Fatigue Crack Growth and Propagation in a Welded Gusseted Connection

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Abstract - **During service condition, a structure is often subjected to cyclic loading which lead to fatigue failure. Nucleation and propagation of cracks caused by cyclic loading leads to catastrophic failure at stress much lower than yield strength. In case of ductile welded joint, crack-initiation period is shorter than the crack-propagation period due to the existence of sharp-edged discontinuities in welds. The existence of sharp discontinuities creates high stress concentration, so the fatigue life estimation of welded joints depends on the fatigue crack propagation. In this paper, a fracture mechanics based approach has been adopted to predict fatigue crack growth characteristics on a welded gusset connection. Numerical study on fatigue crack growth behaviour has been presented here which simulate crack propagation in an axially loaded welded gusseted connection. Crack initiation is determined from the maximum hot-spot stress. An initial crack has been introduced normal to the maximum principle stress at weld roots. For fatigue analysis, Paris law is used to consider the residual stress effect. Stress Intensity factor (SIF) and stress ratio are computed at the crack tip and used in Walker's model to determine the crack growth rate. Fatigue life has been predicted by the requirement of step time by the equivalent number of cycle needed to reach the crack growth to critical size of cross section. The crack propagation has been simulated by using extended finite element method (X-FEM) till the crack grows to a critical value for failure. Finally, number of cycles required to develop critical crack length has been presented.**

Keywords— Gusset connection, Welded joints, Crack propagation, XFEM.

I. INTRODUCTION

In service condition, a structure is often subjected to cyclic loading which leads to fatigue. In particular structural connections are prone to fatigue due to high concentration of localized stress. Fatigue is defined as the accumulation of damage by repeated fluctuating stresses and strains. The damage created in the crystalline structure of the material becomes visible by the plastic deformation. The significant feature of fatigue is that the nucleation and propagation of cracks caused by repeated cyclic loading below the yield strength of a material may cause catastrophic failure. The total fatigue life (N) of initial defect free structure is the summation of 1. Crack initiation fatigue life (N_i) and 2. Crack propagation fatigue life (N_p) i.e. - $N = N_i + N_p$. [1]. In Welded ductile material, crack- initiation period is usually shorter than the crack propagation period because of the existence of sharp-edged discontinuities in welded structure. Due to existence of discontinuities, the fatigue life estimation of welded structures depends on the fatigue crack propagation according to fracture mechanics [2] [3] .The increased awareness of fatigue failures in the last fifty years is a consequence of several tragic accidents. Some of the most and often mentioned accidents due to fatigue failure are probably the disintegration of the two de Havilland Comet jetliners during flights in 1954, and the capsizing of the Alexander L. Kielland oil platform. Analysis and design of fatigue failure are broadly divided into three major approaches [4]; the stress-based approach, the strain-based approach and the fracture mechanics approach. The stress-based approach considers the nominal (average) stresses in the affected areas in the analysis of the fatigue life. The strain-based approach treats the localized plastic deformations or yielding that may occur in regions with stress raisers as edges and notches. However the fracture mechanics approach involves analysing crack growth by using the philosophy of fracture mechanics. These approaches are further divided into a lifetime approach (number of cycles to failure) and a fatigue crack growth approach (damage tolerance). Fatigue Crack Growth (FCG) is defined as crack growth caused by repeated cyclic loading. It has been observed that during high-cycle fatigue (HCF) the crack initiation period be the largest period is larger whereas for low-cycle fatigue (LCF) the crack growth period is the most significant phase.

II. OBJECTIVES AND SCOPES

Objective of this research is to study the fatigue crack propagation of welded gusset connection. As most of the damage models naturally induce material softening but no discrete separation of material yielding extensive straining in case of complete failure. Therefore, a combination of damage and discrete failure is appropriate to model ductile failure such as welded structural connection.

This research presents a computational approach to simulate crack propagation in elastic-plastic media in Two Dimensional (2-D) spaces to examine crack propagation as well as the direction of crack growth in a single computable model using XFEM. The method is extremely efficient as it needs no remeshing for crack propagation thus making it easier to use in structural or mechanical problems.

III. METHODOLOGY

An automated crack onset and growth simulation based on the XFEM is used here. This is able to simulate arbitrary crack growth and composite delamination without remeshing. XFEM is used to enrich the displacement field with jump and asymptotic near-tip solutions and track the crack geometry as it grows. There are two different approaches to model crack propagation, namely-

a. Cohesive segment approaches

b. LEFM approaches.

LEFM uses crack closer technique which is used to propagating cracks in brittle material. This paper is based on cohesive segment approaches that involve plasticity which is appropriate for ductile material [7].

