TIME-DEPENDENT CRACK GROWTH IN STEAM GENERATOR TUBE LEAKAGE

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ABSTRACT

In general, cracks found in steam generator tubes have semi-elliptical shapes and it is assumed to be rectangular shape for conservatism after crack penetration. Hence, the leak and crack growth behavior has not been clearly understood after the elliptical crack penetrates the tube wall. Several experimental results performed by Argonne Nation Laboratory exhibited time-dependent crack growth behavior of rectangular flaws as well as trapezoidal flaws under constant pressure. The crack growth faster than expected was observed in both cases, which is likely attributed to time-dependent crack growth accompanied by fatigue sources such as the interaction between active jet and crack. The stress intensity factor, K_I, is necessary for the prediction of the observed fatigue crack growth behavior. However, no K_I solution is available for a trapezoidal flaw. The objective of this study is to develop the stress intensity factor which can be used for the fatigue analysis of a trapezoidal crack. To simplify the analysis, the crack is assumed to be a symmetric trapezoidal shape. A new K_I formula for axial trapezoidal through-wall cracks was proposed based on the FEM results.

1. Introduction

More than ten incidents of steam generator tube failure have been reported so far in the nuclear power plants around the world[1]. One of them is the steam generator tube failure occurred at Ulchin unit 4 of Korea in 2002. The failed tube was visually examined just after the event at UCN 4. The failure was located near the center of the tube bundle. The failure consisted of a longitudinal split about 80mm long in fish mouth opening shape and a circumferential rupture that completely severed the tube at the top of tube sheet about 80mm high. The failed tube was removed from the steam generator. Fig. 1 shows the failed tube of UCN 4. The circumferentially severed section showed that there were two tearing areas. One was located at the junction area with longitudinal split at the top of tube sheet and the other in the final ligament that seemed to rupture when the ligament could not sustain any more the pressure loads. The severance propagated in a helical way through the direction of 45 degree against the horizontal direction. This indicates that the circumferential severance developed after the longitudinal failure occurred as the secondary effect. The failure in longitudinal direction was in a fish-mouth type opening and the maximum opening was located in the middle of the ruptured section. The longitudinal failure is thought to propagate in both ways, up and down. The upper propagation went through the circumferential severance changing its orientation about 45^o to the circumference of the tube. The lower propagation arrived at the top of the tube sheet and continued in the circumferential direction to about 240^o of the tube circumference. The failure shape is a “T” type that is a combination of normal fish-mouth opening in axial direction and circumferential severance[2].

Fig. 2 shows a typical axial stress corrosion crack developed on the inside diameter of a steam generator tube. In many cases, PWSCC(Primary Water Stress Corrosion Cracking) starts from combining several small cracks together which form along the tube inside. The adjacent small cracks coalesce with each other and grow into one main crack like Fig. 2. Once the crack with a shape of Fig. 2 breaks through the wall, the shape becomes trapezoidal rather than remaining semi-elliptical and grows to a rectangular shape. The precursor of the steam generator tube rupture is leakage whether it is detected or not. Therefore, the leak behavior of PWSCC is important in terms of steam generator tube integrity. It seems that the ligament of the failed UCN 4 tube remains thin along the failed section and the rupture has occurred accidentally. Actually, the tube rupture of UCN 4 did not give any prior indication such as leakage before break[3]. ANL (Argonne National Laboratory) performed a series of tests using steam generator tubes with axial though-wall trapezoidal cracks as shown in Fig. 3 and observed the growth of rectangular cracks as well as trapezoidal cracks under constant bulk pressure[4-7]. Fig. 4 shows the fracture surface of the tube which showed crack growth behavior under constant bulk pressure of 6.9MPa. The trapezoidal crack grew along the outer surface without any change of the inside crack length, $2c_i$, until it became a rectangular shape. ANL showed by experiments that the crack growth is caused by two fatigue sources: one is the pulsation loading of the pump installed in the high-pressure test facility of ANL and the other is the interaction between the cracked tube and the active jet erupted from the trapezoidal crack. To predict the observed fatigue crack growth behavior, a formula of stress intensity factor, K_I, is necessary. However, a K_I solution has not been available. The objective of this study is, therefore, to develop a new K_I solution which can be used for the fatigue analysis of a trapezoidal crack. To simplify the analysis, the crack is assumed to be a symmetric trapezoidal shape. The fracture parameter, K_I, was obtained using FEM and a new K_I formula for a trapezoidal crack was proposed.

