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Interaction Assessment of Stress Intensity Factors of Surface Cracks on Thick Cylinders under Tension Force and Bending Moment

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ABSTRACT

From an engineering perspective, hollow cylinders have various applications in the industry due to their strength, versatility, and geometric properties, making them vital for various applications in diverse industries. Therefore, it could be seen in many aspects such as fluid conveyance, manufacturing and fabrication, rotating machinery, structural components, storage, and pressure vessels. As it is well-known fracture is the most dominant type of failure in cylinders that is caused by defects or flaws. With time, these cracks (flaws) may extend and lead to a tragic failure, posing significant risks to both the nearby environment and humans. Moreover, crack cooperation which is known as (crack interaction) represents a chief apprehension, where cooperation or interaction may accelerate the crack growth and cause unpredictable failure. In this work, a wide variety of crack configurations were examined to quantify the interaction of double-interacting surface cracks located on a thick cylinder numerically via ANSYS software. The Stress Intensity Factor (SIFs) has been utilized as a driving force to describe the crack interaction. The results found that crack interaction influenced both cracks by the same rate, and SIFs distributed along the crack front by the same style as that of a single crack. Also, an inversely proportional relationship has been found between the crack interaction and the separation distance between the cracks. It is possible to conclude that the crack interaction of double interacting cracks exhibited a shielding effect, where SIFs for the case of double cracks were less than those of single crack.

1. Introduction

Because of their structural efficiency and adaptability, hollow cylinders serve a principal part in a widespread assortment of applications in industry. Their significance is seen in a variety of industries, such as aerospace, automotive, energy, and manufacturing. Because of its capacity to endure internal and external stresses, cylindrical structures are commonly utilized as pressure vessels, pipelines,

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storage tanks, and structural components. Despite its strong construction, cylinder failure remains a serious problem in engineering practice. Surface cracks are a major contributor to cylinder failure. Surface cracks can form and spread under the influence of mechanical forces, resulting in severe damage. These cracks behave as stress concentration points, compromising the cylinder's structural integrity. The impacts of such failures are frequently serious, involving dangers to human safety, environmental damage, and large economic losses [1, 2]. Crack interaction is gaining popularity because of its ability to promote crack propagation and create unexpected failure types [3]. In recent years, significant research efforts have been directed toward understanding fracture behavior and its impact on the structural integrity of hollow cylinders. While single-crack investigations have produced useful information, the multiple cracks interaction is now recognized as an imperative topic of research. The interaction of cracks nearby can severely modify the stress distribution, crack propagation rates, and overall failure behavior of the cylinder.

Previously, Isida and Igawa [4] investigated the correlations between SIFs and crack numbers. This work offered valid SIF formulas for collinear and parallel cracks under a range of stress circumstances. Also, Elya [5] implemented finite elements to investigate the interaction of several cracks with specific loading circumstances. The interaction factor and Stress Intensity Factor (SIFs) were explored for various crack geometry characteristics and spacing intervals beneath multiple kinds of loading in this work. The Association involving a double and single crack was also explored. The SIF results were standardized to calculate the factor of interaction and identify the link between one and two cracks. In addition, the nature of the interaction between several surface cracks is investigated [6]. It evaluates the stress intensity factor (SIF) of cooperated semi-elliptical surface cracks employing the finite element technique and the finite element alternating method. Research findings showed that the variation in averaged SIF across a crack front produced by the coalescence of two cracks may be approximated based on the difference in area size. Furthermore, independent of the load scenario or relative crack size, the maximal interaction may be predicted by simply adding the area sizes of two cracks. Moreover, the elastic SIFs and the elastic-plastic J-integral of nearby in-plane surface cracks in a plate are evaluated by (Kim and Huh 2010) to examine the impact of crack interaction. The influence of geometrical characteristics, relative spacing between two flaws, and crack morphology on fracture mechanics measurement parameters were thoroughly examined. The findings demonstrated that current guidelines on crack combination rules are insufficient and give directions for further study.

The interaction of two unequal parallel edge and center fractures in a finite-width plate under distant tensile pressure was studied using (FEM) [7]. The study concentrated on calculating and displaying the distribution of Stress Intensity Factors (SIFs) along the fracture front, which acted as a driving factor for crack propagation. The presence of crack interaction caused stress fields around the crack tips to relax, resulting in the shielding of the SIFs at both crack tips. The larger crack's impact on the shorter crack expanded as it developed, and decreasing the separation distance between the cracks improved their interaction. The interaction between the cracks was low when the longer crack's length was 2.5 times that of the shorter fracture, and the shorter crack was deemed inactive with limited interaction.

