PAPER NAME

AIP_Strength and structural integrity ass essment.pdf

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WORD COUNT

2775 Words

CHARACTER COUNT

14503 Characters

PAGE COUNT

8 Pages

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886.3KB

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Strength and Structural Integrity Assessment of Fillet Weld Attachment Junction on Cylindrical Pressure Vessels

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Abstract. Welding is a method of joining components in manufacturing piping and pressure vessels. This method is used to joint cylindrical vessel and head, vessel and nozzle, and pad attachment for lifting lug. This paper aims to present results of finite element study of strength and structural integrity of fillet weld used for pad attachment of lifting lug to lift a horizontal cylindrical vessel. It is aware that the pad attachment and the cylindrical vessel are not integrally jointed. The joint of pad attachment and the cylinder is only along the peripheral of the rectangular pad. Therefore, there is inherent crack introduced in this structural connection, the crack length equals to the axial and circumferential length of the pad. Study of the effect of crack length on limit load has been performed separately in 2D for circumferential and axial direction. The crack length parameter was 200, 210, 220, 230, 240 and 250 mm. The results surprisingly show that crack length does not increase or decrease the limit load. It seems that strength of material approach does not work for dealing with cracked structures. Linear Elastic Fracture Mechanics (LEFM) analysis then was performed to study the effect of axial crack length on stress intensity factors of K_I and K_{II}. Results show that both K_I and K_{II} increased as the crack length increase.

INTRODUCTION

Fillet and butt welding are the common methods for joining pressure vessel components, such as joining of cylindrical vessel and head, pressure vessel and nozzle, and pad attachment for lifting lug. For welding connection, local stress can occur in the vicinity of welding due to internal pressure, thermal load, and other mechanical loads. In addition, crack-like defect is introduced in welding construction. For pad attachment by fillet weld, for example, surface crack exists in the interface of the pad and the shell wall to which the pad is attached. Clearly, the pad and the shell are not integrally jointed since the joint is only along the peripheral of a rectangular pad attachment. Such junctions are relatively easy to fabricate but can be difficult to access structurally. They are also common sources of failure.

Strength and structural integrity are the two common interesting behaviors of fillet weld. Strength assessment of welded joint is usually performed in limit load analysis and structural integrity (fracture) assessment, which is usually carried out based on stress intensity factors (K_I, K_{II} and K_{III}), crack tip opening displacement (CTOD) and *J*-Integral. Moskvichev [1] considered the effect of yield strength variation on fracture of double-V welded joint of steels 9MnSi5 and X10CrNiTi8-10. The mean value of yield strength was set as gradually change from one zone to another according to piecewise linear function. The ANSYS APDL macro was used and the fracture toughness via the energy criteria J-integral was evaluated. Roy et al., [2] used finite element method to analyze the stress behavior of fillet weld pad attachment on cylindrical shell using ANSYS shell element. The loading considered was internal pressure. Due to the use of shell element, weld condition on the peripheral of the pad was simulated by coupling the

Human-Dedicated Sustainable Product and Process Design: Materials, Resources, and Energy
AIP Conf. Proc. 1977, 030030-1–030030-8; https://doi.org/10.1063/1.5042950
Published by AIP Publishing. 978-0-7354-1687-1/$30.00

translational degree of freedom of coincide nodes. Gomez et al [3] reported to AISI about experimental program to investigate the effect of eccentric in-plane and out-of-plane loading on weld group. Twenty four welded cruciform test specimens were tested to direct tension and 60 specimens were tested to combine shear and bending. The experimental results showed that root notch does not affect significantly the strength of fillet. More comprehensive analysis of fillet weld behavior of pad attachment was reported by Gray et al [4]. The results indicated in two regimes of solution, limit load collapse and linier elastic fracture mechanics stress-intensification factors. However, the reported results are considered to be applied only for welding in the axial direction of a horizontal cylinder. The present paper reported the results of a study of strength and structural integrity of fillet weld typically used for pad attachment of lifting lug of horizontal cylindrical pressure vessel.

CURRENT DESIGN OF FILLET WELD

The theoretical basis for design procedure of fillet weld in manufacturing industry is simple and has small change in many years [5]. It is assumed that integrity of weld can be calculated as nominal shear stress working on the effective throat of fillet weld regardless the direction of loading path. A typical definition of effective fillet weld throat can be found in AWS B1.1 [5] as shown in Fig. 1. The throat size *t* is the height of equal side triangle that can be inscribed within the weld measured perpendicular to outer side. Additional root penetration should be taken into account (Fig. 1(b)). The effective cross-sectional area of fillet weld is then defined by the throat size multiplied by the effective length of the weld run. The effective length of straight fillet weld shall be the overall length of the full-size fillet, including boxing. No reduction in effective length shall be assumed in design calculations to allow for the start and stop crater of the weld. The effective length of curved fillet weld (for example, circumferential direction of a cylinder) shall be measured along the centerline of the effective throat [5].