Fig. 1 Failed tube removed from UCN 4

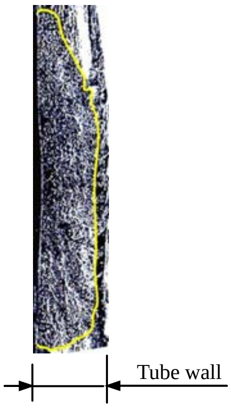


Fig. 2 A typical fracture surface of the tube pulled out from expansion region[8]

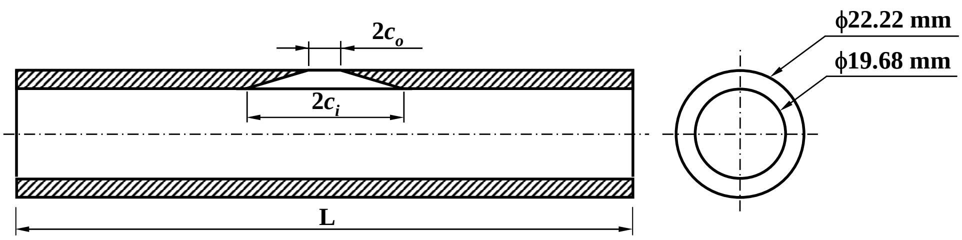


Fig. 3 Geometry and size of tube specimen

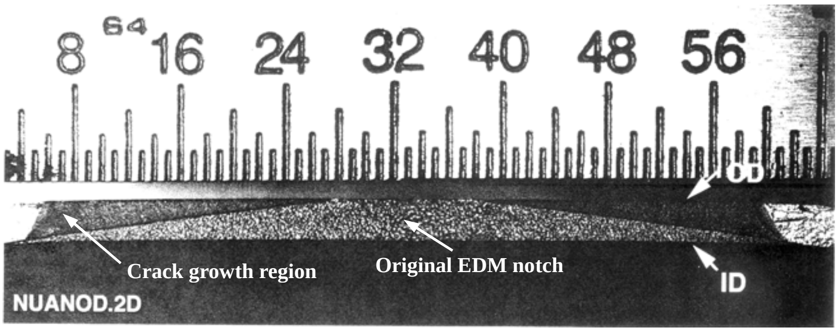


Fig. 4 Fracture surface of the tube specimen with the original flaw length of $2c_i$ = 25.4 mm and $2c_o$ = 4.78 mm.

2. FEM analysis

As a general practice, when a crack is found in a steam generator tube and it penetrates through the wall, the crack is assumed to be rectangular in shape for simplifying conditions whatever the shape is. That is the reason why the stress intensity formula is not available so far for a trapezoidal shape crack. In this study, a closed form of K_I for a trapezoidal crack was derived which can be used to estimate its crack growth behavior.

2.1. Benchmark Analysis

Finite element analysis(FEA) was used for calculating stress intensity factor for trapezoidal cracks and ABAQUS version 6.4 was used as FEA code. In order to calculate reliable K_I values using three dimensional FEA, the crack-tip mesh should be generated as normal to crack front line[9]. For a rectangular crack, it is not a problem. But, when it comes to a trapezoidal crack, it could not be achieved with satisfaction due to the peculiarity of trapezoidal geometry as shown in Fig. 5. Fig. 6 shows a typical finite element mesh of the steam generator tube with a trapezoidal flaw. A quarter of the tube was modeled using the symmetry. The finite element mesh consists of 20-node quadratic brick elements with reduced integration points. The internal pressure and the end-cap load caused by the internal pressure were considered as a loading condition. A benchmark analysis was conducted to obtain reliable K values of a trapezoidal crack as follows:

- Verification of FEA results by comparing with available linear elastic analysis solution for a rectangular crack
- Series of elastic analyses were conducted using FEA to determine an appropriate K_I formula for a trapezoidal crack in steam generator tube

The material properties of Alloy 600 which is widely used as steam generator tubes material of nuclear power plants were used in finite element analyses. The material has an yield strength(σ_y) of 271MPa, an ultimate tensile strength(σ_u) of 634MPa, and an Young's modulus of 200GPa. Fig. 2 shows the shape and geometry of a test specimen having a diameter of 22.22mm and a thickness of 1.27mm.

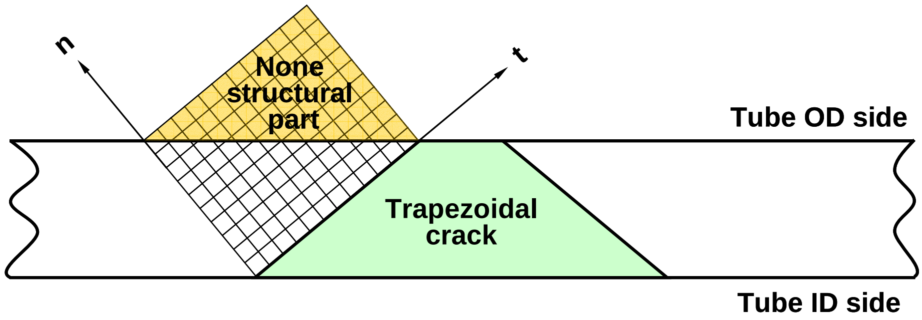


Fig. 5 Generation of crack-tip finite element mesh for trapezoidal crack analysis

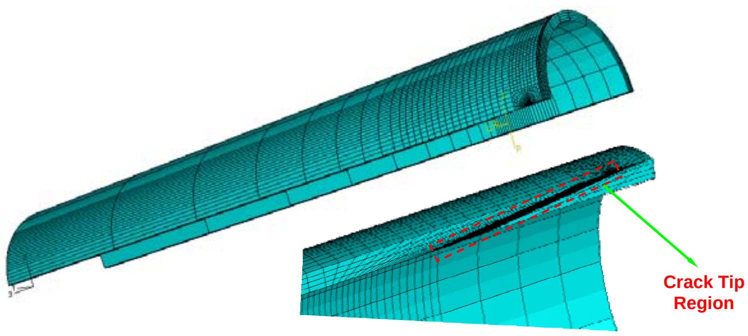


Fig. 6 Typical finite element mesh of SG tube containing axial through-wall trapezoidal crack

2.2. FEM analysis for rectangular crack

For the comparison with available document results, finite element analyses were performed by changing the flaw shape given in Fig. 6 from a trapezoidal one to a rectangular one. The K_I values obtained from 3D finite element analyses showed a good agreement with Zahoor's ductile fracture handbook results[10] within 2%. Besides the direct comparison of K_I values, the bulging factor which was proposed by Erdogan[11] and is being used widely was compared with the bulging factor derived from finite element analysis. The bulging factor, M_T, is defined as the ratio of stress intensity factor for axial crack in a shell, $(K_I)_{Tube}$, versus that for the same crack in an infinite plate, $(K_I)_{Plate}$. The bulging factor proposed by Erdogan is given in equation (1). In this study, a new bulging factor was proposed using an optimization of the results obtained by FEA. The newly proposed bulging factor is presented in equation (2). As shown in Fig. 7, the FEA results agree well with analytical values for λ less than 6 but shows somewhat difference for λ larger than 6.

$$M_T = \frac{(K_I)_{Tube}}{(K_I)_{Plate}}$$

$$= 0.614 + 0.481\lambda - 0.386\exp(-1.25\lambda) \quad \text{by Erdogan} \qquad (1)$$

$$= 0.4895 + 0.551\lambda - 0.0093676\lambda^2 + 0.51054\exp(-1.0859\lambda) \quad \text{by FEM} \qquad (2)$$

$$\lambda = \left[12\left(1-\nu^2\right)\right]^{0.25}\left(c\Big/\sqrt{R_m t}\right) \qquad (3)$$

