XFA3D Toolkit for Fatigue Damage Assessment of Welded Aluminum Structures under Variable Amplitude Loading

Jim Lua¹, Eugene Fang¹, Xiaohu Liu¹, Alireza Sadeghirad¹, and David Chopp²

¹Global Engineering and Materials, Inc., ²Engineering Sciences and Applied Mathematics, Northwestern University

The views expressed herein are those of the authors and are not to be construed as official or reflecting the views of the Commandant or of the U.S. Navy.

ABSTRACT

This paper presents an overview of our recent enhanced 3D extended finite element toolkit for Abaqus (XFA3D) for fatigue damage assessment of welded aluminum structures under block loading. To alleviate the computational burden associated with the insertion and propagation of arbitrary cracks in the presence of a welding induced residual stress field, a nodal enriched displacement field coupled with a level set description is integrated with a hybrid implicit and explicit crack representation approach. A simplified residual stress characterization is implemented without invoking two separate analyses during each step of the crack growth. A stress ratio dependent fatigue damage accumulation model is employed for the fatigue damage accumulation under an arbitrary multi-block loading spectrum. Capability demonstration is performed first for simulation of curvilinear fatigue crack growth prediction in a holed plate and a multi-hole beam followed by its application to three welded components with an initial flaw including a butt welded tensile specimen, a cruciform tensile specimen with a semi-elliptical surface flaw, and a welded T-joint with a through-the-thickness crack.

KEY WORDS

Extended finite element method; fatigue crack growth; residual stress; welded structure.

INTRODUCTION

The design of a large aluminum high-speed vessel that will operate under hostile operating environments requires the welded structure to withstand sub-critical growth of manufacturing flaws and service-induced defects against failure. Fluctuating in-service loads and environmental conditions can continuously grow the damage area, possibly causing complete structural collapse of the damaged part in aluminum ship structures. The key components of total life management of aluminum ship structures are to restore the load-carrying capacity and extend the service life of a damaged aluminum structure, damage detection, residual strength and life assessment, repair implementation, and structural health monitoring. Prior to implementing a life extension option, a reliable residual strength and life assessment has to be performed for the damaged aluminum structure.

The structural complexity, initial stress distribution, crack geometry, and its curvilinear crack growth path has precluded the use of any simplified fatigue analysis tool such as AFGROW [Harter, 2008] or NASGRO (1999) based on a pre-assumed stress intensity factor solution for a given crack configuration. Given the spatial variability and uncertainty associated with these residual and applied stress fields in conjunction with fabrication induced initial flaws, the conventional mesh dependent finite element approach is not well suited for fatigue prediction of ship structural components with an arbitrary initial crack. Since the mesh constructed in the standard finite element method has to conform to the assumed crack configuration, any change in crack configuration (location, size, and shape) will force an analyst to re-build a finite element mesh. This is significantly burdensome for both 2D and 3D analysis, especially when cracks have very complex geometries. Thus, it is essential to employ a mesh independent finite element methodology to determine the stress intensity factor along the moving crack front during the fatigue life prediction. A crack growth pattern in a large scale welded or bolted metallic structure is complex because of the presence of a 3D stress field, local stress concentration, material heterogeneity, structure discontinuity, and applied load mixity. An adaptive remeshing has been used extensively for tracking an arbitrary crack growth. Most of the adaptive remeshing techniques have been implemented with a standalone FEM solver. Given a standalone research code, the code design and implementation is less mature in many aspects. Attempts have been made to integrate the adaptive remeshing technique within a commercial FEM solver, such as Abaqus. Since Abaqus does not allow the user to...
Simulation of an arbitrary fatigue crack growth through a predefined residual stress field is challenging since the residual stress intensity factor evolves with crack growth. While the range of the effective stress intensity factor ($\Delta K_{eff}$) is unchanged, the stress ratio $R$ computed from the ratio of the minimum to the maximum stress intensity factor evolves in the presence of the residual stress field. Two methods have been used to compute the residual stress intensity factor ($K_{res}$). While the application of weight and Green’s function on the initial un-cracked residual stress distribution is straightforward based on the principle of linear superposition, it has been widely used for a 2D cracked body with a line crack. In addition, in the presence of material heterogeneity and nonlinearity associated with a 3D welded structure, an analytical form of Green’s function may not exist. A more general approach based on the finite element method is feasible to resolve these issues with a costly solution procedure. Since two separate solutions at minimum and maximum peak load have to be performed for each step of crack growth, it is essential to explore a simplified solution procedure that can capture the effect of the residual stress with a one step solution. The focus of the present work is to develop a simplified residual stress characterization module and implement it within our existing XFA3D toolkit. To incorporate the stress ratio dependent fatigue crack growth behavior, both Walker [Walker 1970] and NASGRO [NASGRO 2006] fatigue models are used for characterizing the fatigue damage accumulation under combined residual stress and an arbitrary block loading spectrum.