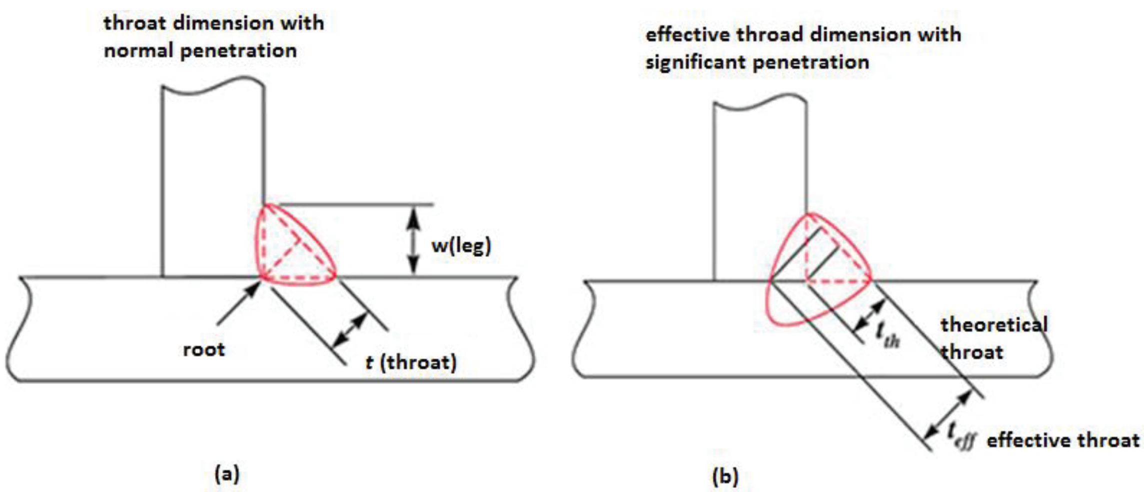


FIGURE 1. Definition of weld throat in fillet weld [5].

BS 5950 [6] approach concerns with the sizing of fillet weld for static loading, and the design criteria based on limit state condition. In this approach, nominal stress is obtained by dividing the vector sum of all shear load on the weld by the throat area, which is related to a limiting uniaxial design strength. A similar approach is adopted in BS 5400 [7] where shear stress is limited to the following value:

$$\tau = \frac{k(\sigma_Y + 455)}{2\sqrt{3}\gamma_m \gamma_{f3}} \tag{1}$$

where, σ_Y is least yield strength of material in the joint, the value of 455 MPa represents the strength of steel weld metal, k is a factor dependent on whether the welds are side or end fillet (0.9 and 1.4, respectively), and $\gamma_m\gamma_{f3}$ is the product of safety load related safety factors (approximately equal to 1.1).

A more complicated formula has also been given in BS 5400, whereby the applied forces are transformed to the throat plane and the resulting normal and shear stresses are then combined to get the following relationship:

$$\sqrt{\sigma^{2}+3\left(\tau_{11}^{2}+\tau_{12}^{2}\right)}=\frac{k\left(\sigma_{Y}+455\right)}{2\gamma_{m}\gamma_{f3}} \tag{2}$$

The main weakness of the foregoing formula is that they do not address the failure mechanism dominated either by crack or by local bending in the welds. It will be the case for fillet weld attachment junction of lifting lug consisting widely space welds with crack-like discontinuity in between.

FINITE ELEMENT MODELING

The fillet weld considered in this study was typical weld used for attachment of pad for lifting lug of horizontal cylindrical pressure vessel (Fig. 2). The radius and thickness of the cylinder was 1200 mm and 10 mm, respectively. The thickness of pad was 15 mm. Fillet weld of 10mm height was applied along the four sides of the rectangular pad. The effects of circumferential and axial length of the pad attachment (crack length) on load-displacement curve were evaluated for 200, 210, 220, 230, 240, and 250 mm.

