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Combined influence of pin-hole interference and additional hole on the stress intensity factor for a pin loaded finite plate

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Abstract

This paper presents the results of Stress Intensity Factors (SIFs) for a crack emanating from a finite width plate with pin loaded cracked hole, through a 2-D plane stress Finite Element analysis using ANSYS®. The effect of pin-hole interference and additional stress relieving holes in the plate is investigated. Initial studies were performed on the pin-loaded plate with various crack sizes at the center of the plate, with different interference levels, typical of industrial components. Later, parametric studies were conducted by inserting an additional hole of different diameters placed at a distance from the central cracked hole that acts as stress reliever. The synergistic effect of interference and additional hole in reducing the SIF has been analyzed and the most beneficial interference level, diameter of additional hole and its position has been identified.

Keywords: Stress intensity factor, pin-loaded component, pin-hole interference, stress reliver hole

1. Introduction

Fatigue crack propagation has been one of the foremost reasons for the failure of dynamically loaded components. Replacement cost of components with a propagating crack is many times costlier than the methods to repair them.

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Wherever possible, efforts are made to delay crack initiation, and arrest the crack propagation by reducing the stress intensity factor – a parameter that governs fatigue crack growth. Towards this, residual compressive stresses have been induced by introducing interference fits at the holes (Prakash et al (1997), Lanciotti et.al (2005), Chakherlou et.al. (2010), Sabbaghi et.al (2017)). Alternatively, stop drilled holes were provided to blunt the crack and additional holes around the crack were provided to further decrease stress concentration and thereby stress intensity (Murdani et.al (2008)). Fatigue crack retrofitting (Zhiyuan et.al (2019)) and weld repair (Miki et.al (2012)) also yielded positive results. Apart from some aspects of the study by Miyazaki (2011), most of them focused on a single method of reducing the crack driving force, viz., SIF. The present study, attempts to study the synergistic effect of combination of two of the methods- i.e.., interference fit at pin to hole interface and provision of additional hole near a pin loaded cracked central hole.

This study is comprised of two parts. In the first part, the effect of increasing the interference level between the pin and the plate was studied by gradually increasing the interference levels. Later, at all these interference levels, additional holes of varying diameters and distances from the crack were introduced as stress relievers and the efficiency of them in reducing the stress intensity factor was studied.

Nomenclature

a	half crack length (mm)
2a	crack length (mm)
D	diameter of central hole (mm)
d	diameter of additional hole (mm)
E	elastic modulus (GPa)
ey	vertical offset of additional hole from central cracked hole (mm)
K_I	stress intensity factor, Mode I (MPa√mm)
l	length of the plate (mm)
w	width of the plate (mm)
ν	Poisson's ratio
σ	remote tensile stress (MPa)
σ_y	yield strength in tension (MPa)
σ_u	ultimate strength in tension (MPa)

2. Methodology

A 120 mm long, 60 mm wide and 2 mm thick rectangular plate with an 8 mm diameter (D) cracked hole at the center (Fig. 1a) was subjected to a load of 9600 N, by means of a pin, to induce a remote stress of 80 MPa in the plate. Stress Intensity Factors (SIFs) were evaluated at different crack lengths (2a = 9, 10, 11, 12, 13, 14, 16, 20, 26, 34 mm) for the chosen levels of pin-hole interference (0%, 0.1%, 0.2%, 0.3% and 0.5% of D).

An additional hole having a diameter (d) was introduced in the model (Fig. 1b) to study the extent of reduction in the SIFs due to stress relieving hole. A parametric study was conducted by varying the diameter of additional hole and the distance between central hole and additional hole (ey) for the aforesaid 10 crack lengths. It may be noted that 'ey' varies as 0.75*(D+d) +5x_i, where x_i = 0 to 4 (Table 1). This meant that nearly 750 simulations were carried out for the results. All simulations were performed using Finite Element Analysis (FEA) software ANSYS® by assuming unit thickness and plane stress conditions. Top edge of plate was fixed and load was applied through the pin. The PLANE183, a 2-D 8-node quadratic element was used for meshing the plate and pin with element size of 2 mm. Edge sizing of 0.05 mm was used at crack regions. CONTA172 and TARGE169 were used to define the contact. Mesh convergence was verified using standard geometries available in handbooks (Murakami Y (1987), Pilkey (2004)) to validate the choice of FE mesh. The error between theoretical and simulated values was found to be less than 0.5%. Mild steel was used for both plate and pin, with properties shown in Table 2.