Also, Jiang [8] investigated the problem of two and three interacting identical cracks in a finite plate, the two and three cracks being treated as core cracks as well as edge cracks. The FEM method was used in this investigation. The SIFs are shown to diminish in the presence of many cracks due to increased plate flexibility. This is accurate, except that when the distance between the cracks exceeds three times the crack length, the problem is evaluated for two independent cracks with no interaction. Mode I SIFs were examined [9] for single and multiple numbers of axial surface cracks on a pressured thick hollow cylinder. The FEM was used for investigation. Furthermore, this study looked at a cylinder with an exterior-to-internal diameter ratio of 2 and N fractures. Where N = 1, 2, 4, 8, 16, 32 fractures, with aspect ratios ranging from 1 to 4 and relative depths ranging from 0.05 to 0.5. The goal was to correlate the FE findings for single and multiple crack examples, which were then utilized to construct empirical equations for mode I SIFs at the crack front's deepest and surface sites. Based on the findings, closed-form equations for quantifying the effects of fracture shape and depth on SIFs for single and arrays of comparable cracks at the inner surface of a thick hollow cylinder have been developed.

In addition, Guozhong *et al.,* [10] examined the interaction of longitudinal exterior and interior cracks in a cylinder. The hybrid boundary element approach was used to carry out numerical analysis and calculate the SIFs over a wide variety of fracture and cylinder geometries. Internal cracks indicated greater SIFs than exterior cracks due to internal pressure loading, according to the results. Furthermore, data showed that the deeper the fractures, the more important they are, which may lead to crack propagation, with all three forms of interaction shown to be identical to what was discovered [11] for internal and exterior cracks in a plate. In terms of the influence of vibrational loading on a cracked component [12-15] have considered this problem. Previously, Zhang [16, 17] used Crack-Tip Opening Displacement (CTOD) to perform 3-D FEA on a circumferentially cracked pipe containing a semi-elliptical surface crack and an elliptical embedding crack. A 3-D elastic-plastic analysis of the interaction behaviors of two collinear cracks was performed. According to the findings of this study, tension combined with high levels of internal pressure can produce the most severe fracture reaction for the various loading circumstances studied. Furthermore, a new strain based CTOD estimate approach for analyzing the fracture behavior of a cracked pipe with two interacting collinear cracks is suggested.

The effect of crack interaction on the Limit Load (LL) was calculated using FEA [18]. Two identical circumferential surface cracks on the interior and exterior surfaces of a pipe exposed to homogeneous tensile stress. The key issue was that the limit load would fluctuate based on the arrangement of the crack and pipe. The results showed that the intensity of contact is determined by the distance between the cracks as well as the geometrical features of the fracture and the cylinder. Furthermore, LL was discovered to be like the combined crack if the cracks were placed in the same plane, regardless of the distance S. Based on the study's findings and analysis, a criterion for the combination rule for the limit load was developed. Furthermore, understanding the interaction of double parallel surface cracks in a hollow cylinder proves essential for assuring the safety and dependability of industrial applications. By having a solid knowledge of this phenomenon, effective techniques for avoiding, minimizing, and governing crack-related failures in essential cylindrical structures may be developed. This study aims to utilize the SIFs as a key to investigate the crack interaction of double parallel surface cracks. A wide variety of crack configurations have been covered in the analysis in terms of crack length, and depth, which were solved using Ansys software. Similarly, different horizontal offsetting distances were employed based on the API 579-1 standard [19]. Also, Ayhan [20] introduced enhanced finite elements modeling of three-dimensional (3D) fatigue fracture growth in structures. Similarly, the Newman-Raju equations for mode I stress intensity factors (SIFs) in longitudinally cracked cylinders are only one example of the simplified solutions for SIFs that have already been published and are used in [21, 22]. The researchers calculate the SIFs generated at the susceptible crotch corner crack by modifying these calculations. This method provides a useful and effective substitute for more intricate computations for this difficult geometry.

It should be noted that the results obtained for a single crack previously [23-27] were utilized to quantify the double crack interaction via an interaction factor. Several other research works can be found elsewhere [28-36], and their interactions are sometimes hard to find [37-45]. Therefore, this paper presents the study on the interaction assessment of surface cracks on the thick cylinders under both tension force and bending moment.