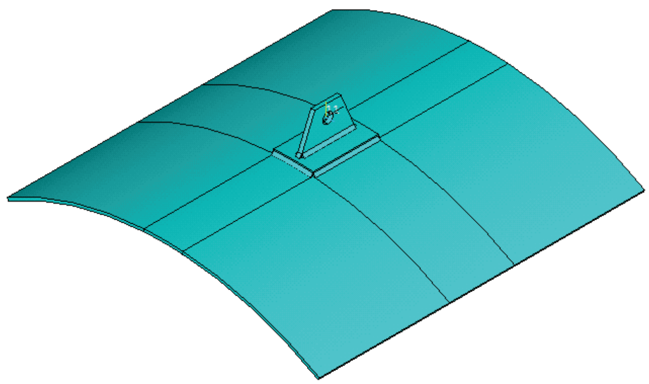
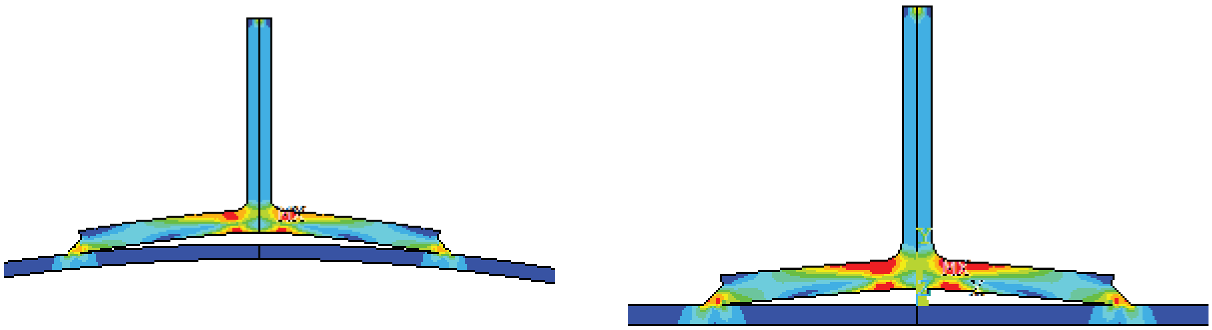


FIGURE 2. Lifting lug for horizontal cylindrical pressure vessel.

Circumferential and Axial Crack

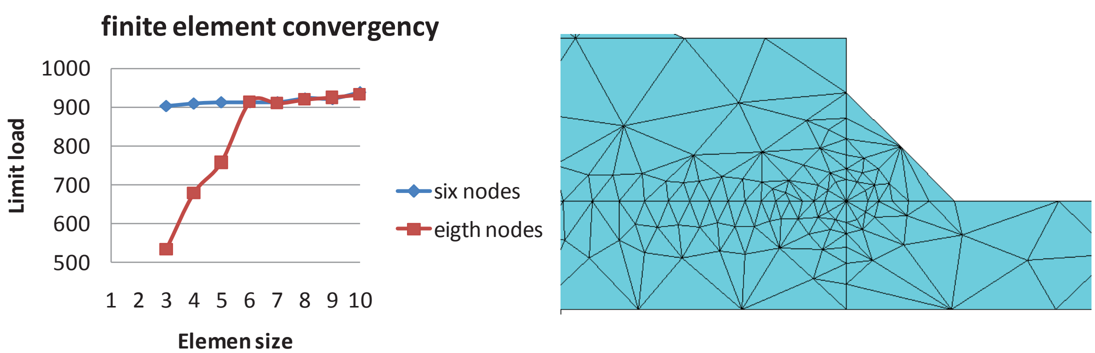
The pad attachment and the cylindrical vessels are note integrally jointed as the joint is only on its peripheral. Therefore, there is inherent crack introduced in pad attachment fillet weld. The length of the crack is equal to the length of pad attachment. In this study, the circumferential and axial crack was evaluated separately in two dimensional as shown in Fig. 3:



(a) (b)

FIGURE 3. The 2D modeling of inherent crack between pad attachment and cylindrical vessels, (a) circumferential crack, (b) axial crack.

The ANSYS PLANE 183 higher order element was used in this study. The element has two degrees of freedom for each node: translation in the x and y direction. Either eight nodes rectangular or six nodes triangular can be chosen, however convergence analysis of finite element (Fig. 4.a) shows that the six nodes element is more stable than the eight nodes element and has been chosen for this analysis.



(a) (b)

FIGURE 4.(a) Convergence analysis of FE shows that six nodes element is more stable than eight nodes element, (b) LEFM Finite Element Model using six-node triangular element.