IV. FATIGUE CRACK GROWTH SIMULATION: GUSSET CONNECTION

Gusset plates are often used in horizontal or vertical bracings to connect more than one member. The joint is achieved by either bolting or riveting the members with the gusset plate, or by welding them together. In case of welded connection, high stress concentration occurs due to non-welded root gaps; residual stresses and distortions due to the welding-process affect the fatigue behaviour of the gusset joint.

Crack initiation is determined from the maximum hot-spot stress. An initial crack is introduced normal to the maximum principle stress at weld roots. For fatigue analysis, Paris law for fatigue is used to consider the residual stress effect. Stress Intensity factor (SIF) and stress ratio are computed at the crack tip and the computed results are used in Walker's model to determine the crack growth size. Fatigue life has been predicted by the requirement of step time by the equivalent number of cycle needed to reach the crack growth to critical size of cross section. The crack propagation is generally simulated by using extended finite element method (X-FEM) till the crack grows to a critical value for failure.

A. Fatgue Crack Growth Simulation

It is usually assumed that the fatigue crack is initiated where the maximum Mises stress, or the hot spot stress is located. This assumption is supported by the experimental observation in [5]. It has also been observed that the fatigue crack starts at the weldment tip not only due to stress magnification but also due to mismatch between base metal and weld filler. The direction of the initial crack is considered to be normal to the maximum principle stress at this location.

1) Static Analysis: To locate the hot-spot stress, a static analysis has been performed over the gusset- angle jointed connection.

a) Modeling: The prototype of the gusset-angle joint has been created by using ABAQUS 6.12 Graphical user interference (GUI). Angle and gusset plate has been modeled as two different parts, using 3D solid by extrusion. The geometric model of gusset plate 12mm thick and Angl section (80×50×8) are shown in figure 1 and 2 respectively.

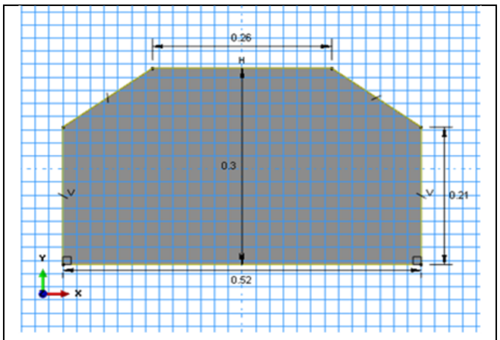

Fig-1: Gusset plate dimension

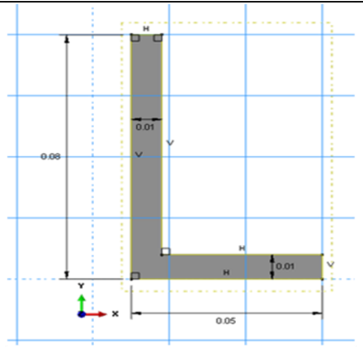

Fig-2: Angle dimension

b) Loadng and Boundary Conditions: Design load has been used in ABAQUS as compressive pressure load direct on angle section. As the gusset plate far end remains welded, so the boundary condition for gusset plate has been considered as pinned (U1=U2=U3=0).

c) Material property and Element Selection:

- *Material properties:*

  General properties -Density(ρ) = 7800 kg/m^3

  Elastic properties –

  Young's modulus (E) = 200 GPa ;

  Poisson's ratio (ν) = 0.3

- *Element selection:*

  Solid tetrahedron element has been selected for static analysis. ABAQUS /explicit library provide wide range of element types which provides flexibility in modeling different geometry and structures. Each element can be characterized by considering- Family, Number of nodes, Degrees of freedom, Formulation and Integration. By constraining degrees of freedom in desired direction we can create boundary conditions. For this modeling C3D10- has been used. The element especially attractive because of the existence of fully automatic tetrahedral meshers.

