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Experimental and numerical fatigue crack growth of an aluminium pipe repaired by composite patch

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ABSTRACT

In this study a cylindrical cracked aluminium pipe is considered. Fatigue crack growth behaviour of the pipe is observed through experimental tests. Stress intensity factors are computed for the pipe with an inclined crack under axial tensile load. Fatigue crack trajectory and also the crack growth curves versus number of cycles of load, are extracted. Validation of results is then achieved through the extended finite element method (XFEM). A stand-alone MATLAB programming package is developed to study such structures with 3D degenerated shell elements. The cracked pipe is finally repaired by glass/epoxy polymer composite and the effect of the patch is observed on the extension of fatigue life through experimental tests and the XFEM framework.

1. Introduction

Crack initiation may occur in different structures such as metal or concrete elements. Fatigue is one of the most common kinds of loading which causes cracking initiation and propagation in structural elements. These structural parts can be found in building area or industry. For example, bridges which are utilized for providing passage of vehicles or trains, are subjected to fatigue loading that may cause damage in the bridge elements. Pipelines are another example of strategic infrastructures which are used for energy transferring. They may contain fluids such as gas, petroleum or water while pressure changes of the fluid would lead to internal fatigue loading in the pipe.

Most of the aforementioned structures can be considered as 3D Shell elements. While this assumption takes into account the three dimensional geometry of the parts, the computational cost will decrease compared with 3D solid element assumption.

Different methods are proposed to analyze shell elements which can be categorized as analytical, numerical and experimental studies. Erdogan et al. [1,2] studied on the cracked panels using an analytical formulation for the fracture parameters such as stress intensity factor. Other closed-form expressions for SIFs are presented by Zahoor [3], Sanders [4] and Forman [5] for cracked cylindrical pipes. Zárate et al. [6] presented a framework to update and predict crack length as a function of the number of cycles in structural elements subjected to fatigue.

Analytical methods are mostly capable to solve just simple geometric problems with particular loading and boundary conditions. Of course, it should be mentioned that the analytical procedures are basis of the recent powerful numerical techniques. Finite element method is one of these techniques that can solve varieties of simple or complex engineering problems. Structures can be modeled and analyzed under arbitrary loading and boundary conditions through this framework. Lam et al. [7] studied on a cracked steel circular tube repaired by FRP patching through FEM method. Tong and Sun [8–11] have studied the effect of curvature existence in elements on the adhesive stress and fracture toughness. Pavlou et al. [12] proposed a new methodology to simulate the crack trajectories under mixed-mode fatigue loading through FEM method.

The conventional finite element method remains simple until there is no discontinuity in the model. Discontinuities in elements would lead to singularities that make solving the problem more difficult. For instance, in problems containing cracked parts the generated mesh should be in a way that the crack body coincides the element edges. Singular elements should also be used as crack tip elements. This would lead to an irregular mashed part of the structure. The problem becomes more complex when crack propagation needs to be considered. In the case of crack propagation such as fatigue crack growth problems the crack body and crack tip will not be coincided with the element edges after growing the crack, so a new mesh generation is needed for the model in each step of solving the problem. This procedure is done in a work by Ghaffari and Hosseini-Toudeshky [13]. They studied on crack growth of a steel pipe under fatigue loading with and without FRP patching through FEM method. An automated re-meshing

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technique is performed through ANSYS Parametric Design Language (APDL) to detect the new geometry of the crack in each step of crack growth and assign adaptive mesh to the cracked panel.

All the deficiencies of the conventional finite element method resulted to appear a new technique known as an extended finite element method (XFEM) in which a regular mesh generation can be used in even cracked parts. The elements in this method can be cut in arbitrary manners and just the formulation of the elements around the crack is modified in a way that the singularity of the problem is taken into account. Areias and Belytschko [14–16] worked on cracked shells by XFEM method considering the material nonlinearities without applying enrichment functions of crack tips. Bayesteh and Mohammadi [17] have extended Areias [14] works to study cracked shells applying Mindlin-Reissner theory, while they also considered the effect of the crack tip enrichment function. Wyart et al. [18] applied extended finite element method to analyze cracks in aircraft thin walled structures.

Experimental testing is another way of studying problems. It is obvious that every structural part cannot be tested experimentally due to time and cost aspects, but the simplest experimental test can be utilized to validate the results of the numerical method.

After a damage or crack is initiated in an element, affordable techniques of repairing are required for the damaged parts. Traditional techniques like using bolts or welding have some disadvantages such as vulnerability of welding to fatigue loading, high stress concentrations near bolts and increasing the total weight of the structure after using metal repairs. Among the new techniques of repairing, polymer composite materials are a proper alternatives which cover the aforementioned deficiencies of traditional retrofitting methods. Glass/epoxy polymer composite is used in this research as a repair patch. Gandhi et al. [19] studied on fatigue crack growth in stiffened steel tubular joints in seawater environment. Kabir and Nazari [20–23] experimentally studied on a cracked cylindrical steel pipe under compressive loading. The results were also compared with FEM models for the patched an un-patched pipe.

In this study a cylindrical cracked aluminium pipe is studied by XFEM method and then validated by experimental tests. Fatigue crack growth analysis of the pipe is performed through the extended finite element method assuming 3D degenerated shell elements. The effect of glass/epoxy patch repair is then observed. The transparency of the patch makes it possible to trace the crack trajectory in the lower panel. Besides developing a stand-alone XFEM package in the MATLAB programming software, similar test specimens are provided to experimentally validate the numerical results.