2. Methodology

In this work, a thick hollow cylinder is considered, and it is presumed to have double external surface cracks which are then subjected to mode I load (tension force and bending moment). It is assumed that the external diameter is 250 mm with a wall thickness of 25 mm which meets the criterion of a thick cylinder. The schematic diagram of the crack is revealed in Figure 1. The crack aspect ratio, a/c considered are 0.4, 0.6, 0.8, 1.0, and 1.2. While, the second parameter is relative crack depth, a/t equal to 0.2, 0.5, and 0.8. Besides, the two cracks are separated by a horizontal varying distance between the cracks, s, which has been used in the normalized form, s/L, s/L= 0.004, 0.008, 0.016, and 0.032, where L=750 mm. ANSYS Workbench software is used to construct a finite element model and the cracks take the semi-elliptical shapes as in Figure 2(a) and Figure 2(b) shows the finite element model for the whole cylinder with the enlarged area of single and parallel cracks in the respective Figures 2(c) and 2(d). One end of the cylinder is fixed in all degrees of freedom and at the other end mode I force/moment is applied remotely.

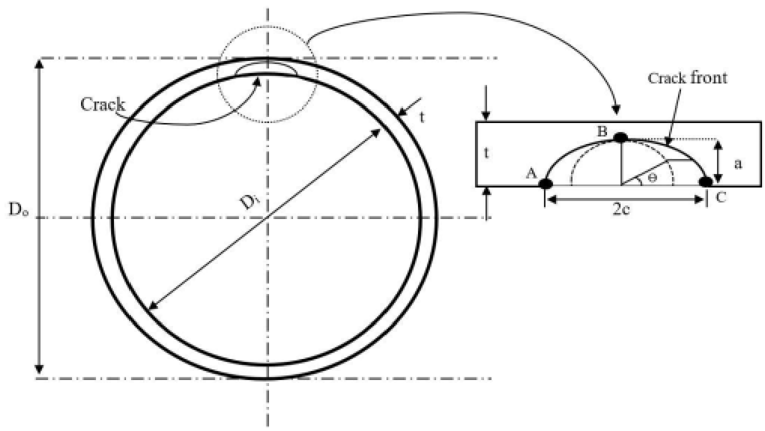
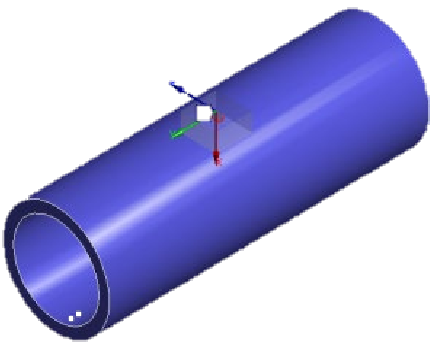
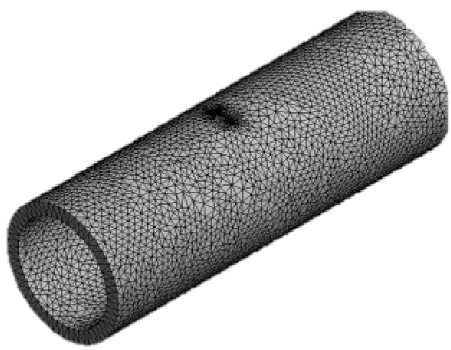


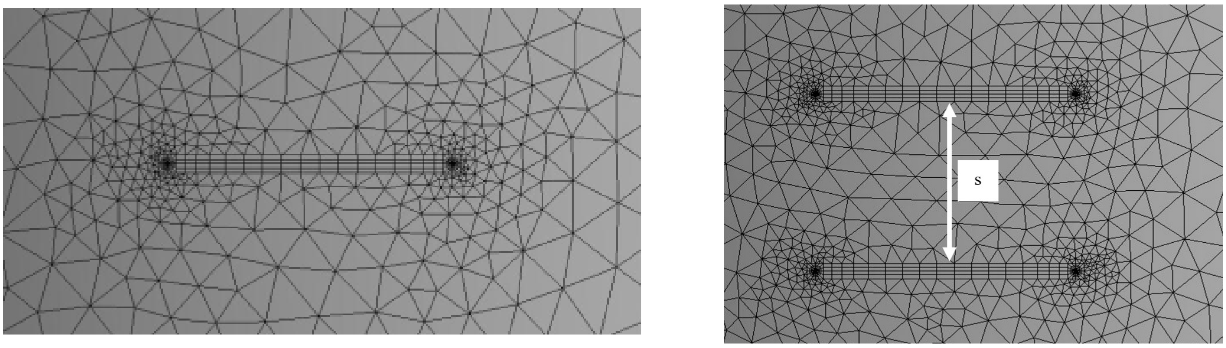
Fig. 1. Schematic diagram of surface crack



