BULETINUL Universităţii Petrol – Gaze din Ploieşti	Vol. LXIII No. 1/2011	73 - 82	Seria Tehnică

Numerical Analysis of Crack Interaction Influence on Crack Propagation

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Abstract

This paper presents a numerical analysis of a two-dimensional plate made from a linear-elastic material with two 10 mm initial cracks. An edge crack situated at the middle of the plate is considered for K_I and K_{II} determination, as well as propagation direction analysis. The second crack is an edge crack situated on the same side with the first one (first case), an edge crack situated on the other side (second case) and an inner crack (third case). The results relieved that crack interaction occurs even if the distance between the cracks is larger than the crack length. The most significant influence is noticed at the crack propagation angle.

Key words: *stress intensity factors, crack propagation, crack interaction, two-dimensional plate.*

Introduction

Numerical analysis programs allow an easy, less expensive and fast assessment of fracture mechanics parameters such as the stress intensity factor (SIF). Nevertheless, in the engineering area, to design a structure able to withstand the imposed stresses even if cracks appear requires the knowledge of the cause-effect relationship regarding each load component, as well as any possible crack interaction that may occur.

The multiple cracks situation has been treated first by Kachanov [5], in order to propose a simpler method to compute the SIF for a two-dimensional problem. Li et al. [6] further developed the method proposed by Kachanov so that the SIF can be computed with better accuracy when the inter-crack distances are small. Sadowski et al. [7] extrapolated these methods for three-dimensional problems regarding orthotropic materials. Furthermore, Neş et al. [1] analyzed the problem of a two-dimensional plate with an edge crack, subjected to normal traction (SECT), then to bending (SENB) and a supplemental crack in the middle.

The current article consists in analyzing the influence of a second edge crack (first case and second case), or a second inner crack (third case) on stress intensity factors and propagation direction of an edge crack. Both cracks have the same initial length of 10 mm. The simulations were done using Cornell University's FRANC2D software, for plane strain conditions.

Procedure description

After modelling the plate and the two cracks, together with the appropriate mesh, the crack propagation option is activated. This procedure was done automatically. There are 30 propagation steps for the first and second cases and 20 for third case, with a crack increment of 1 (one) millimetre. The program computes the SIFs for every step, using the displacement correlation method (DC), while the crack propagation angle is determined using the maximum circumferential stress theory (MCST). Mohammadi [3] gives the relationships for SIF determination using DC method (1, 2). These results are then converted into graphs for easier interpretation. The load $\sigma = 1$ N/mm^2, to minimize its influence on SIFs.

$$K_I = \mu\sqrt{\frac{2\pi}{r}} \cdot \frac{u_y^b - u_y^a}{2\left(1 - \frac{\upsilon}{1+\upsilon}\right)} \quad (1)$$

$$K_I = \mu\sqrt{\frac{2\pi}{r}} \cdot \frac{u_x^b - u_x^a}{2\left(1 - \frac{\upsilon}{1+\upsilon}\right)} \quad (2),$$

where μ is the shear modulus,

υ is Poisson's ratio,

$u_{x,y}^{a,b}$ are the x and y displacements for nodes a and b (a is the crack tip node, b is a node on the crack line).

Note that the results are analyzed only for crack A.

First case: the cracks are on the same side

A two-dimensional plate with two edge cracks with a variable inter-crack distance (d) is subjected to a tensile load (Fig. 1). The inter-crack distance d takes the following values: 10, 20, 30, 40, 50, 60, 70 and 80 mm. One can see that the ratio between the length of the crack and the with of the plate is $\frac{1}{5}$. In this situation, the limited size of the specimen has a certain influence on the SIF. Anderson [2] offers an analytical solution for the case of a single crack (3), mentioning that a more accurate result can be obtained using numerical methods. Note that the relationship previously given is valid only for a crack normal on the tension's direction.

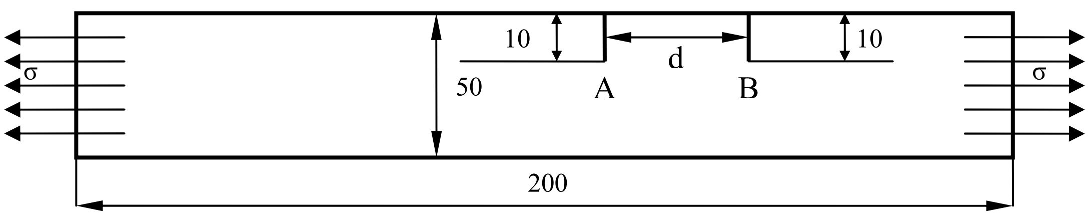

Fig. 1. The specimen's dimensions

$$K_I = \sigma\sqrt{\pi a}\left[sec\left(\frac{\pi a}{2W}\right)\right]^{\frac{1}{2}}\left[1 - 0.025\left(\frac{a}{W}\right)^2 + 0.06\left(\frac{a}{W}\right)^4\right] \quad (3),$$

where σ - the tensile load,

a - the crack length,

W - the specimen width.