**OVERVIEW OF XFA3D TOOLKIT**

XFA3D is an add-on toolkit for Abaqus to perform mesh-independent 3D fatigue crack growth based on XFEM technology and Abaqus/Standard solver. Its features include

1. 3D crack insertion without remeshing;
2. tip and jump enrichment for kinematic description of an arbitrary 3D crack;
3. mixed implicit and explicit crack front tracking along with its associated level set update;
4. fatigue damage accumulation under constant and block loading;
5. residual stress and R-ratio dependent fatigue damage accumulation; and
6. customized Abaqus CAE for XFA3D model generation and results viewing

An illustration of XFA3D work flow is shown in Fig. 1.
As shown in Fig. 1, the pre-XFA analysis module is employed first to insert a crack into the base model without a crack. Based on the size and location of the embedded crack, an enriched zone is defined along the crack front and its wake. Additional XFEM input files are generated based on the user-defined solution options. During the XFEM execution phase, the XFEM preprocessor is performed first to initialize all the levelset values. The XFEM solver is used next to perform the fracture analysis and compute the fracture parameters along the crack front. A customized Abaqus post-processing module is used to visualize the state variables, enrichment types and levelset values. Deformed crack configuration and variation of the strain energy release rate ($G$) or the stress intensity factor ($K$) can be plotted during the post analysis using Abaqus’ CAE.

The key modeling steps in XFA3D is shown in Fig. 2. A kinematic representation of an arbitrary crack in a 3D solid is given via two types of nodal enrichment functions. The Heaviside function ($H$) is employed to describe the displacement jump at the wake of the crack while the tip enrichment function ($\psi$) is used to enforce an asymptotic singular stress field in the vicinity of the crack tip. After solving the finite element equations, both the standard and enriched nodal degree of freedoms can be determined for all the user-defined elements in the vicinity of the cracked region. Using the theory of linear elastic fracture mechanics, the 3D stress intensity factors ($K_I$, $K_{II}$, $K_{III}$) can be extracted from the crack opening displacement defined in a local coordinate system as shown in Fig. 2.

The most challenging component in the XFA3D toolkit is to track an arbitrary crack growth without remeshing. This is accomplished by updating the nodal level set values during the crack propagation. A hybrid approach shown in Fig. 3 has been implemented in XFA3D to characterize a 3D approach via a combination of an implicit level set representation with an explicit triangulated mesh representation. The explicit triangulated mesh is convenient for visualization of the crack front, and for ensuring the data in the level set representation is generated from a consistent crack description. On the other hand, the implicit representation is very convenient for purposes of computing the crack front velocity and for handling situations where the crack front is concave and the velocity vectors may cross. For a 3D crack, there are multiple sampling tip points along the front denoted by $T_i^*$. It is necessary to adjust the crack growth step size at $T_i^* (\Delta a_i)$, which corresponds to tip $T_i^*$, such that the incremental cycle numbers ($\Delta N$) is consistent for all the tip points. With XFEM, a user-defined crack growth size ($\Delta a_{max}$) can be assigned at a location of maximum $\Delta K (\Delta K_{max})$ to compute the $\Delta a_i$ at the rest of sampling points based on their relative magnitude of the crack growth driving force ($\Delta K$). After determination of $\Delta a_i$ at all the sampling points on the crack front, the nodal level set values will be updated to reflect the new crack configuration at $N+\Delta N$. Given the new crack configuration, the types of nodal enrichment will be re-assigned based on the relative position of nodal points and the crack front for next step crack growth simulation.
Figure 2 - Summary of XFEM based K extraction in XFA3D