(a)



(b)



(c) (d)

Fig. 2. Hollow cylinder with single crack (a) semi-elliptical crack setting (b) overall cylinder mesh (c) close to crack region and (d) parallel cracks

In ANSYS software, the stress intensity factor is based on the interaction integral method, and they are normalized according to Eq. (1) and Eq. (2) for tension force and bending moment [23]:

$$F_t = \frac{K_{cal,t}}{\sigma_t \sqrt{\pi a/Q}} \tag{1}$$

$$F_{Ben} = \frac{K_{cal,b}}{\sigma_b \sqrt{\pi a/Q}} \tag{2}$$

where F_t is the normalized SIFs under remote tension loading, K_{cal}, t is the calculated SIFs under tension (the extracted value from the 6th contour), σ_t is the axial stress, where $\sigma_t = P/\pi\ (R^2_o - R^2_i)$, P is the remote applied force, R_o and R_i represent the outer and inner radius of the cylinder, respectively. On the other hand, a is the crack depth, and Q is the shape factor. While F_{Ben} is the normalized mode I SIFs under remote bending loading, K_{cal}, b is the calculated SIFs under bending (extracted from Ansys), σ_b is the maximum bending stress as in Eq. (3):

$$\sigma_b = \frac{M}{[\pi(R_o^4 - R_i^4)/2D_o]} \tag{3}$$

The interaction factor Ψ is defined as the ratio of the SIFs for the case of two cracks to the SIFs of a single crack; therefore, the following expression is used to determine the interaction factor (Murakami and Nemat-Nasser 1982):

$$\Psi = \frac{F_{two\ cracks}}{F_{single\ crack}} \tag{4}$$

where $F_{two\ cracks}$ represents the normalized SIFs for the case of two cracks for any mode and type of loading, and F_{single} crack is the normalized SIFs for the case of single crack. Moreover, the Ψ for tension loading, for example, is the ratio of the normalized SIFs for the case of two cracks concerning normalized SIFs for the single crack case in tension loading also. Thus, the following formula is utilized for this purpose:

$$\Psi > 1 + \Psi_c \tag{5}$$

$$\Psi < 1 - \Psi_c \quad (6)$$

where Ψ_c is the critical or the tolerance value, which was set to 5%. Based on Eq. (4), it should be no interaction when Ψ =1, therefore, Eq. (5) represents the amplification effect, while the shielding effect is represented by Eq. (6). Moreover, the values that lie in between the two limits are treated as isolated cracks. It should be noted that the same tolerance range or critical value Ψ_c has been considered by [17]. Before any further work, it is essential to verify the validity of this finite element model. Then the stress intensity factor of the present model is compared with the existing results as in Table 1.

Table 1
Comparison of SIFs for a single circumferential crack in a thick cylinder under tension

a/c =0.6	Deepest point			Surface point		
	a/t					
	0.2	0.5	0.8	0.2	0.5	0.8
Reference [23]	1.101	1.178	1.285	0.933	1.071	1.285
Present	1.074	1.160	1.243	0.911	1.027	1.243
Error (%)	2.45	1.52	3.26	2.35	4.10	3.26
a/c =0.8	Deepest point			Surface point		
	a/t					
	0.2	0.5	0.8	0.2	0.5	0.8
Reference [23]	1.058	1.103	1.157	1.053	1.156	1.333
Present	1.048	1.114	1.161	1.034	1.161	1.366
Error (%)	0.94	-0.99	0.34	1.80	-0.43	-2.47

3. Results
3.1 Crack Interaction under Tension Force

The examined crack orientation was the parallel cracks, shown in Figure 2 (d), where two parallel cracks were placed on the external surface of the thick cylinder, and then analyzed under tension and, bending loading to calculate the SIFs as well as determine the interaction factor, Ψ. The examined two parallel cracks were always similar, which means both cracks are taking the same geometry, depending on the examined crack geometry. It should be noted, in the subsequent figures, the normalized SIFs of the single crack are named $F_{\_SINGLE}$, while the normalized SIFs in the case of two cracks, F_2, are named according to the normalized separation distance between the cracks s/L. Likewise, F2 – s/L=0.004 represents the normalized SIFs for the case of two cracks when the separation distance ratio between the two cracks s/L is equal to 0.004, and so on for the other remaining distributions.