The relationship (1) gives K_I=5.742 $MPa\sqrt{mm}$, which is 15.23% less than the one obtained numerically. Nevertheless, the same determination using COSMOS 2007 and a 48000 elements model gave a result similar to the one obtained with FRANC2D (a slight 1.1% difference). This means that the large crack length/specimen size ratio has a massive influence on SIFs and the current analytical solutions cannot provide sufficient accuracy for this specific model.

The mesh was done automatically (Fig. 2), with crack tip refinement (Fig. 3). The number of elements (2500) was limited by the available virtual memory of the computer. In order to provide correct mesh characteristics for crack propagation, quadratic elements were used and degenerative elements for the $1/\sqrt{r}$ crack tip singularity. The characteristics of the material are those of usual construction steel, with the modulus of elasticity $E = 2.1 \cdot 10^5$ MPa and Poisson ratio $\nu = 0.3$.

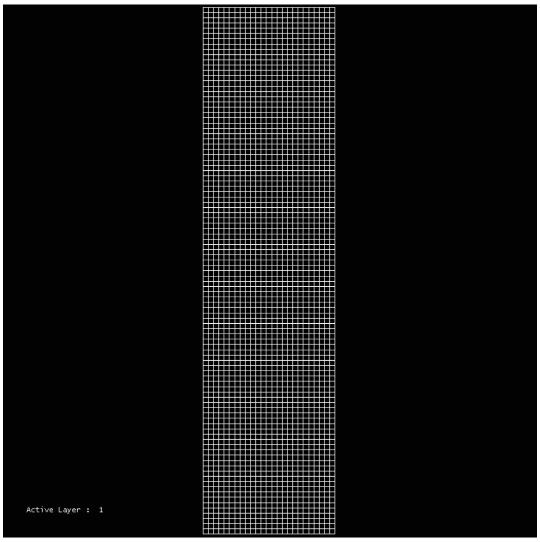

Fig.2. The mesh

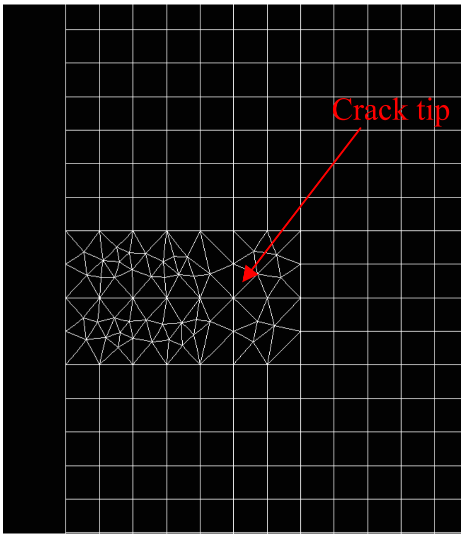

Fig.3. The mesh refinement around the crack line

The effective stress field around the crack tips for d=20 mm is presented in Fig. 4.

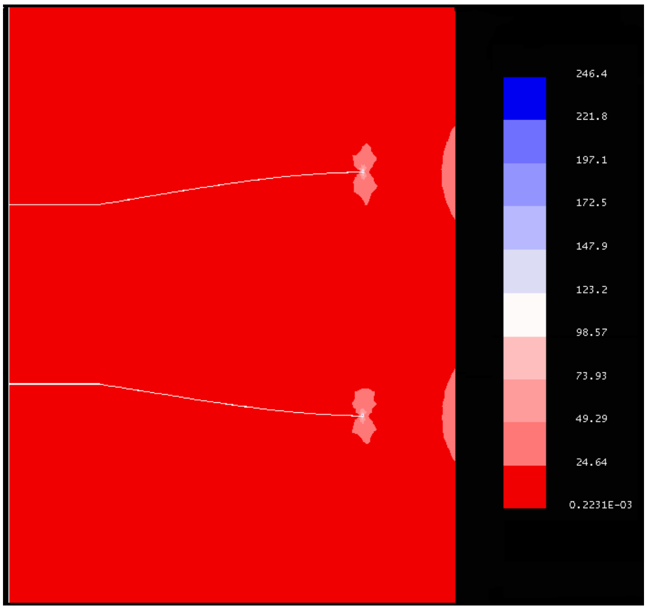

Fig. 4. The stress field (effective stress) around the cracks for d=20 mm

After the propagation was done, the propagation angle and the SIFs were plotted. Because FRANC2D did the propagation alternatively for the two cracks, the results had to be further refined in order to have the correct tendences.
The variation of the crack kink angle is shown in Fig.5, while the variation of the SIFs is shown in Fig. 6 (K_I) and Fig. 7 (K_{II}).

