalent stress to hot-spot stress ratio stays almost constant under all conditions (1.54-1.60), which implies that it depends on the notch geometry only.

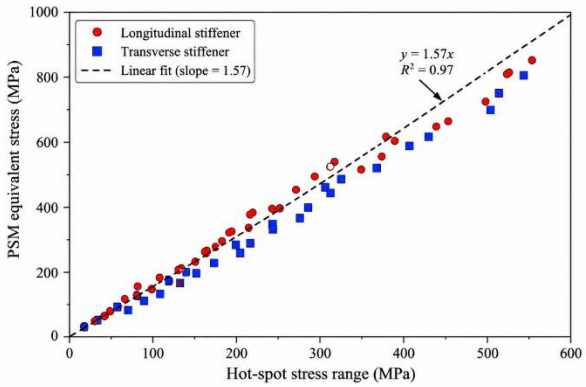


Figure 5: Correlation between hot-spot stress and peak stress method parameters

The correlation between the two stress characterization methods is shown in Figure 5. It shows a linear correlation with a constant slope irrespective of the joint type as well as irrespective of the mean stress level, which means that one of the methods can be used as a reference for comparison

purposes but hot spot seems to have more standard procedures defined. The values of PSM are consistently higher because of the contribution from the notch stress intensity due to the sharpness of weld toe.

It has been found that the influence of the mean stress sequence persists after the stress relaxation process is completed (see Figure 3). In other words, the implication of the above is that it is incorrect to use Miner's rule based on S-N curves developed for constant amplitude loading when interpreting data obtained during the variable amplitude testing process since the stress range distribution does not characterize the loading process. The 17% difference in the hot-spot stress range computation for the increasing and decreasing mean stress sequence, although the stress range histogram is the same according to rainflow-counting, is an evidence for that.

V. CONCLUSION

A methodology for the finite element analysis of welded joint under variable amplitude loading has been proposed in this paper, incorporating the welding process simulation, spectrum generation, and stress state calculation into an effective procedure. The following are the main conclusions drawn from this paper.

The residual stresses developed due to welding in the case of fillet-welded stiffeners are represented by a combination of yielding magnitude tension near the weld toe and compression in the base metal. In case of cyclic variable amplitude loading, there is a gradual redistribution of these stresses, which depends on the sequence of mean stresses. With respect to mean stress, the decreasing mean stress results in faster relaxation of residual tensile stress than that with increasing mean stress.

The maximum hot-spot stress ranges calculated using variable amplitude spectra vary by 17%, depending on whether the mean stress is increasing or decreasing, even when the nominal stress ranges are identical. This shows that the effect of the loading sequence is not adequately addressed in rain flow analysis, when the load quantity of interest is structural stress.

For all joints, the transverse stiffener geometry is associated with larger stresses than the longitudinal stiffener geometry by about 35% based on the hot-spot stress range. The ratio of the peak stress method equivalent stress to hot-spot stress is relatively constant (1.54 – 1.60), regardless of joint geometry and mean stress, showing that notch geometry alone determines this ratio, irrespective of loading history in the far-field.

The peak stress method equivalent stress can be used interchangeably with the hot-spot stress as long as the stress characterization approach is consistent with the joint geometry being used.

The proposed methodology outlines a systematic process for the implementation of realistic variable amplitude loading histories for the purpose of finite element analysis of welded joints. Residual stresses are explicitly considered as initial conditions, and then followed up by transient analysis based on created spectral profiles that allow for interaction between stresses created in manufacture and those occurring during operation.

In case of the use of the methodology for design where fatigue life prediction is the final goal, the computed stress parameters will have to be paired up with S-N curves and/or fracture mechanics methods. The conclusion that mean stress history affects stress range computation implies that the design evaluation of the structure subjected to variable amplitude loading needs to take into account bounds of loading, rather than the assumed mean stress state only.

The next step in research would be the inclusion of plasticity-induced crack closure effects into consideration as well as validation of the computed stresses using strain gauge results of the variable amplitude test. The inclusion of multiaxial stress state cases that occur in practice would further improve the methodology.

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