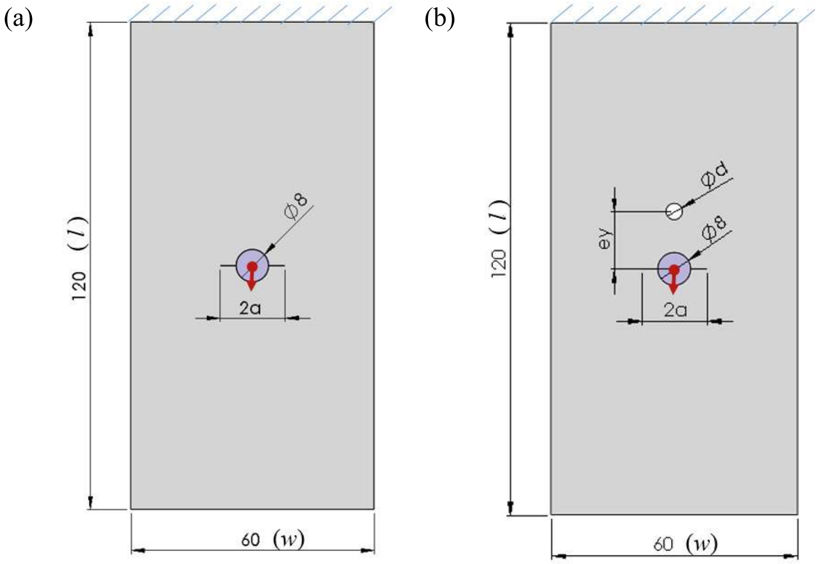

Fig. 1. Schematic of: (a) Pin loaded plate; (b) Pin loaded plate with additional hole of diameter 'd' at a distance of ey

Table 1. Diameter and position of additional holes

	d = 4 mm	d = 6 mm	d = 8 mm
xi	ey, mm	ey, mm	ey, mm
0	9	10.5	12
1	14	15.5	17
2	19	20.5	22
3	24	25.5	27
4	29	30.5	32

Table 2. Material properties

Elastic modulus, E, GPa	Poisson's ratio, ν	Yield Stress, σ_y, MPa	UTS, σ_u, MPa
200	0.3	250	450

3. Results and Discussion

3.1. Effect of interference

Figure 2 shows the variation of SIF with crack size for different percentages of interference between the pin and hole in the plate, for the case of pin-loaded plate with no additional hole. Figure 3 shows the same in terms of geometric factor β, where,

$$\beta = \frac{K_I}{\sigma\sqrt{\pi a}} \tag{1}$$

Here, K_I is the mode-1 Stress intensity factor, σ is the nominal stress in the plate and a is the half crack size. Considerable improvement was observed in the SIF values at all interference levels compared to 0% interference, till a crack length of 16 mm or 2a/w of 0.27. But as the crack length increased, the difference between SIF values observed at all interference levels tend to decrease. To quantify the benefit of interference, the results are plotted in terms of percentage reduction in SIF compared to no interference (Fig. 4). Till a crack length of 2a/w = 0.23, interference of 0.3% yielded the highest reduction of SIF amongst all interference levels considered (viz., 22.38% at 2a/w=0.15), followed by 0.5%, 0.2% and 0.1%. It was also observed that beyond 2a/w=0.23, 0.5% interference yielded the best reduction in SIF and at longer crack lengths, the maximum possible benefit achievable using any of these interference levels is less than 5%.