Linear Elastic Fracture Mechanics

The approximate solution to the model junction considered in this study was adopted from Gray et al [4]. The finite element model was created using two-dimensional, six-nodes plane stress element (Fig. 4.b). Crack tip elements were used to model crack-tip region. Crack tip stress-intensity factors were calculated by displacement extrapolation method. The calculation of stress-intensity factors was included explicitly in the ANSYS post-processing stage [8]. Both K_{I} and K_{II} were calculated in this study.

Thickness of the vessel and the pad was 10 mm and 15 mm, respectively. Welding was modelled as equal leg triangle with 10 mm perpendicular side. The crack length represents the length of the axial or circumferential pad attachment was made various: 200, 210, 220, 230, 240, and 250 mm.

The material properties of parent material and the weld were assumed homogenous. Linear material properties (Young's modulus and Poisson's ratio were 207000 MPa and 0.3, respectively). For the purpose of limit load analysis, nonlinear material properties, i.e., yield stress was 227 MPa. Material was assumed to behave as elastic-perfectly-plastic. The model was constrained at the bottom of the shell wall. Vertical loading was applied at the lug.

The geometry configuration in the present study was characterized by a long crack intersecting finite neck of material of the weld, the load being applied at single central point. For such a configuration, the displacement solution for doubly built-in beam (DBB) assumed to be applied (Fig. 5). Gray et al., [4] extended the treatment to derive stress-intensity factors for a discontinuity between two unequal thicknesses and arrived to the following expression:

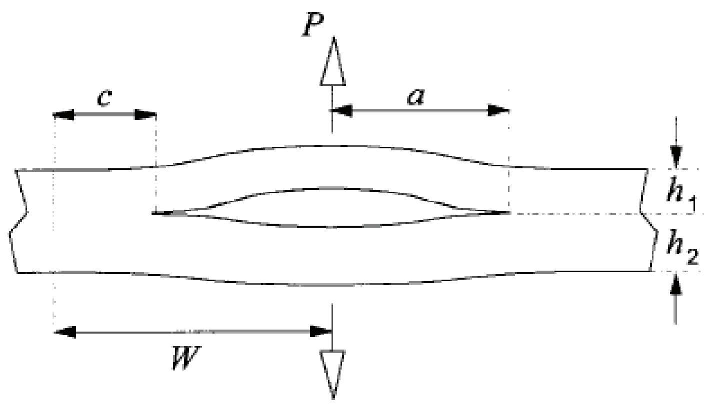


FIGURE 5. Double build-in beam (DBB) model of fillet weld attachment [4].

$$K_{I.} = \frac{\sqrt{6}}{8} P \left[\frac{4a^2\left(h_1^3 - h_2^3\right)}{\left(h_1 h_2\right)^3} + \frac{0.4}{h_1}\frac{E}{G} \right]^{1/2} \left\{ \frac{\tan\left[\pi a'/2W\right]}{\pi a'/2W} \right\}^{1/2} \tag{3}$$

where, $W = L + b + \left(2 - \frac{h_1}{h_2}\right) h_1$ and $a' = L + b$

Limit State

Gray et al [4] used the DBB model to derive an expression for limit load. The pad was treated as a built-in beam with yield strength of σ_Y, in-plane height of h_1, and half length of a. They arrive at the following formula for limit load P_L for the rectangular cross-section of the pad:

$$P_L = \frac{\sigma_Y \left(h_1\right)^2}{a} \tag{4}$$

As in the case of DBB fracture model, the effect of finite welds shape and the influence of central stiffening of the loading lug would results in significant departures from the simple DBB.

RESULTS AND DISCUSSION

Figure 6 shows typical stress contour plot for the limit state condition, plotted for 250 mm crack length. It can be seen that the highest stress occurs in the fillet weld, both for axial crack and longitudinal crack.

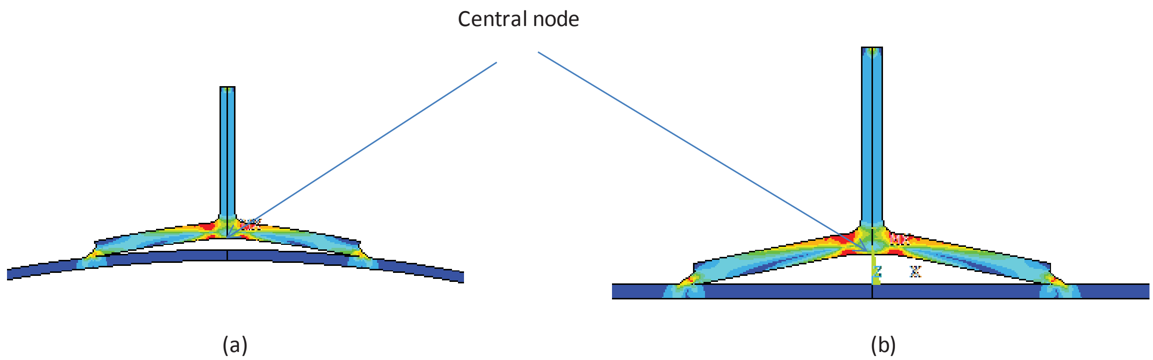


FIGURE 6. Stress contour plot for limit state condition (a) circumferential crack, (b) axial crack.