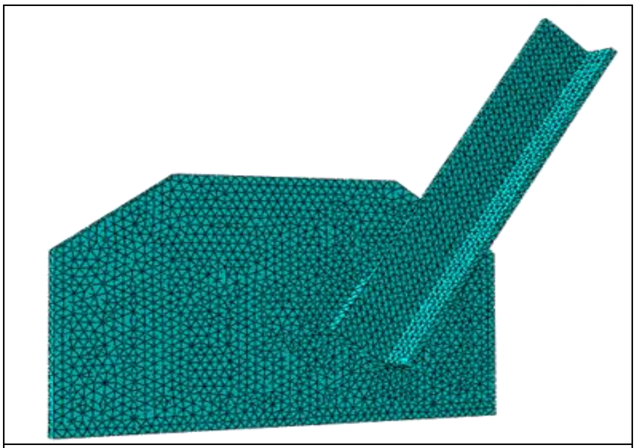

Fig- 3: Meshed model

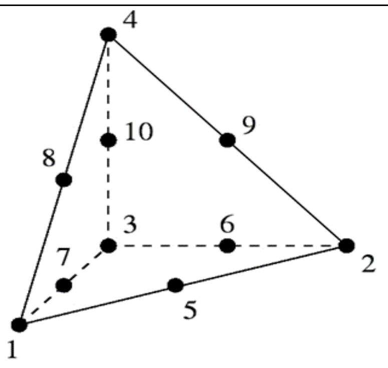

Fig-4 C3D10 element

d) Results and determination of Hot-spot Stresses: After the analysis in ABAQUS stress contour of misses stress are presented and maximum stress concentration has been determined.

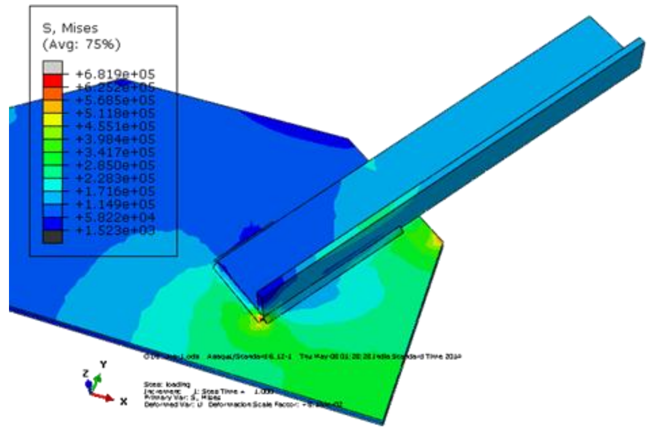

Fig- 5 : Front stress contour plotted result

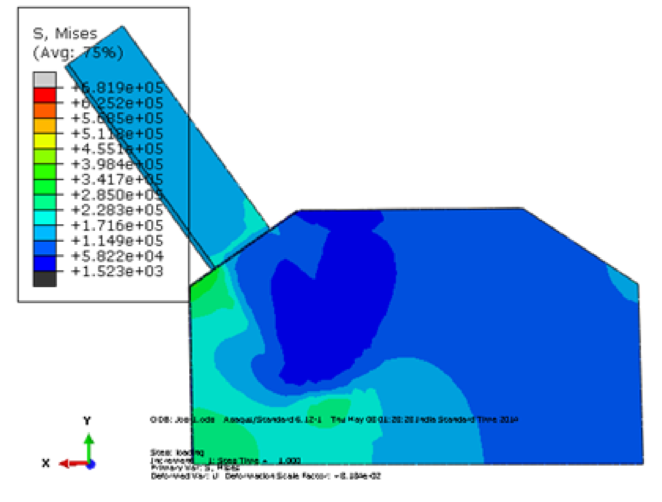

Fig- 6: Back view of stress contour.

2) Crack Growth Simmulation: Crack growth simulation consists of Crack initiation, Crack Propagation and Failure. All these steps are simmulated usin XFEM elements in ABAQUS without re-meshing near the crack tip. The special features of XFEM crack growth has been used in crack growth simulation. The maximum principle stress criterion used here is represented in eqn 1.

$$f = \left\{ \frac{\langle \sigma_{\max} \rangle}{\sigma^0_{\max}} \right\} \tag{1}$$

Where $\sigma^0_{\max}$ represents the maximum allowable stress. The symbol < > represents the Macauley bracket with the usual interpretation (i.e. $\langle \sigma_{\max} \rangle = 0$ if $\sigma_{\max} < 0$ and $\langle \sigma_{\max} \rangle = \sigma_{\max}$ if $\sigma_{\max} \geq 0$) Damage is used to initiate from the hot spot stress region and when maximum principle stress ratio reaches a value of unity.

3) Computation of crack propagation Direction:

Maximum tangential stress criterion has been used to calculate crack propagation angle θ_{cr} . With this criterion the fracture angle of the crack growth is defined to be perpendicular to the maximum tangential stress at crack tip. For this analysis 1mm crack has been inserted at the hot-spot location and it is allowed to grow shown in (Fig –7). The crack propagation direction has been simulated using XFEM in ABAQUS.

For fracture criterion, maximum principal stress as 242 MPa was used as criteria for crack initiation. Critical energy release rate as 12.367 kN/m and unit power coefficient were used as criteria for crack initiation with power law. All values of fracture criteria has been adopted from [6].