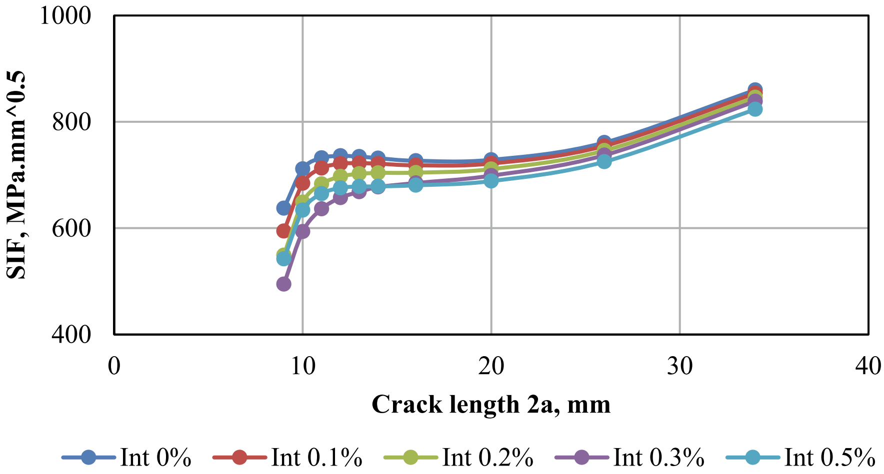

Fig. 2. Variation of SIF with crack length at different interference levels – No additional hole

3.2. Effect of size of additional hole

Additional holes of diameters 4 mm, 6 mm and 8 mm were incorporated as mentioned in Table 1 at five locations for each case. Placing the additional hole too close or too far away to the existing center hole of diameter D would not decrease the stress concentration, while keeping the additional hole at an optimum distance would cause stress shielding. To compare the effect of size of additional hole, SIFs were considered at the nearest position of additional hole from the central hole, i.e., x_i=0. Variation of β and the percentage reduction in SIF, when compared to the case of no additional hole for the 0.3% interference level are shown in Figs. 5(a) and 5(b) respectively. Similar trend was observed at other interference levels also except in case of 0.5% interference (Figs. 6(a) and 6(b)) where minor deviation in the pattern was observed at shorter crack lengths.

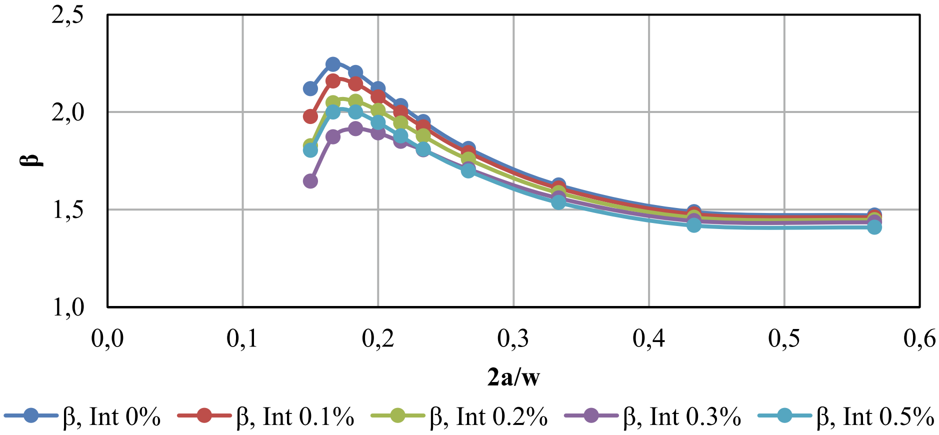

Fig. 3. Variation of β with crack length at different interference levels – No additional hole