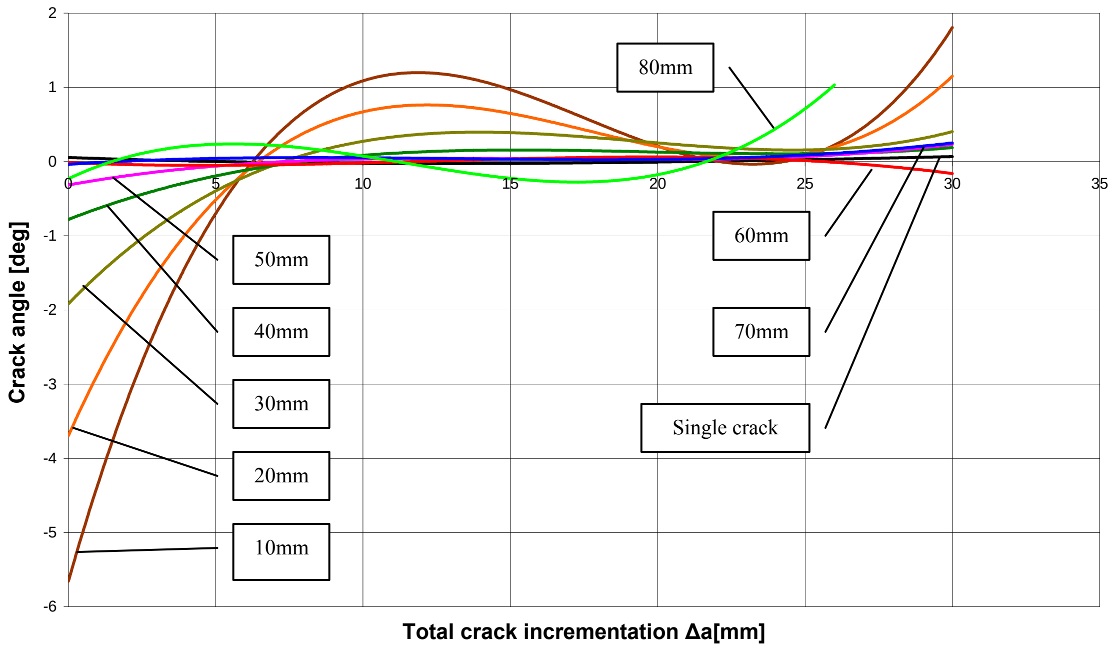

Fig. 5. The crack interaction influence on propagation angle (same side) – crack A