Figure 3 - Crack management and tracking in XFA3D

To facilitate users’ preparation of XFA3D input files, an add-on GUI within the Abaqus’ CAE for automatic generation of XFA3D input files is displayed in Fig. 4. Both the base model creation and crack insertion and geometry definition can be accomplished through the use of Abaqus/CAE while all the XFEM solution parameters are defined using an XFA3D user interface. After importing an existing or creation of a FEM model without a crack using Abaqus’ CAE, three methods can be used to insert or define a crack within an existing solid structure model without a crack: 1) use of a cutting plane to
define crack location and orientation; 2) use of sketch for the crack part within Abaqus’ CAE to define crack location and orientation; and 3) use of an existing orphan mesh for the crack when a previous Abaqus’ crack file exists. The use of sketch has been selected for the crack definition in all the examples in this paper because of its versatility and built-in capability of Abaqus’ CAE to define a separate meshed crack plan along its front.

Next, meshed crack plane is inserted into the base model via an assembly process and the XFEM input files are created. At the end of each load increment, analysis results are saved into a separate ODB file using the Abaqus C++ API, so that the users can use Abaqus/Viewer for post-processing needs. Since Abaqus/CAE is unable to display the user-defined elements used in the XFEM zone, additional nodes and cells used during the slicing are reused to re-generate the element connectivity information for plotting cracked geometry. Note that these artificial elements do not contribute to the XFEM solution process, but are rather for recording the XFEM results in the Abaqus’ ODB file.

**Figure 4 - Illustration of model/input generation for XFA3D**

A SIMPLIFIED RESIDUAL STRESS CALCULATION MODULE FOR XFA3D

In view of the evolution of the residual stress induced stress intensity factor \( K_{res} \) during the fatigue crack growth, two separate solutions have to be performed to determine \( K_{max} \) at the maximum load of \( P_{max} + P_{res} \) and \( K_{min} \) at the minimum load of \( P_{min} + P_{res} \). While the range of the stress intensity factor \( \Delta K = K_{max} - K_{min} \) remains unchanged in the presence of the residual stress field, the stress ratio \( R \) defined by \( R = K_{min}/K_{max} \) changes during the fatigue crack growth. For a 3D fatigue crack growth simulation in a complicated ship structural component, performance of two separate finite element based fracture analyses at each fatigue crack growth step \( (\Delta a_i) \) will add a large computational burden on an analyst during the initial conceptual design and damage tolerance analysis. It is imperative to develop a simple approach to capture the effects of residual stress in fatigue crack propagation without requiring two separate analyses at each increment of crack propagation.

This simplified approach is rooted on an assumption that the ratio of contributions of the residual stress and external loading is constant during the fatigue crack propagation simulation. This ratio is computed based on two preliminary simulations: 1) considering only the maximum loading, and 2) considering only the residual stress. The associated stress intensity factors are computed from these simulations, i.e. \( K_{load}^{initial} \) and \( K_{res}^{initial} \).

While both \( K_{max}^{load} \) and \( K_{min}^{res} \) can be changed during the crack propagation, it is assumed that the ratio of these factors is to be constant during all the increments, namely,

\[
\alpha = \frac{K_{res}^{load}}{K_{load}^{load}} = \frac{K_{min}^{load}}{K_{max}^{load}} = \text{const.} \quad (1)
\]

Using the \( \alpha \) factor, the load ratio \( (R) \) and \( \Delta K \) considering both the loading and residual stress in the final simulation can be calculated as:

\[
\begin{align*}
K_{max} & = K_{max}^{load} + K_{res}^{load} \\
K_{min} & = K_{min}^{load} + K_{res}^{load} \\
\Delta K & = K_{max} - K_{min} = K_{max}^{load} - K_{min}^{load} = (1 - R_0) K_{max}^{load} \\
R & = \frac{K_{min}}{K_{max}} = \frac{K_{min}^{load} + K_{res}^{load}}{K_{max}^{load} + K_{res}^{load}} = \frac{R_0 + \alpha}{1 + \alpha}
\end{align*}
\]

where \( R_0 = K_{min}^{load} / K_{max}^{load} \) is the load ratio associated with the loading only.