Visual insight into Fig. 6 clearly shows that vertical displacement at the limit condition is higher for axial crack than circumferential crack. Figure 7 shows the maximum vertical displacement normalized by pad thickness (h_1 = 15 mm) to obtain a non-dimensional curve. The displacement was evaluated for central node of the pad in vertical upward direction. It can be seen from Fig. 7 that maximum displacement for axial crack is much greater than for circumferential crack. It can be observed from Fig. 7 that crack length influences the maximum displacement, the bigger the crack length, the bigger the maximum displacement.

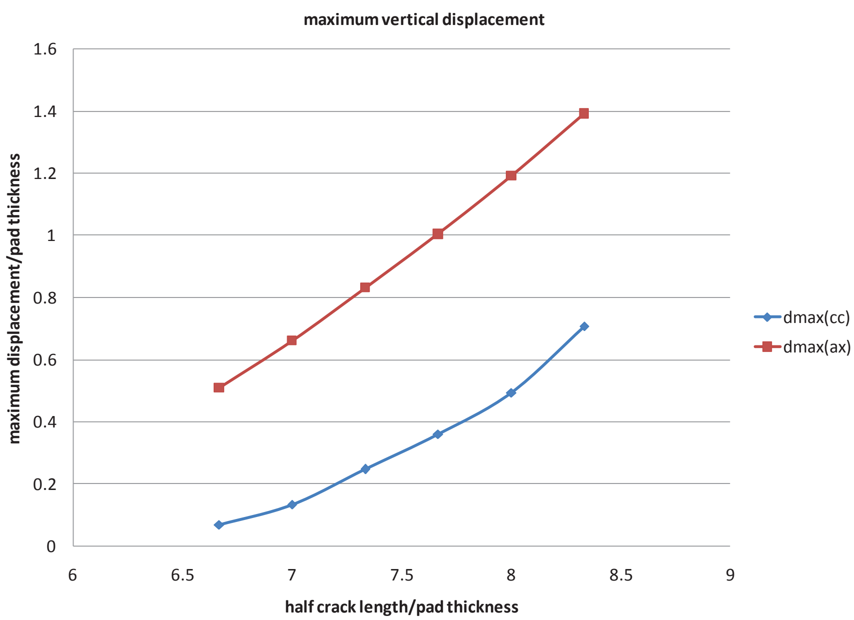


FIGURE 7. Load displacement curve for various circumferential and axial crack lengths.

It is surprising that limit load from finite element results were not influenced by crack length both for circumferential and axial crack. It seems that the strength of material approach is not appropriate to deal with cracked structures. However, theoretical approach shows that limit load decreases significantly as the crack becomes longer as shown in Fig. 8. Theoretical limit loads in Fig. 8 were calculated using Eq. (4). There was significant difference of limit loads between finite element and theoretical results. it is believed results from the effect of finite width of welding and stiffening effect of loading lug.