2.3. FEM analysis for trapezoidal crack

The finite element analysis for a trapezoidal flaw was conducted with three different crack-tip meshes, including two meshes consisting of elements parallel to the axial direction of tube as shown in Fig. 8(a) and (b), and a mesh of elements that are normal to the crack front line as shown in Fig. 8(c). Fig. 9 shows a comparison of K_I along the crack front line for three mesh cases. The K_I values are in a good agreement except the two extreme areas, next to inside and outside of tube wall. It is concluded, therefore, that the K_I values of the through-wall trapezoidal cracks can be obtained using a sufficiently fine crack-tip mesh elements parallel to the axial direction except the both end sides of the wall.

The stress and strain data normal to the crack front line are needed for the calculation of K_I. However, as mentioned before, these data at inner and outer surfaces are not available due to the characteristic of the trapezoidal geometry. In this case, the ABAQUS code calculates these data by extrapolating the stress and strain data at the integration points of the available internal elements. Because of the steep gradient of the stress field near outside surface, such extrapolation leads to unstable K_I values that are physically meaningless. It is unlikely that the actual K_I value at the outside surface is maximal because the stress state at outer surface approaches a plane stress condition. Fig. 10 shows the calculated K_I values along the crack front line at the pressure of 6.9MPa for trapezoidal cracks being of 20mm long inside and with a variation of outside crack length from 5mm to 20mm. A relatively stable K_I value could be obtained up to x/t = 0.98 in all the cases. Based on this observation, the K_I values at x/t = 0.98 was selected as an approximate maximum K_I values for a trapezoidal crack.

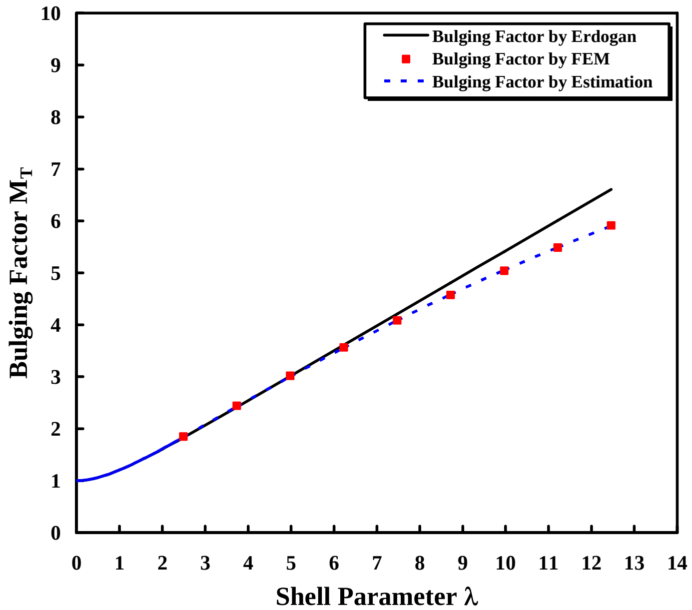
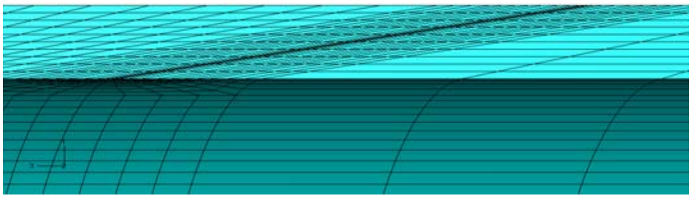
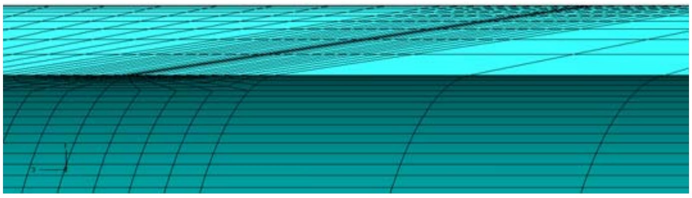