In the final simulation, we do not need to separately analyze the model under the residual stress since its effects are taken into account by applying the factor \( \alpha \) in calculation of \( R \).

An initial residual stress field is introduced based on the user-defined stress field for a welded component without a crack. A spatial variation of the 3D residual stress components is tabulated in a 9-column data file including \( \{ x_i, y_i, z_i, \sigma_{xx}(i), \sigma_{yy}(i), \sigma_{zz}(i), \sigma_{xy}(i), \sigma_{yz}(i), \sigma_{zx}(i) \} \) at an arbitrary set of sampling points \( (i = 1, 2, 3, \ldots, m) \). A numerical interpretation is applied to determine the residual stress components at all Gaussian points of elements based on the corresponding components at these sampling points. Two XFA3D analyses are performed for the welded component with an initial crack to determine \( K_{max}^{load} \) and
\[ K_{res} \] associated with the load case of the applied peak load \( P_{max} \) and a pre-defined residual stress field without the applied load. Because of the presence of the crack, the initially defined residual stress field will be redistributed to reach a new self-equilibrium condition. By substituting \( \alpha \) computed from Eq. (1) into Eq. (2), the stress ratio \( (R) \) can be computed and used in a \( R \)-ratio dependent fatigue damage accumulation model.

**SUMMARY OF R-RATIO DEPENDENT FATIGUE MODELS IN XFA3D**

Two stress ratio \( (R) \) dependent fatigue damage accumulation models have been implemented in XFA3D. The first \( R \)-ratio dependent model is based on the Walker’s model [Walker 1970]. The Walker’s model is given by the following relationship:

\[
\frac{da}{dN} = C \left[ \frac{\Delta K}{(1-R)^{1-\beta}} \right]^n
\]

in which \( \gamma \) is the Walker’s constant for the material. In Eq. (3), \( \Delta K \) can be computed by \( \Delta K = K_{max}(1-R) \). A conventional Paris fatigue model can be recovered if \( \gamma=1 \).

The NASGRO equation [NASGRO 2006] represents one of the most comprehensive fatigue crack growth law formulations considering the mean stress effect, threshold, the onset of fast fracture and crack closure. The NASGRO equation is given by:

\[
\frac{da}{dN} = C \left( \frac{1-f}{1-R} \right)^n \left[ \frac{1-\Delta K_{th}}{\Delta K} \right]^p \left( \frac{1-K_{max}}{K_{crit}} \right)^q
\]

where \( C \) and \( n \) are empirical parameters describing the linear region of the fatigue crack growth data (similar to the Paris and Walker models) and \( p \) and \( q \) are empirical constants describing the curvature in the fatigue crack growth data that occurs near threshold (Region I) and near instability (Region III), respectively. In Eq. (4), \( \Delta K_{th} \) is the threshold stress intensity range and \( K_{crit} \) is the critical stress intensity factor. The crack tip opening function \( f \), is determined using the following formulation

\[
f = \begin{cases}
\max \left\{ R, A_0 + A_1 R + A_2 R^2 + A_3 R^3 \right\}, & R \geq 0 \\
A_0 + A_1 R, & -2 \leq R < 0 \\
A_0 - 2A_1, & R \leq -2
\end{cases}
\]

where

\[ A_0 = (0.825 - 0.34\beta + 0.05\beta^2) \left( \cos \left( \frac{\pi S_{max}}{2 S_0} \right) \right)^{1/\beta} \]

\[ A_1 = (0.415 - 0.071\beta) \frac{S_{max}}{S_0} \]  \hspace{1cm} (6)

\[ A_2 = 1 - A_0 - A_1 - A_3 \]

\[ A_3 = 2A_0 + A_1 - 1 \]

In Eq. (6), \( \beta \) is the plain stress/strain constraint factor and \( \frac{S_{max}}{S_0} \) is the ratio of the maximum applied stress to the flow stress.

