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Evaluation of stress intensity factors for multiple surface cracks in bi-material tubes

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ABSTRACT

This paper presents stress intensity factors (SIFs) of multiple semi-elliptical surface cracks in bi-material tubes subjected to internal pressure by boundary element method. In this case the water-tube boiler with oxide scale formed on the inner surface due to prolonged exposure at elevated temperature is considered as the bi-material tubes. Variations of modulus of elasticity and thickness for the oxide scale are used to evaluate their effects on the stress intensity factors. The increasing of thickness of the oxide scale causes decreasing values of the normalized stress intensity factor as the modulus of elasticity for the oxide scale is greater than that of the tube metal. Conversely, if the modulus of elasticity for the oxide scale is smaller, the increasing of thickness of the scale would also give increasing values of the normalized stress intensity factor.

1. Introduction

Boundary element method (BEM) has become a robust tool for various engineering analyses. Brebbia [1] described applications of the boundary element method in providing an excellent basis for the development of integrated design and analysis systems. The technique possesses the advantages of simple model generation, easy-to-understand requirements, high accuracy, relative insensitivity to mesh refinements and the ability to accurately model the most difficult stress concentration problems. A BEM system that combines these features with close integration with CAD systems, highly automated mesh generation, in-built error estimation and design optimization technology provides a powerful tool for use in engineering analysis and design. Brebbia [2] also narrated a chronicle of recent innovations in BEM. Nowadays, the BEM technique has been proven to successfully analyse various engineering problems.

This work is concerned with the problems of tubing in power plants. For prolonged exposure of service under elevated temperatures oxide scales may be formed on the inner surface of boiler tube as reported by Port and Herro [3] and French [4]. Surface cracks may be developed either on the internal or external surface of tube. In order to evaluate creep fatigue in tube as described by Viswanathan [5] or fatigue crack growth in tube as stated in API 579 [6], stress intensity factor (SIF) solutions are required. No available analytical expression for evaluating stress intensity factors of surface crack in a tube made of bi-material has been reported. This work presents the ability of the BEM in evaluating complex problems of tubes consisting of multiple semi-elliptical surface cracks in the presence of the oxide scale on the inner surface subjected to internal pressure. Analyses conducted are assumed and preserved to be using the concept of linear elastics fracture mechanics. Three different values of modulus of elasticity and three different values of thickness for the oxide scale are used in order to study their effects on the stress intensity factors. All the modeling and analysis are carried out by using the boundary element software package of BEASY [7].

2. Crack modeling in BEASY

BEASY uses dual boundary element method (DBEM) for three-dimensional crack analysis. The DBEM incorporates two independent boundary integral: the displacement equation applied at the collocation point on one of the crack surface, and the traction equation on the opposite surface. Analysis of three-dimensional crack problems by using the DBEM has been successfully carried out by Mi and Aliabadi [8]. The modeling strategy of three-dimensional crack problems may be summarized as follows [8]:

- Crack surfaces are modeled with discontinuous elements.
- Surfaces intersecting a crack surface are modeled with edge-discontinuous quadrilateral or triangular elements.
- The displacement integral equation is applied for collocation on one of the crack surfaces, i.e. the upper surface Γ^{+}.
- The traction integral equation is applied for collocation on the opposite crack surface, i.e. the lower surface Γ^{-}.

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- The displacement integral equation is applied for collocation on all other surfaces and the continuous quadrilateral elements are used.

Treatments of singular and hyper-singular integrals which appear in the dual boundary element formulations have also been established, and the detailed expressions were presented in [8]. The stress intensity factors along the crack front are successfully evaluated using the described technique of the DBEM.

3. Simulation models

Model for multiple semi-elliptical surface cracks on the outer surface of the tube containing oxide scale is shown in Fig. 1. The model needs to be divided into two zones, i.e. inner region for the first zone (oxide scale) and the outer region for the second zone (tube metal). Modeling procedures for a compound structure have to be made in order to evaluate the problem accordingly. All the surfaces of the first zone are defined to be in outward normal direction. Next, for the second zone, the surface for the interface between the inner and outer regions has to be defined to be in inward normal direction, whereas the rest of the surfaces of the second zone are defined in outward normal direction.

Two-dimensional quadratic elements are used to discretize all the surfaces of the model. Internal pressure of 4 MPa used for all the models is applied on inner surface of the tube. A spring boundary condition for displacement constraints in x, y and z directions is applied on either top or bottom of the cross sectional surface. The stiffness value of the spring is taken as 2% of Young's modulus for the tube metal as recommended by BEASY [7].