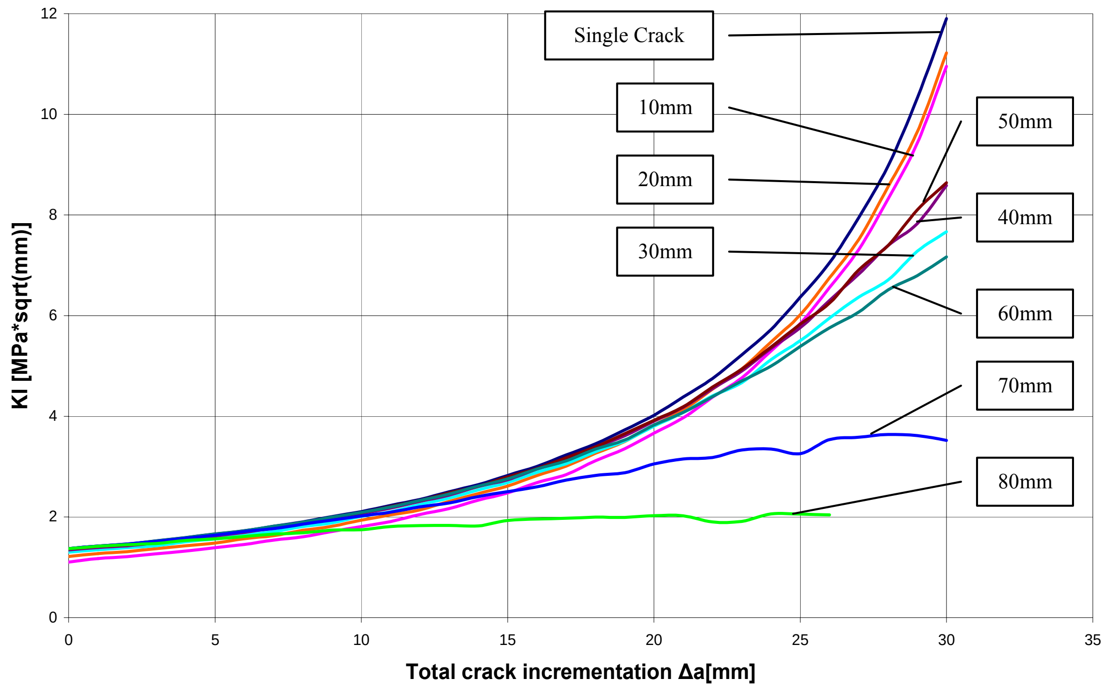

Fig. 6. The crack interaction influence on K_I (same side) – crack A

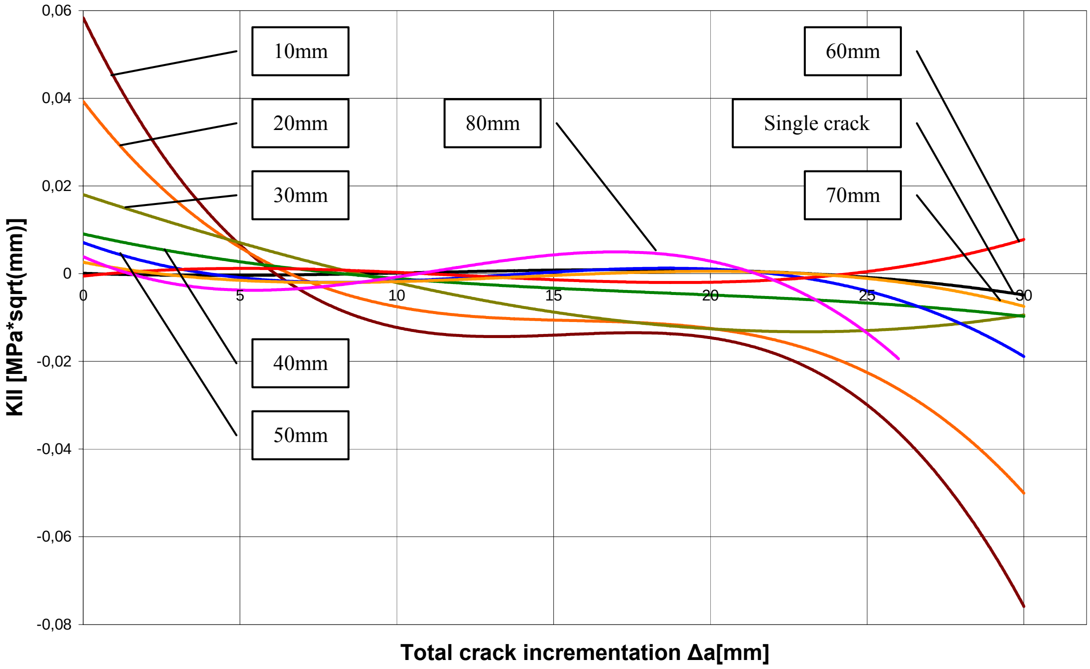

Fig. 7. The crack interaction influence on K_{II} (same side) – crack A

Second case: the cracks are on opposite sides

A two-dimensional plate with two edge cracks with a variable inter-crack distance (d) is subjected to a tensile load (Fig. 8). The inter-crack distance d takes the following values: 0, 10, 20, 30, 40, 50, 60, 70 and 80 mm. The mesh parameters, as well as the material's characteristics are the same as in the previous case.

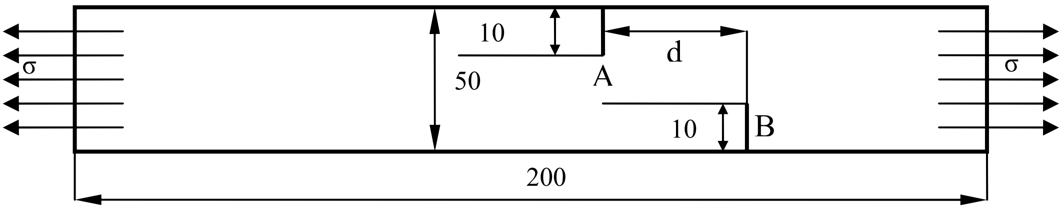

Fig. 8. The specimen's dimensions and layout

The effective stress distribution around the two crack lines for d=20mm is shown in Fig. 9. The variation of the crack kink angle is shown in Fig.10, while the variation of the SIFs is shown in Fig. 11 (K_I) and Fig. 12 (K_{II}).