**FATIGUE DAMAGE ACCUMULATION UNDER BLOCK LOADING**

To represent a real loading scenario during a ship service life, a most simplified form of variable amplitude loading called block loading has been used extensively during the lab tests for the fatigue damage assessment of ship components. The fatigue loading spectrum associated with the block loading can be uniquely described by multiple loading blocks where each block is defined by a constant amplitude loading sequence with a given minimum \( (\sigma_{min}) \) and maximum \( (\sigma_{max}) \) stress values and the associated number of cycles. Because of the potential change of the stress ratio \( R \) \( (\sigma_{min}(\sigma_{max}) \) from one block to its next one, a stress ratio dependent fatigue damage accumulation model discussed above has to be used for the life prediction under a variable amplitude loading. Figure 5 displays a variable amplitude loading sequence for a 3-block loading spectrum. In addition to the change of minimum and maximum values of stress in each block, the associated number of cycles for each block also varies.
For a block loading simulation shown in Fig. 5, the number of blocks, peak load values at each block, load ratio at each block, and total number of cycles for each block have been introduced to the XFA3D input file. The required input parameters for the block loading have been added into the *.xin file. Figure 6 illustrates how these parameters are defined via this input file. A multiplier is used to define the maximum peak load with respect to a reference load used in the Abaqus static analysis associated with a peak load of $P_{\text{max}}$.

In the implementation of the block loading module for the XFA3D code, static simulation is done based on the first load magnitude of the first block and then, using the theory of linear elasticity, the obtained stress intensity factor at each increment is multiplied by the load magnitude factor (multiplier) associated with that block load. This approach is applicable since the existing practice for fatigue analysis is largely based on the linear elastic fracture mechanics.

**Input data:**

They should be specified in *.xin file:

*X3DLOAD, PROPERTY=load1
1, XFEM=crack1
1, XFEM=crack1
1, XFEM=crack1
1, XFEM=crack1
1, XFEM=crack1
1, XFEM=crack1
1, XFEM=crack1
1, XFEM=crack1
1, XFEM=crack1
1, XFEM=crack1

**CAPABILITY VERIFICATION OF XFA3D FOR SIMULATION OF CURVILINEAR CRACK GROWTH**

Prior to demonstrating the applicability and accuracy of the simplified residual stress characterization module based on the single step solution, a capability verification of XFA3D is performed first via its application to the curvilinear crack growth simulation in a single-hole and a multi-hole component. In the first example, a holed plate under tension with an initial crack emanating from the hole is analyzed. The geometry of the plate is shown in Fig. 7. The initial crack is inclined by 45° and has a length of 2 mm and the radius of the hole is 10 mm. The material is Aluminum alloy with $E=71.2$ GPa and $v=0.33$. Paris Law parameters $C=2.2e-10$ and $m=3.545$ are used to characterize the fatigue crack growth. The plate is subjected to cyclic tensile loading with a peak load of 5200 N and a load ratio of 0.1. The same example has been studied by Boljanović et al. (2011) using the program package MSC/NASTRAN. The finite element mesh of the model is shown in Fig. 8 with the XFA3D zone highlighted. The total number of elements is 46568, 17964 of which are XFA3D elements. The refined part of the mesh has a typical element size of 0.5 mm.
Figure 9 shows the snapshots of crack propagation and Fig. 10 displays the comparison of the final crack path, which shows that the XFA3D prediction is consistent with both the experimental result and the simulation result from [Boljanović et al. 2011].

![Figure 9 - Crack propagation snapshots from initial stage to final stage](image1)

**Figure 9 - Crack propagation snapshots from initial stage to final stage**

![Figure 10 - Comparison of crack propagation path](image2)

**Figure 10 - Comparison of crack propagation path**

To further verify XFA3D simulation, the computed equivalent stress intensity factor ($\Delta K_{eq}$) as a function of crack length is plotted in Fig. 11 with comparison to the analytical solution given in [Boljanović et al. 2011]. Good agreement is observed between the two solutions.

![Figure 11 - Equivalent stress intensity factor as a function of crack length](image3)

**Figure 11 - Equivalent stress intensity factor as a function of crack length**

In the second example, an edge-cracked PMMA beam is studied. Fig. 12 shows the geometry, boundary and loading condition of the problem. The polymethyl methacrylate material has a Young’s modulus of 3.3 GPa and poisson’s ratio of 0.38. Paris Law parameters are taken from [Antunes et al. 2002] and have values of $C = 2.0 \times 10^{-3}$ and $m=6.46$. The beam is simply supported and subjected a cyclic load at mid-span with a peak load of 5000 N and a load ratio of 0.1.