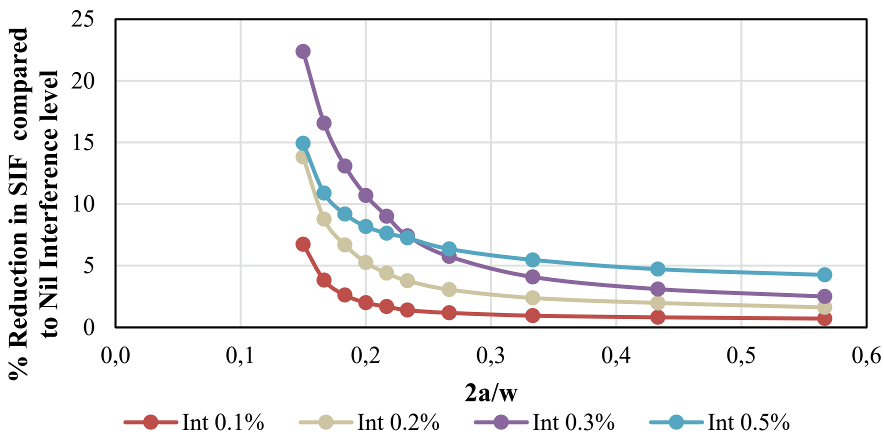

Fig. 4. Percent reduction in SIF due to interference at pin-hole interface with the case of zero interference

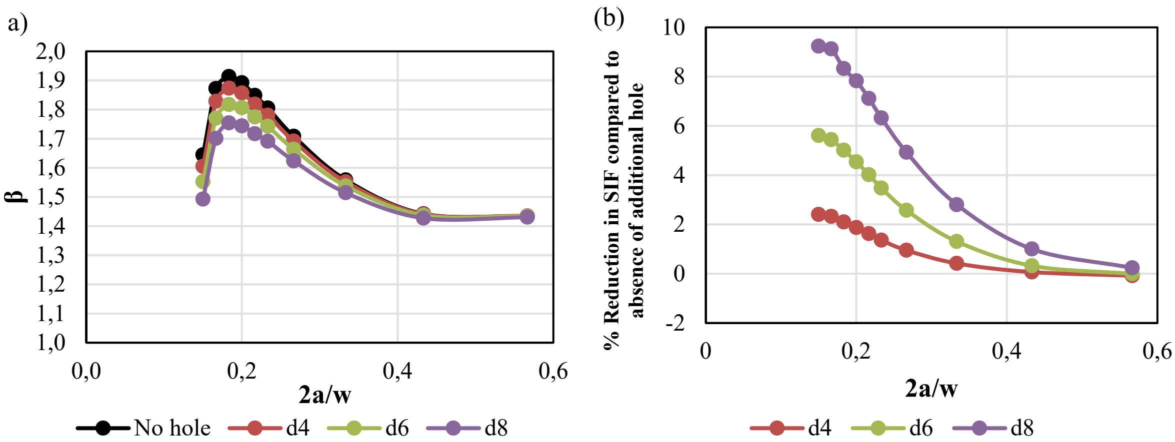

Fig. 5. (a) Variation of β with crack length and diameter of additional hole, for xi=0 and 0.3% pin-hole interference; (b) Percentage reduction in SIF compared to the case of no additional hole at 0.3% interference.