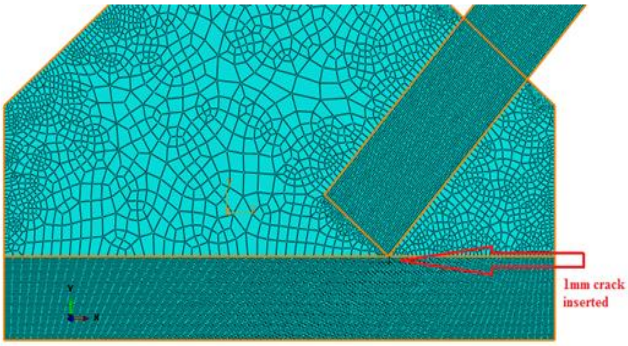

Fig-7: 1mm Crack inserted at hotspot stress

4) Fatigue Crack Growth: A simplification from 3D to 2D model is made to save computational time.The component is considered failed once the total crack growth size reached a critical value. The fatigue life as a number of cycles is equivalent to the step time when the critical size is reached. It is noted that the X-FEM elements are used only in the region around the initial crack. By using X-FEM , the crack growth is completely independent on the mesh. Crack tip can move arbitarrily in the region and no remeshing is needed.

The fatigue crack growth and the Mises stress in the XFEM region is shown in Fig-8. In the analysis crack propagates in the direction of the highest stress.

Fig-8(a) Increment- 0; Step time 0.0
(Initial Stage)

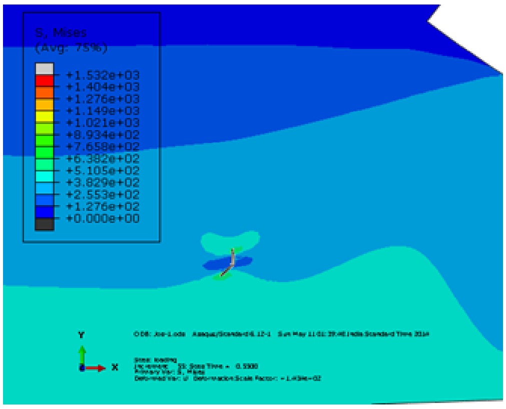

Fig-8(b) : Increment – 25 ; Step time 0.33

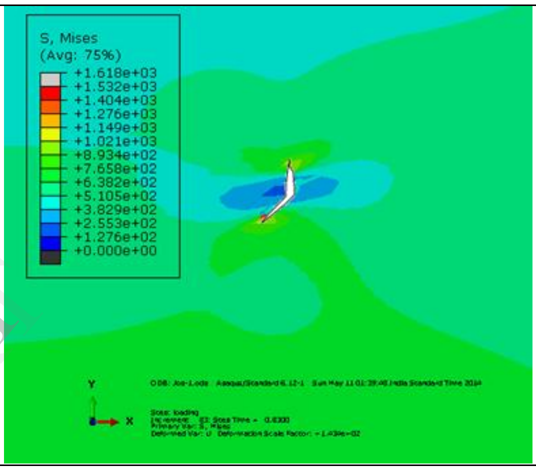

Fig-8(c) : Increment -50 ; Step time 0.59

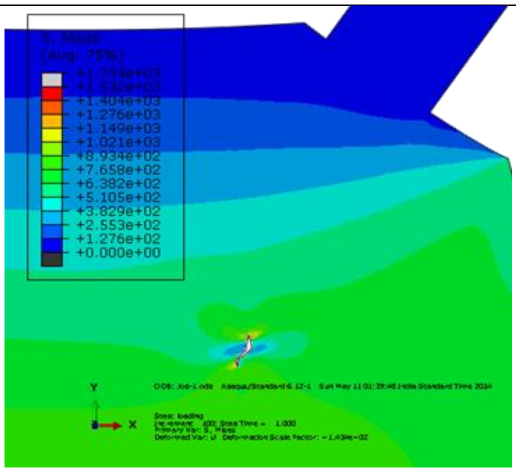

Fig-8(d) : Increment – 100 ; Step time- 0.83
(Final stage)

CONCLUSION

The fracture mechanics based fatigue crack propagation in a gusset connection has been simulated and the crack propagation pattern is presented here. The crack propagation using cohesive segment approaches based on traction separation laws has been successfully used for the fracture analysis of welded gusset connection. The crack propagation direction has been simulated using the XFEM in ABAQUS. To simulate Fatigue Crack Growth using XFEM gives new possibilities to the analysis method as it is much challenging compared to other techniques. This method has reduced computation time for each increment significantly. The requirement of a very refined mesh around the crack tip makes the partitioning and meshing challenging. The refined mesh area is preferably as small as possible, but without making an influence on the crack path. Finally this paper gives a fracture based analytical application that can be adopted in the design procedure for much clear description of crack propagation in structural connection.

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