![Figure 12 - Initial geometry of the edge-cracked PMMA beam](image4)

**Figure 12 - Initial geometry of the edge-cracked PMMA beam [Boljanović et al. 2011]**

The finite element mesh is shown in Fig. 13. The total number of elements is 23128 of which 5884 are XFA3D elements. The typical element size is about 3 mm. Figure 14 displays three snapshots of the crack propagation process. Figure 15 shows cracked specimen on one side with the crack surface highlighted. It shows how the original finite element mesh is sliced by the evolved crack surface. Please note that the triangular faces shown in Fig. 15 were created via post-processing based on level set function values for better visualization of the crack.
The key interest of this example is how well the crack propagation path can be predicted. Figure 16 compares the XFA3D-predicted crack propagation path to what was observed experimentally, as well as the prediction by [Boljanović et al. 2011]. It can be seen that the XFA3D prediction agrees with the other solutions very well and it did so with a relatively coarse mesh that is truly random. This example demonstrates XFA3D’s ability to predict curvilinear crack growth in a mesh-independent way.

XFA3D FOR FATIGUE LIFE PREDICTION IN WELDED COMPONENT

Butt Welded Tensile Specimen

To verify the implementation of the residual-stress treatment, in situ fatigue crack growth in a welded 2024-T351 aluminum alloy is simulated. The experimental results for this example are available in [Liljedahl et al. 2010] where the evolution of the residual stresses in the welded plate of 500 mm x 500 mm was studied both experimentally and numerically. The model geometry is given in Fig. 17. The maximum applied load in the longitudinal direction is 33.71 kN with the load ratio of $R_o = 0.1$. The modulus of elasticity and Poisson’s ratio are taken as $E=72$ GPa and $\nu=0.33$. The NASGRO fatigue equation is used in this example, for which all the required material constants are available in [Forman et al. 2005].
Initial residual stress is measured using neutron diffraction [Forman et al. 2005]. The measured longitudinal and transverse stress along a non-cracked section are presented in Fig. 18. In this figure, the red line is the approximated longitudinal residual stress profile introduced to XFA3D. In the transverse direction, no residual stress is introduced to XFA3D.

The discretized finite element model, consisting of 14924 elements and 19320 nodes, is shown in Fig. 19. The middle part of the problem domain is modeled with the UEL elements to use the XFEM formulation for the crack propagation. The applied boundary conditions are also shown in this figure.

In this example, to run the preliminary residual stress simulation to obtain initial $K_{res}$, an extended XFEM zone was used so we could easily apply residual stress in UEL elements. Since the residual stress exists everywhere in the problem domain in this example, the initial stress should be introduced to the entire problem domain in the preliminary residual stress simulation. Figure 20 displays the stress ($\sigma_{yy}$) distribution in the problem domain in the preliminary residual stress simulation. The associated stress intensity factor with this simulation is $initial K_{res} = 277.24 \text{ MPa} \sqrt{\text{m}}$. After running the second preliminary simulation under only the maximum external loading ($P_{\text{max}}$), the $\alpha$ factor can be calculated by Eq. (7). Based
on Eq. (2), we can conclude that the effect of residual stress has a dominant effect on $R$ as compared with the applied load ratio for this case:

$$\alpha = \frac{K_{\text{res}}}{K_{\text{load}}} = \frac{277.24}{165.91} = 1.67 \quad (7)$$

Figure 21 - Three snapshots of the final simulation including the residual stress effects at three different crack sizes of (a) 10.7 mm, (b) 26.7 mm, and (c) 46.8 mm. These snapshots are colored based on the von Mises stress values.