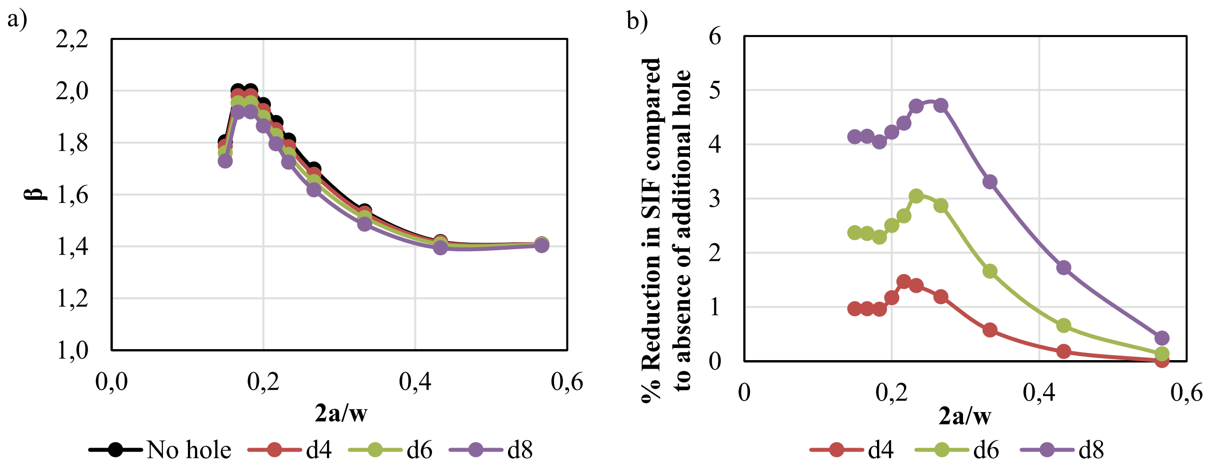

Fig. 6. (a) Variation of β with crack length and diameter of additional hole, for xi=0 and 0.5% interference; (b) Percentage reduction in SIF compared to the case of no additional hole at 0.5% interference

It was observed that among all interference levels, 0.3% level is more efficient in reducing the SIF; amongst the chosen set of diameters of additional holes, d8 has the most beneficial effect with 9.23% reduction in SIF at 0.3% interference followed by d6 and d4. To understand the combined benefit of both interference as well as additional hole, the case of d8 with 0.3% interference is compared with no-additional hole and no-interference case. Figure 7 shows that the combined effect reduced SIF by 29.5 % at 2a/w=0.15. At very long cracks, i.e., 2a/w=0.567, the advantage gained due to addition of hole is negligible, i.e., with or without additional hole, SIFs at all interference levels remain mostly unaffected. This can be observed by comparing Figures 4 and 7 (with interference alone in absence of additional crack).

It is also observed that unlike no additional hole case where 0.5% interference is more beneficial than that of 0.2% for all 2a/w, in presence of d8 hole, till 2a/w=0.2, 0.2% interference is more beneficial than 0.5% interference. Also, the transition of 0.5% becoming more beneficial than 0.3% occurred at 2a/w of 0.27 instead of 0.23.

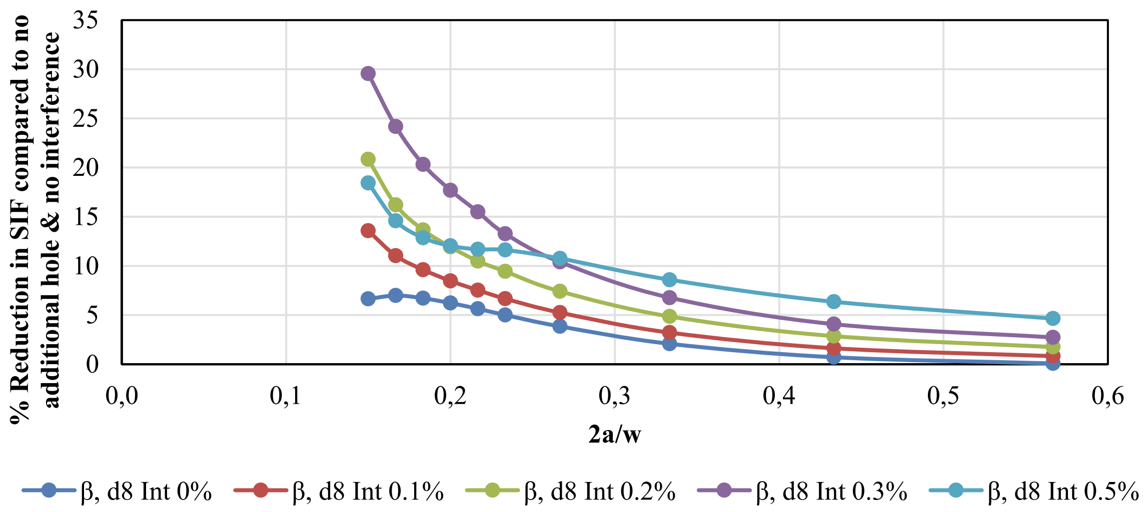

Fig. 7. Percentage reduction in SIF for an additional hole of diameter mm compared to case of plate without interference and no additional hole.