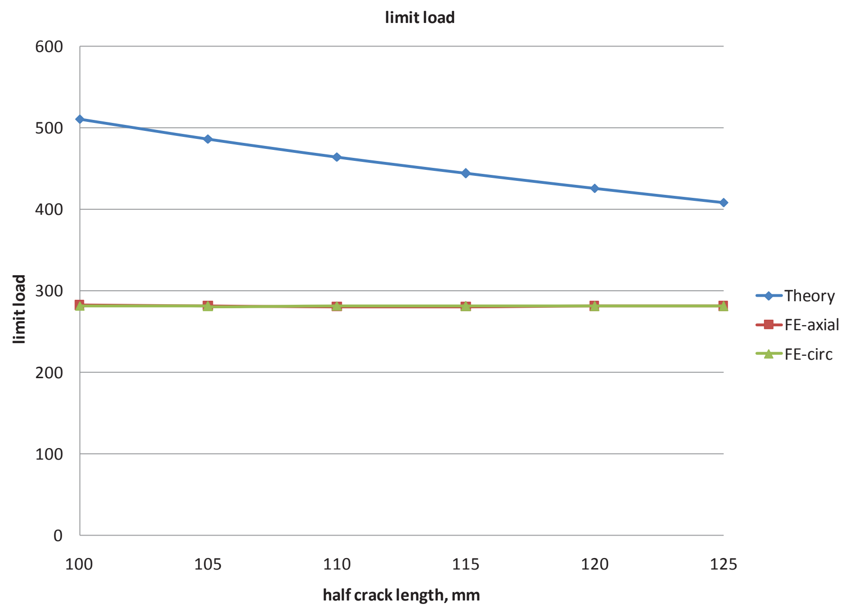


FIGURE 8. Limit load for axial and circumferential crack and their comparison with theoretical results.

Stress-Intensification Factors K_I and K_{II} for axial crack were evaluated for various crack lengths (Fig. 9). However, the authors were not able to obtain the stress-intensification factor for circumferential crack. In this study, the thickness of shell and pad attachment was kept constant, 10 mm and 15 mm, respectively. The axial crack lengths were 200, 210, 220, 230, 240, and 250 mm. Figure 9 shows that mode I (opening) is bigger than mode II (in-plane shear) stress-intensity factors. However, both K_I and K_{II} increase as the crack length becomes larger. Comparison of K_I between the finite element results and those calculated using the approach of double built-in beam (DBB) shows that finite element gives much bigger values.

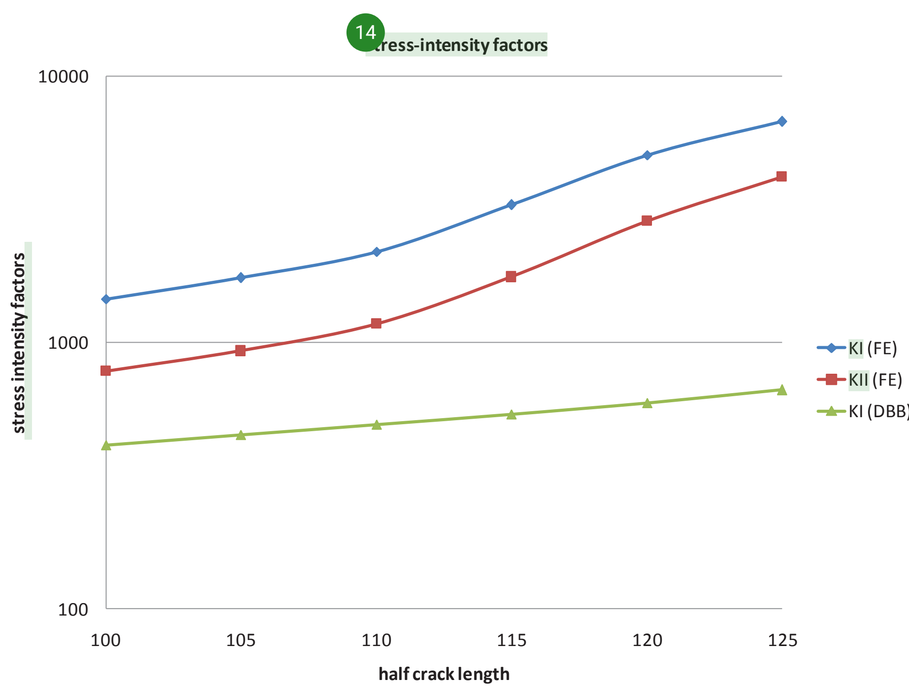


FIGURE 9. Stress-intensification factors, crack in axial direct ion.

CONCLUSION

The study of the effect of crack length introduced in the pad attachment on cylindrical vessel has been carried for both in circumferential and axial directions. The results revealed that crack length does not influence the limit load. It indicates that the strength of material approach does not appropriate to deal with structures with crack. It also observed that vertical upward displacement due to vertical load is bigger if axial crack is present compared to longitudinal crack of the same length. Comparing the results obtained from finite element and theoretical approach, show that limit load obtained from finite element analysis is lower than those calculated using the theoretical (DBB) approach. Meanwhile, the stress intensity factor K_I from finite element result is much higher than those calculated using the theoretical approach.

ACKNOWLEDGMENT

The authors are grateful to the Research Institute (LPPM), Universitas Lampung for funding this research under the scheme of Graduate Research FY 2017.

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ACKNOWLEDGMENTThe authors
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