Three snapshots of the final simulation at three different crack sizes of 10.7 mm, 26.7 mm, and 46.8 mm are depicted in Fig. 21. These snapshots are colored based on the von Mises stress values. Two $da/dN$ curves obtained from the simulations with and without considering the residual stress are depicted in Fig. 22. The results from the simulation without residual stress cannot reproduce the experimental results, indicating that the residual stress has non-negligible effects on the results. Due to the dominant effect of the tensile residual stress distribution, the fatigue life has been reduced in the presence of the residual stress due to the faster crack growth rate shown in Fig. 22. Also, the results from the XFA3D simulation with residual stress are in a very good agreement with the experimental results, which verifies the implemented residual-stress treatment.

Figure 22 - $da/dN$ versus crack length curve with and without residual stress effects

Cruciform Tensile Specimen with a Semi-Elliptical Surface Crack

In this example, fatigue crack growth in a cruciform tensile specimen under constant-amplitude loading condition is simulated, and the effects of residual stress are investigated. The specimen sizes and material properties are borrowed from [Barsoum and Barsoum 2009]. The specimen is made from 6061-T651 aluminum and the modulus of elasticity and Poisson’s ratio are taken as $E = 10000$ ksi and $\nu = 0.33$. Walker’s fatigue law is used for the life prediction in this example, for which the following parameters are taken: $C=1.17E-09$, $m = 3.7$, and $\gamma = 0.641$. Problem domain geometry and the initial crack configuration are shown in Figs. 23 and 24 respectively. The applied peak load is 7.3 kips and the associated applied load ratio is -1.0.
Following the proposed procedure to consider the residual stress effects, two preliminary simulations at the initial configuration were run: 1) under only the residual stress and 2) under only the external loading. Two major components of the applied residual stress field around the welding zone are shown in Fig. 25 along the longitudinal and transverse direction. Figure 26 shows the stress distribution in the problem domain from the residual stress simulation after reaching a self-equilibrium state. Using stress intensity factors computed from two preliminary simulations, the factor $\alpha$ defined in Eq. (1) is calculated as:

$$\alpha = \frac{K_{\text{res}}}{K_{\text{ext}}} = 0.158$$

(8)
Figure 26 - Stress distribution in the preliminary residual stress simulation in the Cruciform Tensile Specimen: (a) \( \sigma_{xx} \), (b) \( \sigma_{yy} \), (c) \( \sigma_{zz} \).

Three snapshots of the final simulation, colored based on the von Mises stress values, are depicted in Fig. 27. A part of the problem domain is removed in these snapshots for clearer depiction of the crack. Number of cycles versus crack growth step numbers obtained from the simulations with and without considering the residual stress are depicted in Fig. 28. This figure shows that the presence of the residual stress leads to lower number of cycles for the fatigue life prediction. This is mainly due to the tensile residual stress introduced near the crack location as shown in Fig. 25.

Figure 27 - Three snapshots of the final simulation of the Cruciform tensile specimen, colored based on the von Mises stress values. A part of the problem domain is removed in these snapshots for clearer depiction of the crack.

Figure 28 - Number of cycles versus crack growth step number (increment number) obtained from the simulations with and without considering the residual stress.
A Welded T-Joint with a Through-the-Thickness Crack

Fillet welded plates, as shown in Fig. 29, are considered in this example. The plates are made from steel and the modulus of elasticity and Poisson’s ratio are taken as $E=200$ GPa and $\nu=0.3$. Walker’s fatigue law is used for the life prediction in this example, for which the following parameters are taken: $C = 4.75 \times 10^{-12}$, $m = 3.0$, and $\gamma = 0.0$. Problem domain geometry and the initial crack configuration are shown in Figs. 29 and 30 respectively.

Figure 29 - Geometry of the welded T-joint and the domain the XFEM zone for crack growth simulation

Figure 30 - Discretized FE model of the welded T-joint

Welding residual stress for this example is reported by Barsoum and Barsoum (2009) and Ma et al. (1995). Two major components of the applied residual stress field around the welding zone are shown in Fig. 31.