3.3. Effect of position of additional hole

For shorter crack lengths, SIF was the least when the additional hole was at the nearest position to the cracked hole, i.e., x_i=0. As the additional hole moved farther, SIF slowly increased till certain crack length (which varies with d and interference level), where, the difference between SIFs for the nearest and farthest positions reduced to zero; thus, there is a limiting crack length, at which there is no significant difference in the SIF values, irrespective of the position of additional hole. Sample case can be seen in the Table 3, where β is shown for various positions of additional hole diameter of 4 mm at 0.3% interference. Here the limiting crack length is 20 mm or 2a/w=0.33.

Table 3 Variation of β along the various positions of additional hole, at 2a/w=0.33 and 0.3% interference

ey, mm	β
9	1.552
14	1.548
19	1.548
24	1.549
29	1.551

For all the combinations of diameters of additional hole and interference levels, this limiting crack length varies, which can be seen from the figures 8 to 10. It was also observed that the limiting crack length tends to move towards higher crack lengths, with an increase in diameter of the additional hole. Also, it is noted that for d=8mm, the difference in the SIFs is the highest (8.29% at 0.3% interference), followed by 0.2%, 0.1%, 0% and 0.5%. Beyond this limiting crack length, the SIF at the nearest position is slightly higher than that of the farthest position, showing a negligible negative difference, as can be inferred from the figures 8 to 10.

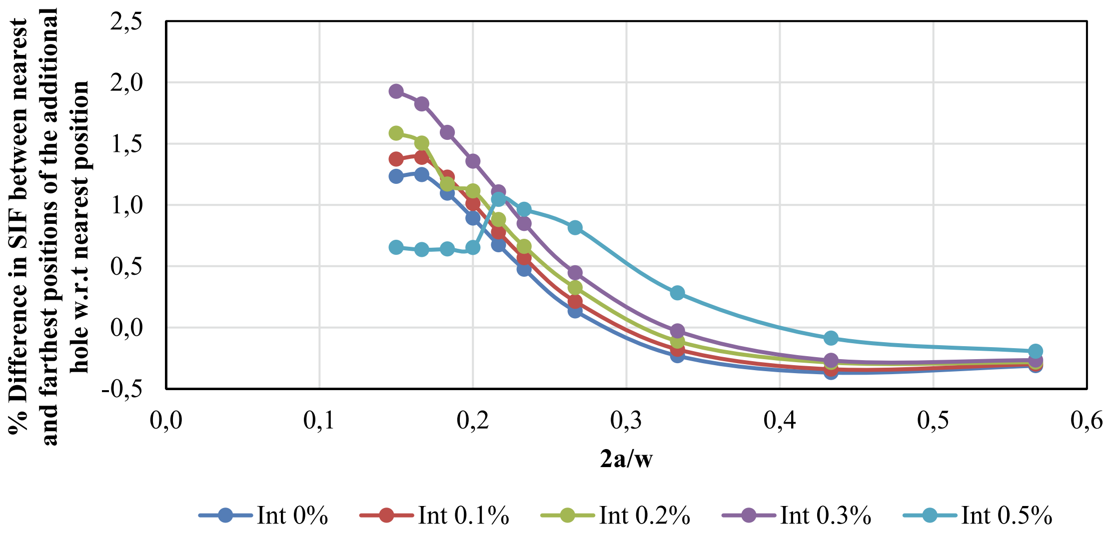

Fig. 8. Percentage difference in SIF between the nearest and the farthest positions of an additional hole w.r.t the nearest position, for d=4 mm