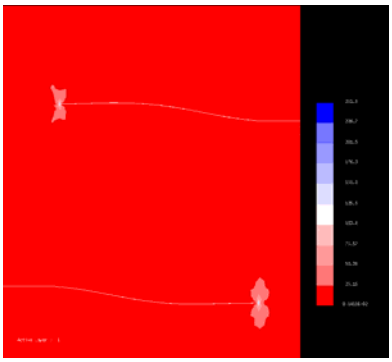

Fig. 9. The effective stress distribution for d=20mm

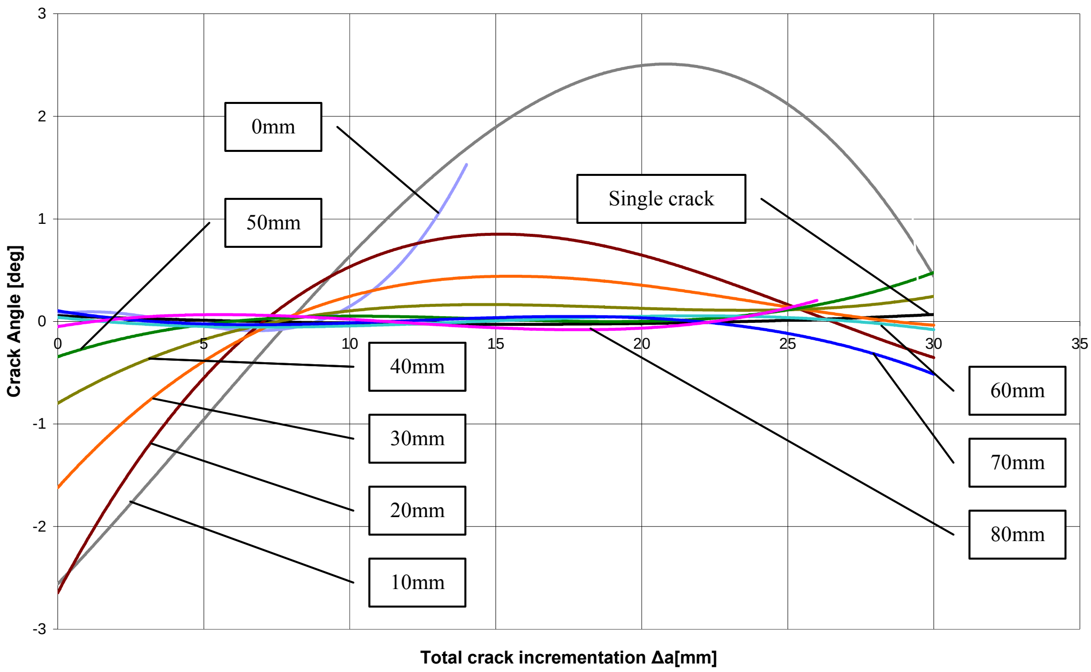

Fig. 10. The crack interaction propagation angle (opposite sides) – crack A

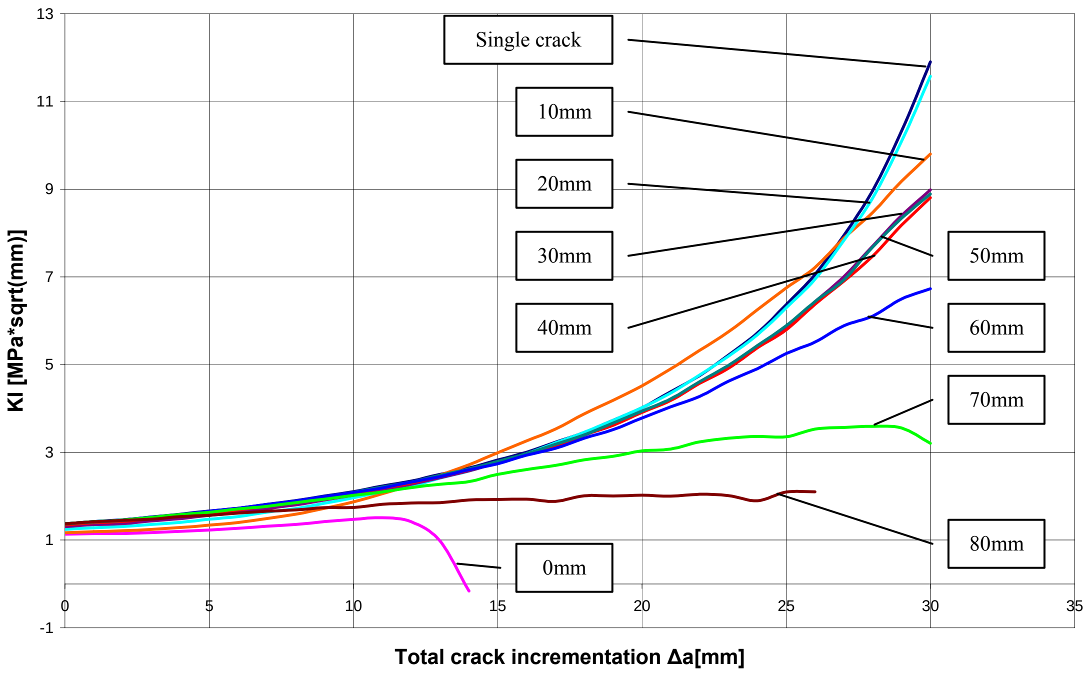

Fig. 11. The crack interaction influence on K_I (opposite sides) – crack A

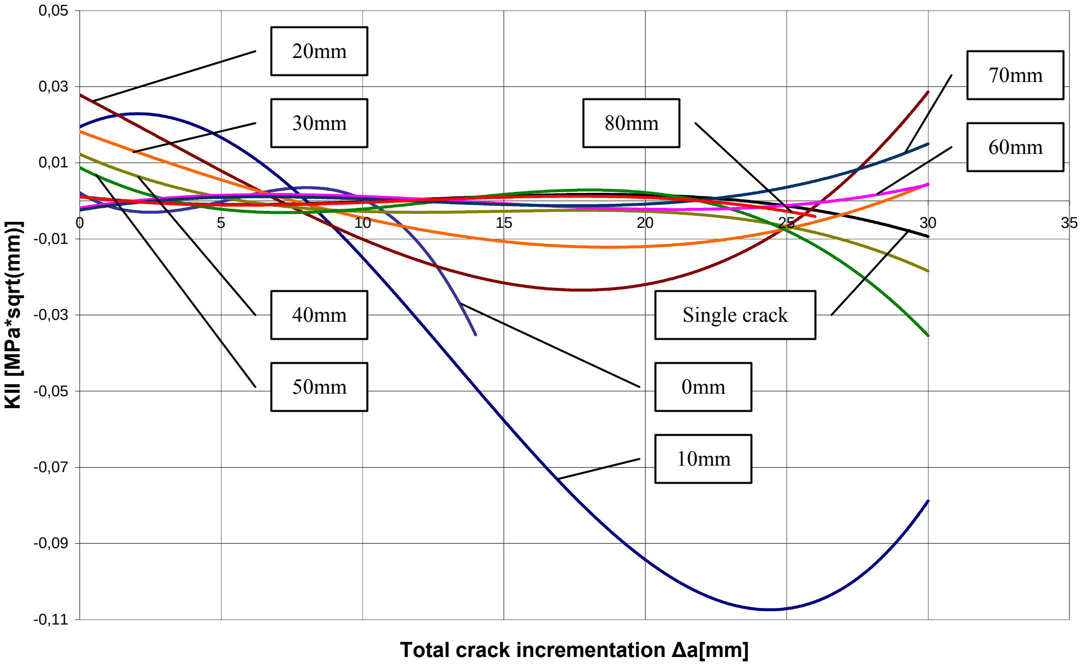

Fig. 12. The crack interaction influence on K_{II} (opposite sides) – crack A

Third case: inner crack

This time, the two-dimensional plate has an edge crack and an inner crack, with a variable inter-crack distance (d) (Fig. 13). The inter-crack distance d takes the following values: 10, 20, 30, 40, 50, 60, 70 and 80 mm. The mesh parameters, as well as the material's characteristics are the same as in the previous cases.

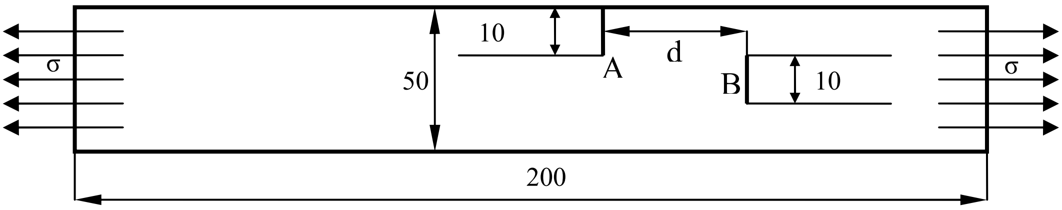

Fig. 13. The specimen's dimensions and layout

The inner crack's tips are situated at equal distances from the nearest edges. In Fig. 14 the distribution of the effective stress for d=20mm is ploted. The variation of the crack kink angle is shown in Fig.15, while the variation of the SIFs is presented in Fig. 16 (K_I) and Fig. 17 (K_{II}).