The analysis includes aspect ratios, a/c equal to 0.4, 0.6, 0.8, 1.0, and 1.2, for each a/c, three relative crack depths, a/t equal to 0.2, 0.5, and 0.8, were examined under tension, and bending, respectively. Each case of crack geometrical parameters was tested for four values of s/L, these are, s/L= 0.004, 0.008, 0.016, and 0.032. It should be mentioned that the distribution of the normalized SIFs for the case of parallel cracks configuration was found to be similar at both cracks; therefore, the distribution of one crack (one from the two interacting cracks) shown in Figure 3, is presented in this study. Also, due to the same trend shown by the SIFs distribution for the considered aspect ratio range, results for only a/c=0.4 were presented. Furthermore, it should be remarked that each presented figure shows the distribution of the normalized SIFs for different crack geometrical parameters as a function of the normalized crack front position, 2Θ/π, where this normalized term describes the location on the crack front. The interaction factor, Ψ, for each examined case, is explained in detail by a separate table, which means for each normalized SIFs figure, there is a subsequent table explaining in detail the interaction factors for each considered case based on the crack geometrical parameters as well as the separation distance between the cracks.

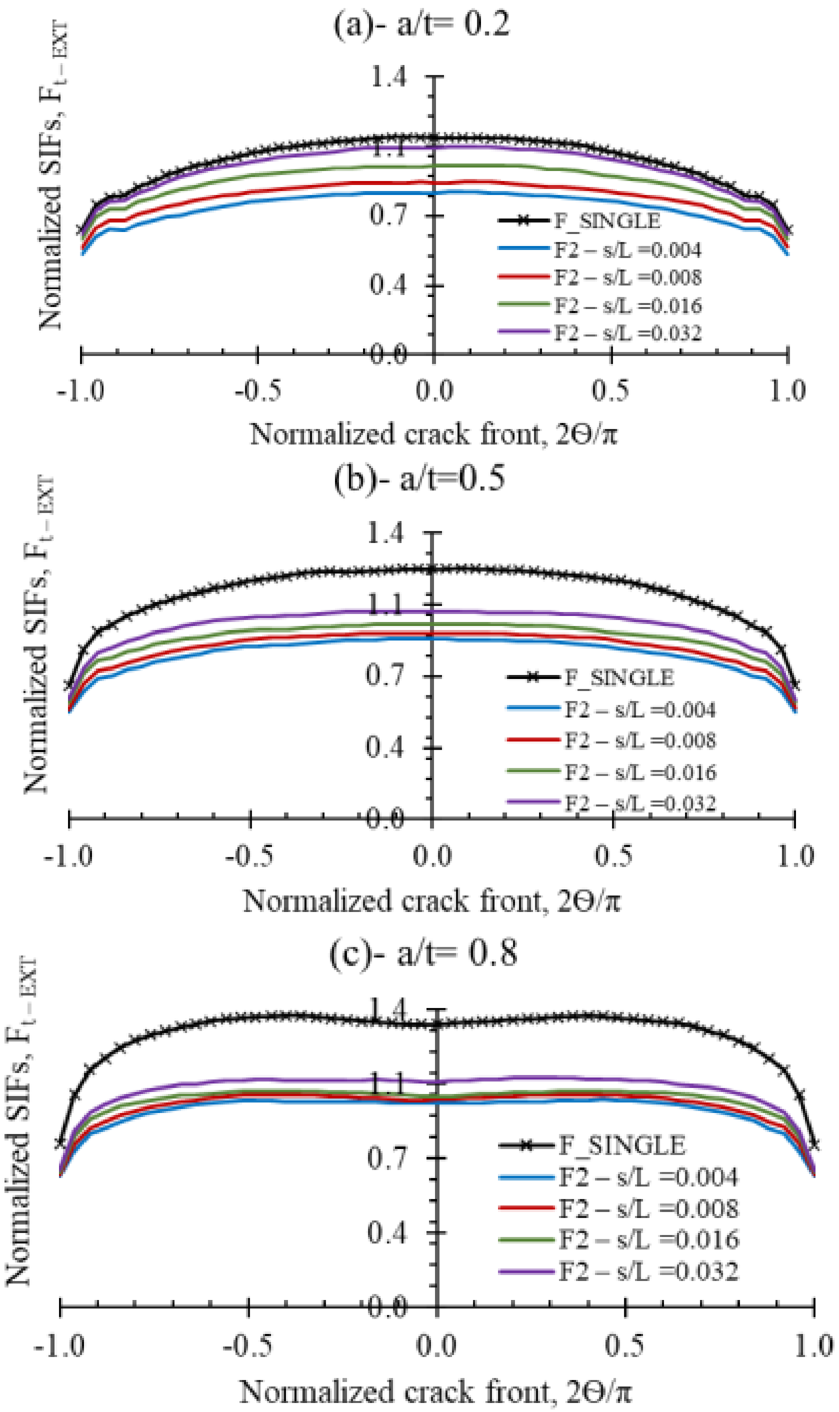


Fig. 3. The normalized SIFs for external parallel cracks under tension, for a thick cylinder, a/c=0.4 (a) a/t=0.2, (b) a/t =0.5 and (c) a/t=0.8