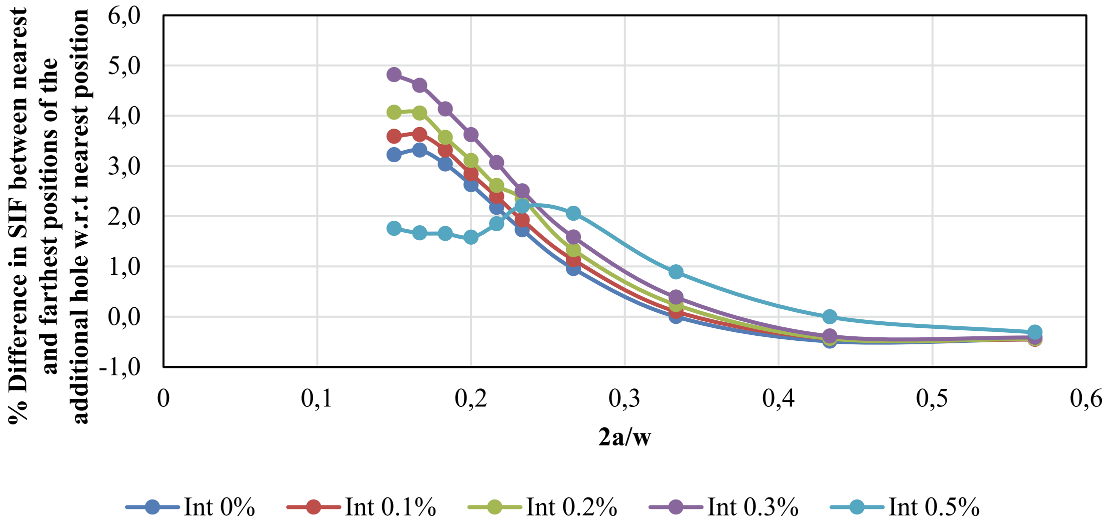

Fig. 9. Percentage difference in SIF between the nearest and the farthest positions of an additional hole w.r.t the nearest position, for d=6 mm

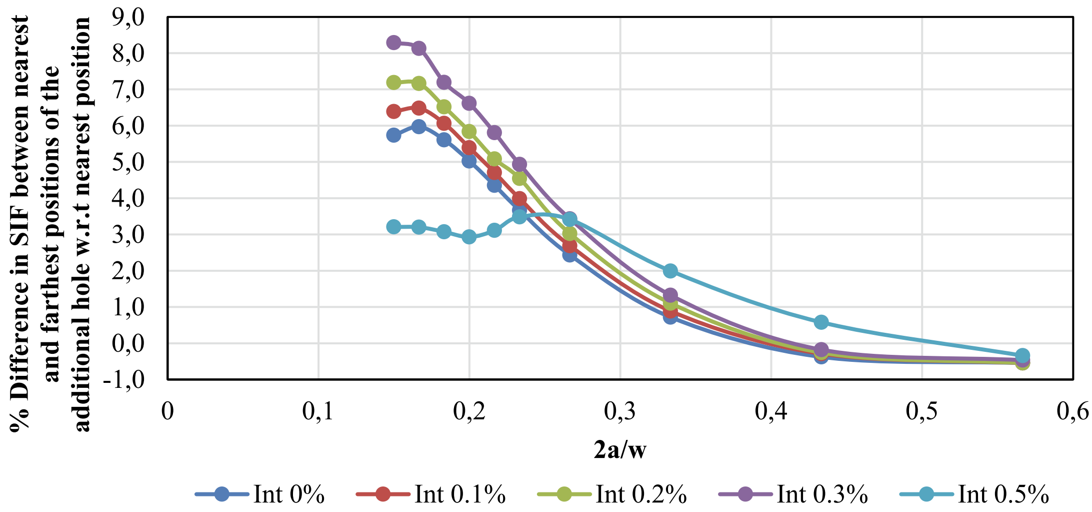

Fig. 10. Percentage difference in SIF between the nearest and the farthest positions of an additional hole w.r.t the nearest position, for d=8 mm

4. Conclusion

In this work, a numerical study was performed on estimation of stress intensity factor for a pin loaded centrally cracked plate having various interference levels, with and without introducing an additional hole with varying diameters and distances from the center of cracked hole. The percentage reduction in SIFs in both cases were analyzed individually and in combination The highest reduction in SIF was observed due to the combined effects of presence of 8 mm diameter additional hole and 0.3% interference till 2a/w= 0.267, beyond which 0.5% interference was found to be more beneficial. Limiting crack lengths beyond which SIFs remain the same irrespective of the levels of interference as well as distance of additional hole from the crack were identified, which could assist in design of pin loaded joints.

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