2. Numerical formulation

2.1. Degenerated shell element

Using the so-called degenerated shell element formulation, computations are done similarly in a planar scheme, while the 3D properties of element are kept. Fig. 1 shows schematic of a degenerated shell element, nodal points and coordinate systems.

The geometry of an element is described as

$$\begin{Bmatrix} x \\ y \\ z \end{Bmatrix} = \sum_{i=1}^{8} N_i(\xi,\eta)\left\{\begin{Bmatrix} x_i \\ y_i \\ z_i \end{Bmatrix} + \frac{1}{2}M_i(\zeta)\begin{Bmatrix} l_{3i} \\ m_{3i} \\ n_{3i} \end{Bmatrix}\right\} \tag{1}$$

where ξ,η are the two curvilinear coordinates in the middle of plane of shell and ζ is a linear coordinate in the thickness direction. $N_i(\xi,\eta)$ are shape functions in element plane directions, $\{x_i \quad y_i \quad z_i\}^T$ is the Cartesian coordinate. $M_i(\zeta) = \zeta\frac{t_i}{2}$ is the one dimensional shape function in ζ direction and t_i is the thickness

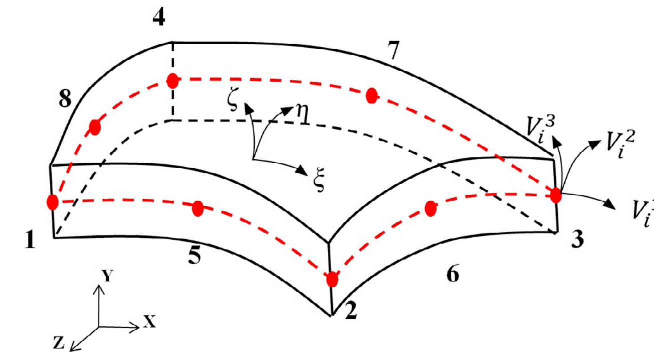

Fig. 1. Schematic of a degenerated shell element, nodal points and coordinate systems.

at node i in the middle surface. $\{l_{3i} \quad m_{3i} \quad n_{3i}\}^T$ is related to direction cosine vector v_{3i}.

2.2. XFEM formulation

In XFEM formulation, the displacement field is divided into two parts

$$\mathbf{u} = \mathbf{u}^{FE} + \mathbf{u}^{ENR} \tag{2}$$

in which $\mathbf{u}^{FE}$ is the conventional finite element displacement.

$$\mathbf{u}^{FE}(\mathbf{x}) = \sum_{i=1}^{n} N_i(\xi,\eta)\left\{\hat{\mathbf{u}}_i - M\hat{\alpha}_i\mathbf{e}_{1i} + M\hat{\beta}_i\mathbf{e}_{2i}\right\} \tag{3}$$

Five degrees of freedom are considered in the conventional shell formulation which consist of three nodal displacements $\hat{\mathbf{u}}_i$ and two local rotations $\hat{\alpha}_i, \hat{\beta}_i$ with respect to local orthonormal vectors $\mathbf{e}_{2i}$ and $\mathbf{e}_{1i}$.

$\mathbf{u}^{ENR}$ is related to the enriched part of approximation. To model weak or strong discontinuities in XFEM framework, one need to incorporate two types of enrichment functions into displacement approximation. The first type of enrichment function which is used to present the discontinuity across the crack, is the Heaviside step function. Dolbow introduced this function to simplify the representation of crack away from the tip. The Heaviside function is

$$h(x) = \begin{Bmatrix} 1 & \text{above the crack} \\ -1 & \text{below the crack} \end{Bmatrix} \tag{4}$$

The Heaviside function comes in the degenerated shell formulation as below [17]

$$\mathbf{u}^{Heaviside}(\mathbf{x}) = \sum_{i=1}^{n} N_i(\xi,\eta)\Big\{(H(\phi(\mathbf{x})) - H(\phi(\mathbf{x}_i))) \times\Big(\mathbf{a}_i - Ma_i^{\alpha}\times\mathbf{e}_{1i} + Ma_i^{\beta}\times\mathbf{e}_{2i}\Big)\Big\} \tag{5}$$

where a_i is the vector of enriched displacement degrees of freedom at the mid-surface of the shell and a_i^{α} and a_i^{β} are rotations with respect to $\mathbf{e}_2$ and $\mathbf{e}_1$ respectively.

The second type of functions called crack-tip enrichment functions, is usually derived from the asymptotic analytical solution. They are used to represent the singularity of stress field near the crack tip. The crack tip enrichment functions are used in a similar formulation as shown in Eq. (5) for shell elements, which consist of in-plane and out-of-plane enrichment functions as below [17]

The enrichment functions for in-plane degrees of freedom are

$$F(r,\theta) = \left\{\sqrt{r}\sin\left(\frac{\theta}{2}\right), \sqrt{r}\cos\left(\frac{\theta}{2}\right), \sqrt{r}\sin\left(\frac{\theta}{2}\right)\sin(\theta), \sqrt{r}\cos\left(\frac{\theta}{2}\right)\sin(\theta)\right\} \tag{6}$$