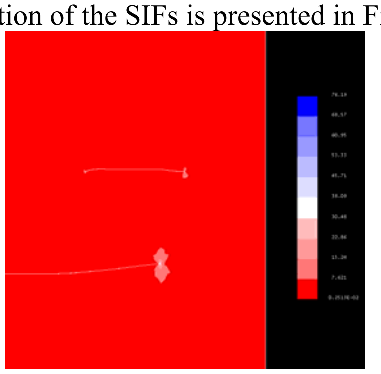

Fig. 14. The effective stress distribution for d=20mm

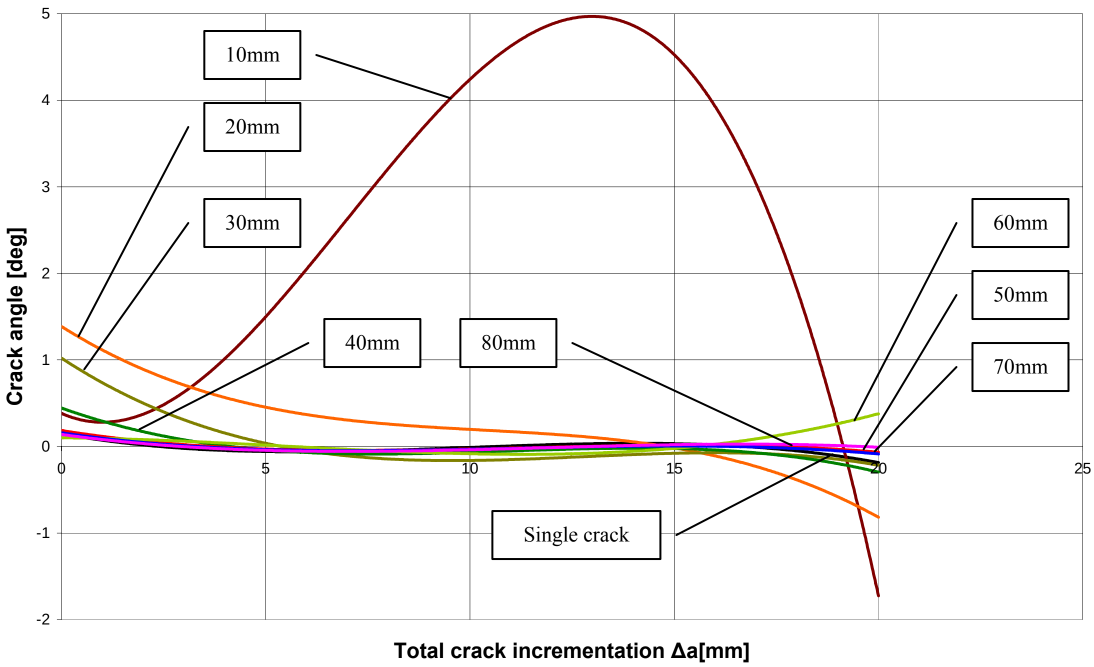

Fig. 15. The crack interaction propagation angle (inner crack) – crack A

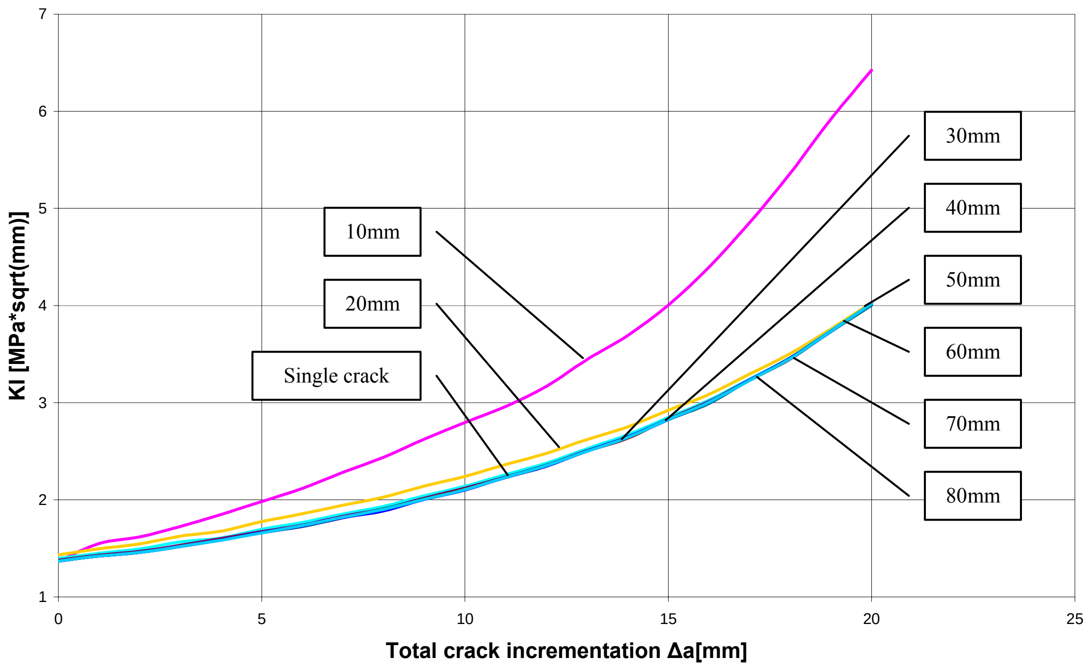

Fig. 16. The crack interaction influence on K_I (inner crack) – crack A

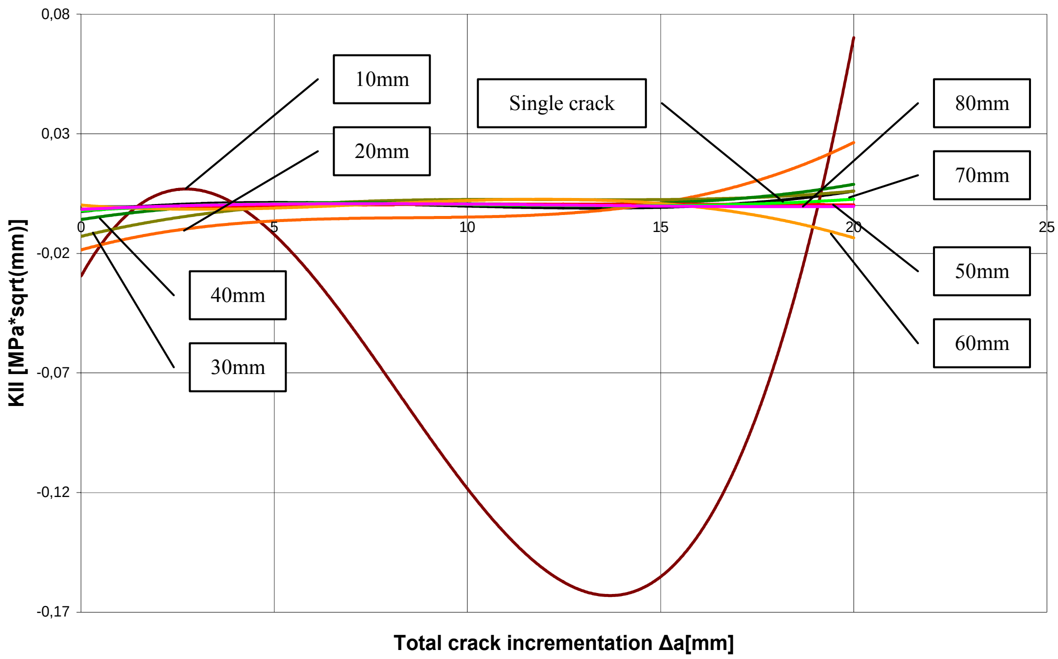

Fig. 17. The crack interaction influence on K_{II} (inner crack) – crack A

Discussions

In Fig. 18 is presented the layout of the plate with both cracks grown to the maximum size (40 mm), in both undeformed and deformed state. The distance d=20mm.

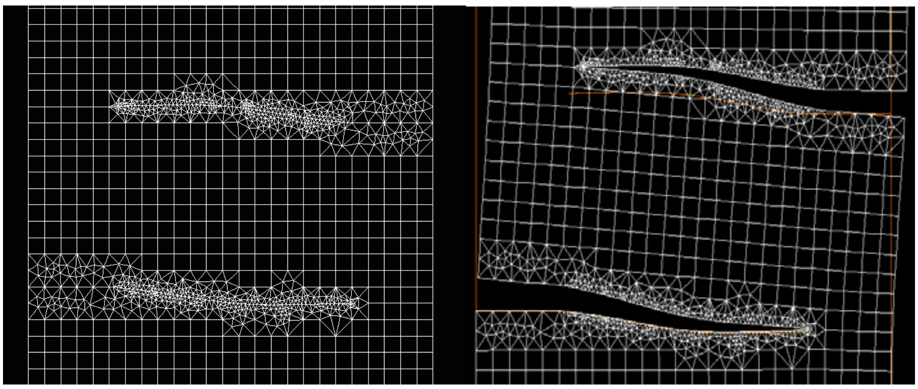

Fig. 18. Two fully propagated cracks

These two images illustrate the most important phenomenon observed during the simulations: the two cracks "reject" each other as the propagation approaches the two tips. As one can see in the crack angle – propagation distance correlations, as well as in the K_{II} – propagation distance figures, this evolution is due to the tendency of reducing and eliminating Mode II propagation. This means that even if the inter-crack distance is quite large, the stress field around the crack lines in general and around the crack tips in particular, interact. This rejection is more important because it contrasts with the attraction that occurs when a crack passes near a hole.
The curve described by the crack lines is accurately described by the crack angle variation graphs.

Conclusions

After analyzing the influence of crack interaction on crack propagation for a finite size plate, the following conclusions were drawn:

1. Crack interaction occurs even at inter-crack distances larger than the crack length;
2. Crack interaction occurs for different layouts: cracks on same side, cracks on different sides, edge crack and inner crack;
3. Even if the inter-crack distances vary significantly, there still can be seen an obvious difference between the results;
4. The crack propagation directions diverge;
5. The interaction is more obvious when there are two edge cracks;
6. The SIFs and the crack angle follow similar paths for every distance d.
7. For larger inter-crack distances, the propagation of the analyzed crack slows down, and even stalls;
8. Cracks propagation direction evolves in order to eliminate Mode II fracture.

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Analiză numerică a influenței interacțiunii fisurilor asupra propagării fisurii

Rezumat

În cadrul acestui articol este prezentată o analiză numerică a unei placi bidimensionale, dintr-un material cu comportare linear-elastică, cu două fisuri inițiale de 10 mm. Determinarea lui K_I şi K_{II}, precum şi analiza direcției de propagare sunt făcute pentru o fisură de margine, situată la mijlocul plăcii. Cea de-a doua fisură este o fisură de margine situată pe aceeaşi parte cu prima (primul caz), o fisură de margine situată pe marginea opusă primei fisuri (al doilea caz), respectiv o fisură interioară (al treilea caz). Rezultatele au reliefat faptul că interacțiunea apare chiar dacă distanța dintre fisuri este mai mare decât lungimea acestora. Cea mai semnificativă influență s-a remarcat la nivelul ungiului de propagare a fisurii.