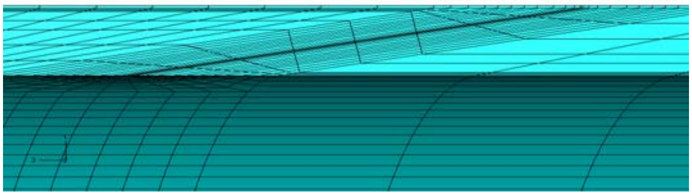
Fig. 7 Comparison of bulging factors between Erdogan's results and finite element results



(a) crack-tip mesh parallel to the axial direction (non-biased, uniform spacing through thickness)



(b) crack-tip mesh parallel to the axial direction (biased outward, closer spacing on the OD side)



(c) crack-tip mesh normal to the crack front line over the inner part of the tube thickness

Fig. 8 Crack-tip meshes used for benchmark analysis

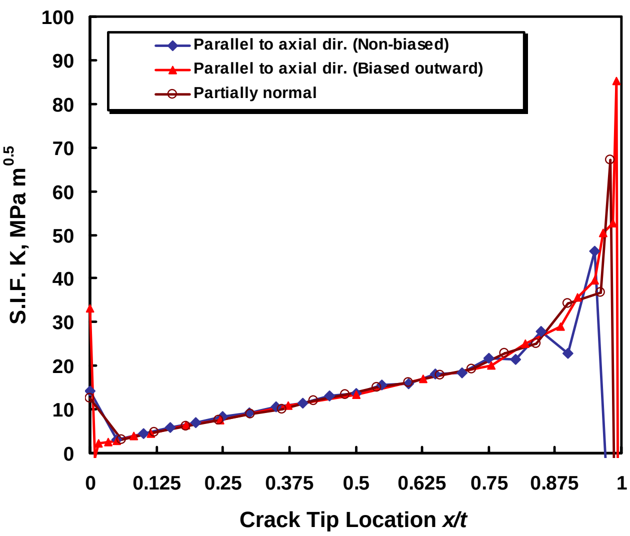


Fig. 9 Variation of stress intensity factors along the crack front line of a trapezoidal crack with $2c_i$ = 25.4 mm and $2c_o$ = 12.7 mm (P_i = 7.1 MPa)

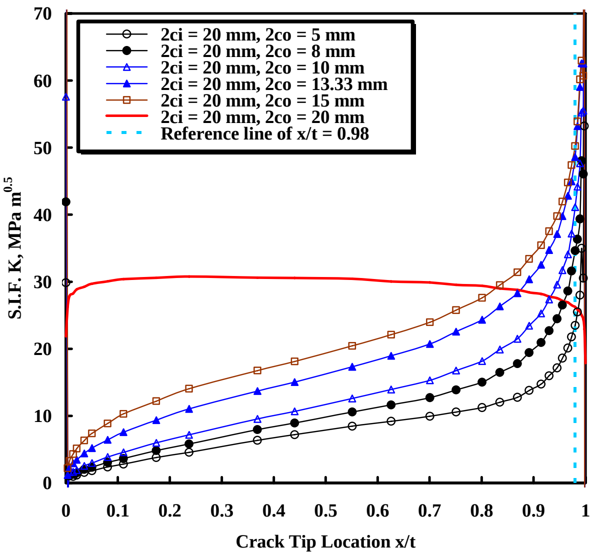


Fig. 10 Variation of stress intensity factors along the crack front line of trapezoidal crack and rectangular crack (P_i = 6.90 MPa)