It should be noted that Figure 3 presents the distribution of the normalized SIFs for external parallel cracks configuration under tension loading, which have shown a noticeable shielding effect for all examined configurations and separation distances. While Table 2 presented the interaction factor, Ψ, for the same considered cases in Figure 3, at three points, A, B, and C.

Figure 3 shows the distribution of the normalized SIFs for external parallel cracks configuration, F_{t-EXT}, under tension loading, where a/c =0.4 for a/t= 0.2, 0.5, and 0.8, respectively. It is obvious that F_{t-EXT} has been distributed symmetrically along the crack front despite the existence of crack interaction. Also, a/t has a noticeable influence on the F_{t-EXT} trend, where the highest F_{t-EXT} is attained for the maximum a/t value and vice versa. Besides, the increase in a/c was accompanied by a decrease in F_{t-EXT} for all a/t examined ratios.

It can be noticed that F_{t-EXT} distribution followed an exactly similar trend to that of a single crack for all the examined separation distance ratios, s/L. It can be inferred from graphs that as the distance between the cracks increases, s/L ratio increases, the F_{t-EXT} approaches to the F_SINGLE value, which means the crack interaction has high influence when the cracks were placed close to each other, while as the separation distance between the cracks increases, each crack found to be isolated from the other, this what has been interpreted by the similar value of single crack to that of double cracks, where no influence for the interaction. Therefore, the minimum SIFs attained at F2 – s/L=0.004, and the maximum SIFs attained at F2 – s/L=0.032, where both values are considered minimum and maximum concerning the normalized SIFs for the single crack case. Generally, in terms of crack interaction influence, an obvious shielding effect was remarked on due to the decrease in the F_{t-EXT}, where F2 for all the examined s/L ratios was found to be less than $F_{\_SINGLE}$.

Table 2
Interaction factor for parallel external cracks on thick cylinder under tension when a/c= 0.4

Point	a/t = 0.2			
	s/L=0.004	s/L=0.004	s/L=0.004	s/L=0.004
A	0.806	0.863	0.922	0.967
B	0.745	0.793	0.869	0.954
C	0.803	0.856	0.921	0.965
Point	a/t = 0.5			
	s/L=0.004	s/L=0.004	s/L=0.004	s/L=0.004
A	0.806	0.863	0.922	0.967
B	0.745	0.793	0.869	0.954
C	0.803	0.856	0.921	0.965
Point	a/t = 0.8			
	s/L=0.004	s/L=0.004	s/L=0.004	s/L=0.004
A	0.806	0.863	0.922	0.967
B	0.745	0.793	0.869	0.954
C	0.803	0.856	0.921	0.965

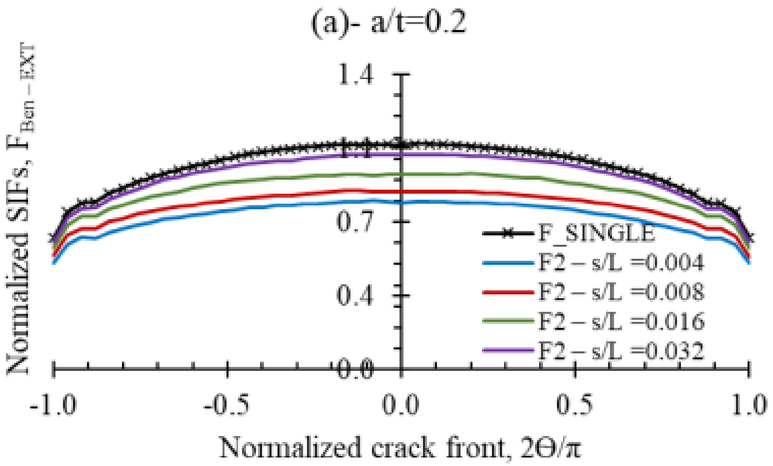
In addition, Table 2 shows the interaction factor, Ψ, for the case considered in Figure 3, for three points on the crack front A, B, and C, where A and C are the surface points of the crack front when 2ϴ/π=1, -1, respectively, and B denotes to the deepest point on the crack front when 2ϴ/π=0. It should be noted that Ψ showed that both A and C experienced the same interaction level, which is a reduction effect. Besides, under tension loading the maximum Ψ has been seen at the deepest point on the crack front, B. Furthermore, the results depicted those deep cracks, which the cracks with high a/t, require a large separation distance to be deemed free from any interaction effect, unlike cracks with small a/t, which can be isolated within small ranges of s/L. Thus, in Table 2, when s/L=0.032, based on Eq. (6), it can be identified that for a/t= 0.2, Ψ, at A, B, and C points indicating that F_{t-EXT} found to be similar to that of $F_{\_SINGLE}$, which means that the interaction influence between the cracks was diminished, and each crack is isolated from the other crack.