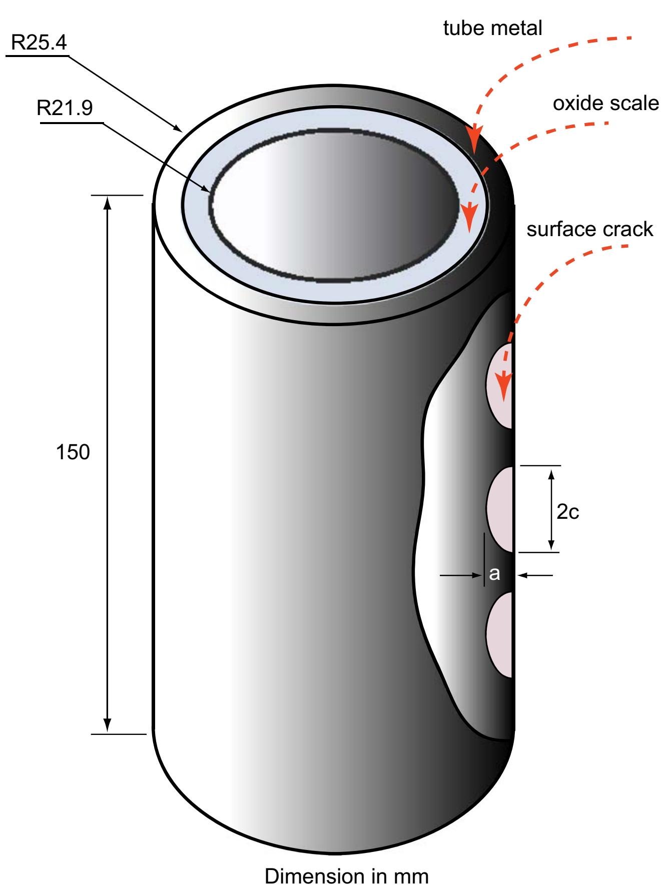

Fig. 1. Studied model of the multiple surface cracks on the outer surface of a water-tube boiler in the presence of the oxide scale.

Displacement constraints are also applied in normal directions on both top and bottom surfaces. Surface crack including its meshing is generated by using the Crack Wizard of BEASY [7]. The J-integral method is chosen to evaluate the stress intensity factors.

The modulus of elasticity for the outer region may be taken to be constant with $E_{outer} = 163{,}410$ MPa. Three different values for modulus of elasticity for the inner region are used, i.e. 150,000, 163,410 and 175,000 MPa [9]. Variations of the model for different values of modulus of elasticity for the inner and outer regions are evaluated to show their effects on the stress intensity factor values. As the modulus of elasticity for the inner region is 163,410 MPa, the model is considered as a free scale tube. The tube used in this study has outer radius and inner radius of 25.4 and 21.9 mm, respectively.

4. Numerical results and discussion

In order to show the accuracy of the results, comparison of the SIFs results obtained by using BEASY [7] and from Mettu et al. [10] for a longitudinal semi-elliptical crack on the inner surface of a cylinder is made. The results are plotted in Fig. 2. It can be seen that the results are shown to be in good agreement. The largest difference is found at midpoint of the crack front (90°) and is within 5%.

Again, in order to demonstrate the accuracy of the results obtained by using BEASY [7] for the analyses of surface cracks in the tube made of bi-material, the model with three collinear external surface crack ($a = 0.5$ mm each) in a tube composed of two zones made of the same material is evaluated. The distance of mid-crack to another adjacent mid-crack is 10.714 mm. Both zones are defined to have Young's modulus of 163,410 MPa. The thickness of the oxide scale is 1.8 mm. The crack front is relatively close to the zones, interface which might affect the interaction of the geometries. It can however be seen from Fig. 3, the normalized stress intensity factors of both models are shown to be in very good agreement. The biggest difference occurred at outer points (angle of 0° or 180° of position along the crack front) of the outer cracks, but it is within 1%. Fig. 4 shows the mesh refinements generated by Crack Wizard of BEASY [7] and Von Mises stress contour around crack tip. It shows that the tool possesses the advantages in generating mesh refinements with high accuracy and the ability to accurately model the complexity of the problem with stress intensities.

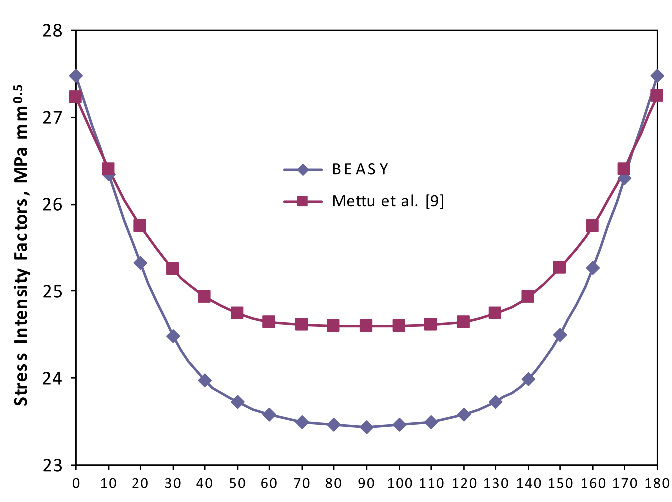

Fig. 2. Comparison of the SIF values for longitudinal semi-elliptical crack on inner surface of tube obtained by using BEASY [7] and by Mettu et al. [9] ($a/c = 1$; $a = 0.5$ mm).