3. Proposed K_I solution for trapezoidal crack

To calculate stress intensity factor used in the fatigue analysis of trapezoidal cracks, finite element analyses were carried out for 67 cases by changing the crack length ratio, crack shape parameter, tube radius and thickness. The flaw shape varied from rectangular cracks with 10mm to 50mm long to trapezoidal cracks with inside length of 50mm and outside length varying from 10mm to 50mm. As mentioned in Paragraph 2.3, it is assumed that the maximum K_I values is obtained at the location of x/t = 0.98. As shown in Fig. 4, it is observed by experiment that a trapezoidal crack grows along the outer surface without any change of the inside crack length, $2c_i$, until it became a rectangular shape. Therefore, only the maximum K_I value is used for the fatigue analysis of the trapezoidal crack. Based on the FEA results of the 67 cases, a new equation for the maximum stress intensity factor for a trapezoidal crack was proposed as follows:

$$K_I = M_T \sigma \sqrt{\pi c_m} \left(1 + \frac{A_P}{P} \frac{2t}{2R_m - t} \right) \left(F_1 \cdot F_2 + \sqrt{c_o / c_m}\, F_3 \cdot F_4 \right)$$

where

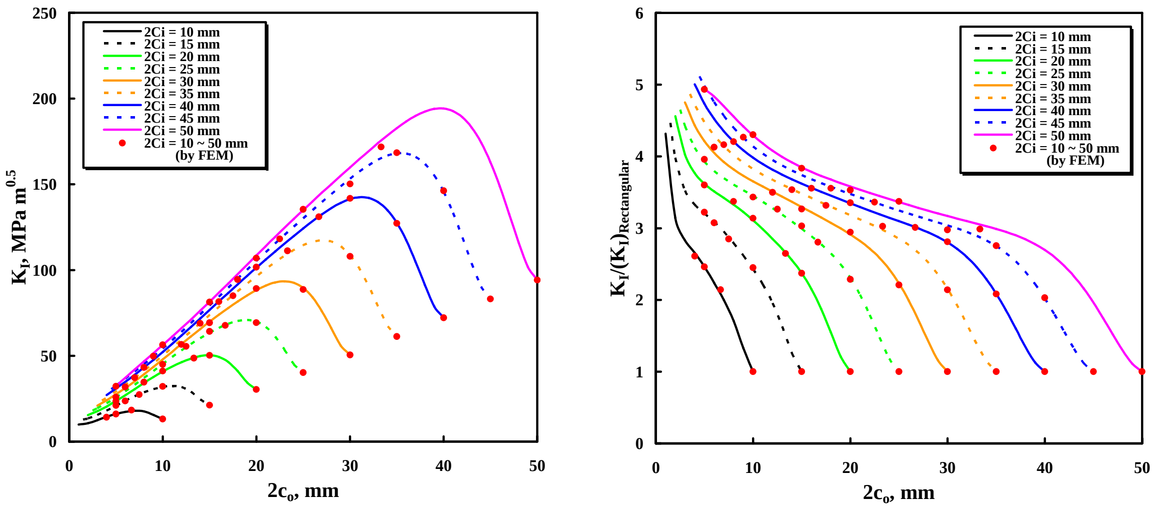
$$\begin{aligned} M_T &= 0.4895 + 0.551\lambda - 0.0093676\lambda^2 \\ &\quad + 0.51054\exp(-1.0859\lambda) \\ \lambda &= \left[12(1-\nu^2)\right]^{0.25} (c_m / \sqrt{R_m t}) \\ \sigma &= P_i R_m / t,\ c_m = (c_i + c_o)/2,\ R_m = (R_i + R_o)/2 \\ A_P &= \begin{cases} 0 & \text{without leakage} \\ P_i & \text{with leakage} \end{cases} \\ F_1 &= 3.7692 - 25.061 Q_1 + 1.0588 \times 10^2 Q_1^{\,2} - 2.4117 \times 10^2 Q_1^{\,3} \\ &\quad + 3.0362 \times 10^2 Q_1^{\,4} - 1.964 \times 10^2 Q_1^{\,5} + 50.679 \times 10 Q_1^{\,6} \end{aligned} \qquad (4)$$