On the other hand, for deep cracks, when a/t=0.5, where F_{t-EXT} approaches about 89% of $F_{\_SINGLE}$ at points A and C, and 82% of $F_{\_SINGLE}$ at point B, which means that the interaction influences are still notable. A similar effect was noticed for a/t higher than 0.5, when a/t=0.8, but with a slightly bigger reduction influence, where at points A and C, F_{t-EXT} was 84% of $F_{\_SINGLE}$ and 79% at point B. Here again, an emphasis on the fact that deep cracks required large separation distances to be free from any other crack effect, unlike shallow cracks. Also, another indicator, is that cracks with a high a/t ratio show a significant interaction effect compared to cracks with a low a/t ratio. The overall distribution of the F_{t-EXT} along the crack front followed three curve shapes depending on the crack aspect ratio, a/c, they are convex, concave, and an approximate straight line.

Furthermore, for slender cracks, which are cracks with low a/c, a/ c < 0.65, the F_{t-EXT} trend follows a convex curve, where the maximum value is attained at the deepest point of the crack, point B. While, for transverse cracks, the trend of F_{t-EXT} along the crack front follows a concave curved shape, which can be seen for a/c ≥ 0.75, where the maximum value is reached at the surface points. While for 0.65 ≤ a/c ≥ 0.75, the orientation of F_{t-EXT} follows an approximate straight line. In fact, a transition phenomenon occurs, where [24] has shown that for each relative depth of the crack, there is a crack aspect ratio for which the location of the maximum SIFs shifts from the deepest point on the crack front to the surface points A and C (the points of intersection between the crack front and the surface, 2ϴ/π = 1, -1).

3.2 Crack Interactions under Bending Moment

In Figure 4 the distribution of the normalized SIFs for parallel external cracks under bending loading, $F_{Ben-EXT}$ is shown, where the aspect ratio a/c= 0.4, for a/t=0.2, 0.5, and 0.8. Generally, the $F_{Ben-EXT}$ trend was found to be like that of parallel cracks under tension loading Figure 3, with a slightly lower magnitude. Also, the change in a/t ratio produces the same effect, which was shown by the same crack configuration underneath tension loading, where cracks with a high value of a/t, showed higher $F_{Ben-EXT}$ compared to cracks with less a/t. It can be inferred from the figure that both surfaces points A and C, bear an equal value of $F_{Ben-EXT}$, while the highest value is located at the deepest point B, on the crack front except at a/t=0.8. Table 3 illustrates the interaction factor Ψ for the two parallel cracks configuration under bending loading, when a/c=0.4, for a/t=0.2, 0.5, and 0.8. The interaction factor results revealed that point B experienced a severe interaction effect compared to A and C points; this effect was directly proportional to the increment in crack depth, where high crack depth showed a high interaction effect and vice versa.