Figure 31 - Initial residual stress in the welded T-joint

Two preliminary simulations at the initial configuration were run: 1) under only the residual stress and 2) under only the external loading. Figure 32 shows the stress distribution in the problem domain in the preliminary residual stress simulation. Using stress intensity factors computed from two preliminary simulations, the factor $\alpha$ is calculated as:

$$\alpha = \frac{K_{\text{res}}}{K_{\text{load}}} = 0.077$$

Three snapshots of the final simulation, colored based on the von Mises stress values, are depicted in Fig. 33. The crack length ($a$) versus the number of cycles ($N$) obtained from the simulations with and without considering the residual stress are depicted in Fig. 34. This figure shows that the presence of the residual stress leads to lower number of cycles for the fatigue life prediction due to the presence of tensile residual stress. In addition to the simulations under constant-amplitude loading, this example also was re-run under variable-amplitude loading, considering the block loading shown in Fig. 34. The loading in this case consists of three blocks with load ratios of 0.1, 0.0, and 0.3. Comparison of $a(N)$ curves from the 3-block loading simulations with and without considering the residual stress are depicted in Fig. 35. Again the presence of the tensile residual stress has a detrimental effect on the service life of the welded T-joint.
CONCLUSIONS

A simplified residual stress characterization model has been developed and implemented within XFA3D for 3D fatigue crack growth prognosis of welded structures. A single-step solution process has been created to determine the ratio \( \alpha \) of the stress intensity factors from the residual stress field alone \( (K_{\text{res}}) \) and the applied peak load alone \( (K_{\text{max}}) \) case using the original crack configuration. While both \( K_{\text{res}} \) and \( K_{\text{max}} \) vary during the crack propagation, it is assumed that their ratio \( (\alpha) \) remains unchanged during the crack growth. To account for the stress ratio \( (R) \) dependent fatigue crack growth, two stress ratio dependent fatigue damage accumulation models have been implemented in XFA3D based on Walker’s and NASGRO’s formulation. Based on the assumption of linear fracture mechanics, the fatigue damage accumulation from an arbitrary block loading spectrum has been included in XFD3D using a reference solution in conjunction with a load scale factor associated with each block loading.
The solution capability and numerical accuracy for XFA3D have been demonstrated via the curvilinear fatigue crack growth path prediction in a holed plate and a multi-holed beam. The predicted crack paths are in good agreement with the experimental observation. The equivalent stress intensity factor \( (K_{eq}) \) and the path prediction are both accurate and this indicate the validity and efficiency of the XFA3D methodology based on the nodal enrichment coupled with a level set characterization and tracking of an arbitrary distribution of cracks. Despite of the use of a simple \( K_{eq} \) extraction based on the near tip crack opening displacement, a high accuracy can be retained because of the use of the additional nodal degree of freedoms based on the tip enrichment function.

Three welded components have been selected to explore the applicability and accuracy of the simplified residual stress characterization module for XFA3D. The simulation result for the butt welded tensile specimen has clearly indicated the importance of the inclusion of the residual stress and the accurate prediction in comparison with the test data. The use of simulation model for the cruciform tensile specimen is to demonstrate the ability of the XFA3D in characterizing a complex crack growth pattern in the presence of detrimental tensile residual stress. Finally, the combined effects from the residual stress and a variable amplitude loading on the fatigue damage accumulation have been demonstrated via the toolkit application for a welded T-joint subjected to a 3-block loading spectrum.

Current field engineers and structural analysts are well-versed with both the safe-life approach and the damage tolerance design approach using the \( S-N \) and \( da/dN-\Delta K \) test data collected from coupon testing at various levels of applied load ratio \( (R) \). The prediction toolkit for Abaqus can be used effectively and efficiently to assist a designer and rule-maker to answer the following questions: 1) Does the proposed design have an acceptable risk of fatigue failure? 2) How tolerant is the proposed design to a crack without the risk of catastrophic failure? 3) If a crack is found in service, how long is it safe to leave the crack before repair? 4) If the ship’s mission and operational profile have changed, what are its implications on fatigue risk? 5) How often should the structure be inspected for fatigue cracks? and 6) How can measured loads from a structural health monitoring system be used to update the fatigue risks? It is anticipated that the XFA3D toolkit will lead to new insights into the design drivers of fatigue damage evaluation of welded metallic structures, cost effective repair designs, and in the future new ways to certify damage tolerant ship structures.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support from ONR Code 331 under contract N0001413C0108 with Dr. Paul Hess as the program monitor. Authors would like to thank Yared Amanuel at NSWCCD for providing his verification results of XFA3D and suggestions on its capability extension.

REFERENCES