$$
\begin{aligned}
F_2 &= 0.7603 - 0.055934Q_2 - 0.014315Q_2^{\,2} + 3.3526Q_2^{\,3} \\
&\quad - 3.002\times10^{-4}Q_2^{\,4} + 1.2943\times10^{-5}Q_2^{\,5} - 2.2153\times10^{-7}Q_2^{\,6} \\
F_3 &= 0.1393 + 2.9315Q_1 - 12.863Q_1^{\,2} + 43.046Q_1^{\,3} - 81.822Q_1^{\,4} \\
&\quad + 78.921Q_1^{\,5} - 30.229Q_1^{\,6} \\
F_4 &= 5.0208\times10^{-4} + 1.2805Q_2 - 0.2406Q_2^{\,2} + 0.026691Q_2^{\,3} \\
&\quad - 1.6948\times10^{-3}Q_2^{\,4} + 5.6805\times10^{-5}Q_2^{\,5} - 7.788\times10^{-7}Q_2^{\,6} \\
Q_1 &= c_o / c_i \\
Q_2 &= (c_i - c_o)/t
\end{aligned}
$$

$$\text{Assumption}: K_I = (K_I)_{\text{Rectangular}} \quad \text{when} \quad Q_1 = 1 \ \text{or} \ Q_2 = 0$$

$$\text{Applicability}: Q_1 \geq 0.1,\ Q_2 \leq 18,\ \text{and}\ 5 \leq R_m/t \leq 50$$

In the above equation, F_1~F_4, Q_1, and Q_2 are the correction coefficients for stress intensity factor, crack length ratio, and shape parameter, respectively. As shown in equation (1) or (2), the K_I value of a rectangular crack is a function of three parameters: crack length, mean radius of tube, and thickness. However, for a trapezoidal crack, the crack length ratio, Q_1, and the shape parameter, Q_2, should be taken into account additionally. In this study, the FEA results are bounded by Q_1 greater than 0.1, Q_2 less than 18, and the ratio of mean radius to thickness being in the range of 5 to 50. The equation (4) should be, therefore, applicable within these limitations. Fig. 11(a) shows the variation of K_I values as a function of outer crack length, $2c_o$ and (b) shows the K_I values of trapezoidal cracks which are normalized by the K_I values of rectangular cracks. In this figure, the solid and dotted lines stand for the K_I values calculated using equation (4) and the symbols for those obtained from the FEA. The value of K_I increases as the outer crack length, $2c_o$, grows with a constant $2c_i$, whereas it tends to decrease as the $2c_o$ approaches 2 c_i. The peak values of K_I for a trapezoidal crack, in average, are two times higher than K_I values obtained from a rectangular crack that equals $2c_i$ in length.



(a) $K_I - 2c_o$ curve

(b) normalized $K_I - 2c_o$ curve

Fig. 11 Variation of stress intensity factor as the crack size and shape change

4. **Conclusions**

In this paper, a study on fracture parameter was carried out as a first step to investigate the growth behavior of axial through-wall trapezoidal cracks under constant pressure loading, and the following conclusions were obtained.

- A modified bulging factor was developed newly by performing finite element analyses and optimizing the results. The bulging factor proposed by Erdogan was obtained based on the shell theory and the bulging effect is overestimated as the shell parameter increases, i.e., the crack length increases. But the newly suggested bulging factor can cover both short cracks and long cracks.
- By performing benchmark analyses, it was demonstrated that the maximum K_I value of a through-wall trapezoidal crack can be obtained using sufficiently fine crack-tip mesh elements parallel to the axial direction instead of crack-tip mesh elements normal to the crack front line.
- The K_I value at x/t = 0.98 can be selected as an approximate maximum K value of a trapezoidal crack. A new K_I solution for a trapezoidal crack was proposed in this paper. The maximum K_I value estimated using the new solution for a trapezoidal crack is higher than that of a rectangular crack with the flaw length equal to the inner flaw length of a trapezoidal crack. Since the maximum K_I value is obtained near the outer surface of a tube, it can be expected that the trapezoidal crack may grow along the outer surface without any change of the inside crack length, $2c_i$, until it became a rectangular shape. This trend coincides with the crack growth behavior observed in the experiment.

5. **Reference**

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