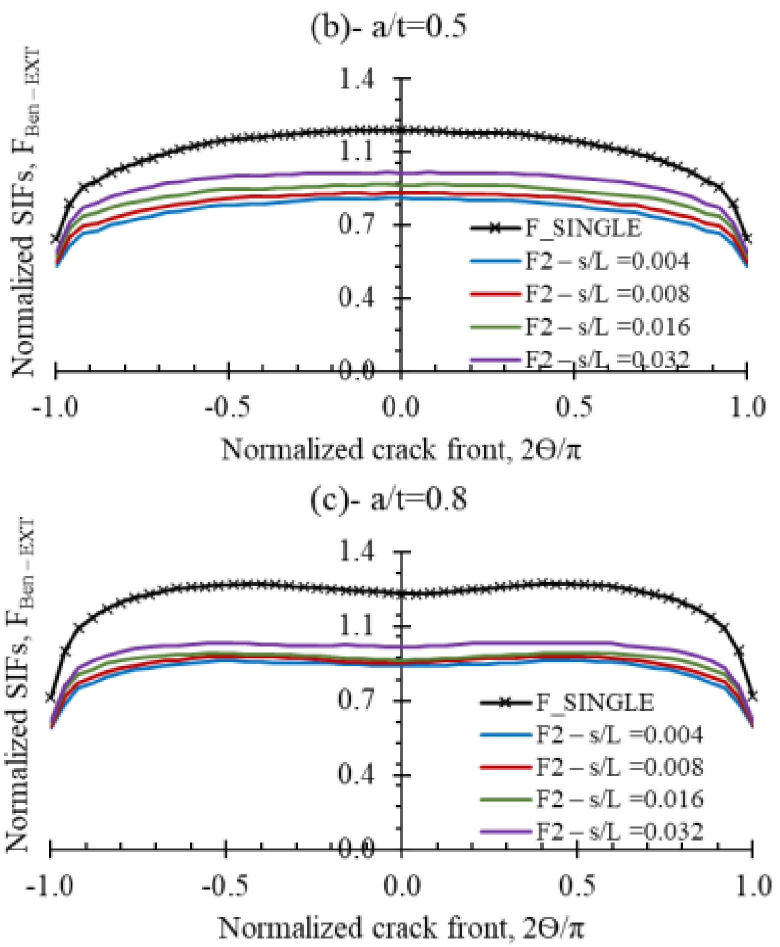


Fig. 4. The normalized SIFs for external parallel cracks under bending, for thick cylinder, a/c=0.4 (a) a/t=0.2 (b) a/t =0.5 and (c) a/t=0.8

Table 3
Interaction factor for parallel external cracks on thick cylinder under bending when a/c= 0.4

Point	a/t = 0.2			
	s/L=0.004	s/L=0.004	s/L=0.004	s/L=0.004
A	0.804	0.856	0.920	0.965
B	0.743	0.791	0.867	0.954
C	0.806	0.863	0.924	0.968
Point	a/t = 0.5			
	s/L=0.004	s/L=0.004	s/L=0.004	s/L=0.004
A	0.800	0.828	0.867	0.895
B	0.719	0.740	0.774	0.825
C	0.800	0.826	0.868	0.895
Point	a/t = 0.8			
	s/L=0.004	s/L=0.004	s/L=0.004	s/L=0.004
A	0.800	0.807	0.825	0.834
B	0.720	0.729	0.739	0.791
C	0.805	0.812	0.832	0.843

The overall interaction behavior was a shielding effect due to the decrement in the $F_{Ben-EXT}$ compared to the value of $F_{\_SINGLE}$; this is applicable for all the examined s/L values. Furthermore, for points A and C, about 20% reduction in $F_{Ben-EXT}$ due to the interaction between the cracks for a/t=0.2

when s/L=0.004, while for point B, the reduction was about 25.7% for the same s/L distance, whilst for s/L=0.032, $F_{Ben-EXT}$ for A, B, and C found to be similar to $F_{\_SINGLE}$ since the difference between the values was less than 5%, which means the cracks could be treated as isolated cracks.

Additionally, when s/L=0.032, for a/t=0.5, the value of $F_{Ben-EXT}$ reached about 89.5% of $F_{\_SINGLE}$ at A and C points, and about 82.5% at the deepest point, at all points, a notable interaction effect was noticed despite the large distance between the cracks, this is true also for a/t=0.8 but with more significant interaction influence. This indicates that deep cracks require considerable separation distance to be free from any other neighbor crack effect, unlike cracks with less depth which could be isolated with a small separation distance.

4. Conclusions

In this study, the interaction of double parallel surface cracks located on a hollow thick cylinder under two different types of loading was examined numerically by Ansys software. This research aimed to investigate the interaction phenomenon within the cracks; therefore, SIFs have been evaluated for this purpose. A broad diversity of crack geometries have been employed and examined in terms of crack length and depth to guarantee to cover widespread probable crack configurations. According to the findings, crack interaction impacted both cracks at the same rate, and SIFs scattered across the crack front in the same way as a single crack. Also, the interaction phenomenon of the inspected configuration displayed a shielding effect, with SIFs for the case of two cracks being fewer than those for a single crack. Furthermore, each crack surface operated as a closing force for the opposite crack since both loading types are mode I loading (opening). Besides, an opposite link has been discovered between crack interaction and horizontal offset distance. It should be noted that in this study only straight pipe was considered under mode I loading (tension and bending), thus, it would be valuable if loading types such as combined loading and internal pressure would be considered for the same formation.

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