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# Evolution of stress intensity factors in mixed mode with presence of mismatch effect

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## Abstract

In this study, numerical models based on finite element method are developed for several applications of fracture mechanics. The use of cracked specimen formed by different material properties has allowed us to analyse the effect of the crack position to the interface and to have a well understanding of mismatch effect for the case of mixed mode of fracture. In other hand, we have noticed that it is very interesting to see the effect of the interface position and loading for the case of symmetrically cracked ring specimen under compression loading.

Keywords: crack, interface/bi-material/mixed mode/stress intensity factor/mismatch effect.

# 1. Introduction

Actually,most of the structures and mechanical components are formed within at least two dissimilar materials. For almostallcases, the use of heterogeneous materials is due to strength issues, protection against corrosion, rubbing......etc. The difficulty is to describe the stress field which is perturbed at the crack tip near the interface. So many researchers have tried to analyse stress fields and to evaluate fracture parameters of cracked bi-material specimen. In the mid 1960, various research works have been carried out by [Erdogan 1963], [Rice and Sih 1965] to verify [William's 1959] finding of complex singularities and oscillating stresses near the crack tip. The well know [Dundurs 1977] parameters where used by so many researchers to predict the stress intensity factors for bimaterial when the crack was perpendicular to the interface. [Comninou 1977] resolved the crack interface problem by assuming that there is a small contact zone near the crack tip which is extremely small. For interface crack in tension, the contact zone model provides a contact zone of the order  $10^{-4}$  of the crack length. Recently, some formulations and new technics were developed such as [Wang & Stahle 1998], [Marur and Tippur 1999] who have solved the interfacial crack problems in bi-material plates analytically by developing the stress field relationships as analytical series. Stress intensity factor for crack

in bi-material interface has been studied by [Bjerken and Persson 2011] and [Ikeda &Sun 2001]. The first authors have applied integral method for the determination of complex relationships of stress intensity factors, the second authors have used the virtual crack extension technique for cracked bi-material specimen under thermal loading. [Kang Yilan and Lu Hua 2002] have developed a calculation procedure for displacement field near the crack tip emanating from interface. Experimental methods have been used by [Jiang & al 2004] to describe the evolution of J-R curves and to study the propagation of cracks emanating from interface of bi-material specimens under three points flexion loading. Another experimental method based on RGB photoelasticity has been carried out by [Cirello and Zuccarelo 2006] to analyse the propagation of cracks perpendicular to interface of bi-material plates. Numerical models have been developed by [Madani & al 2007], [Ouinas & al 2008] and [Kazi Tani& al 2009]to show the effect of interfaces on crack propagation in bi-material specimen. The restitution energy rate G and the stress intensity factor(SIF) have been determined by those authors for several crack positions between dissimilar materials.

In this present paper, two important points are discussed; the first one is to describe the effect of mixed mode on the decreased curves of stress intensity factor obtained by Cirello and Zuccarelo using RGB photoelasticitytechnique [Cirello and Zuccarelo 2006] and confirmed numerically by [Kazi Tani& al 2009] on bi-material plates PSM1/AlPolycarbonate/Aluminium, for the first mode of fracture. The second point concerns the influence of the interface position and loading direction on the stress field near the crack tip of bi-material ring specimen where cracks are symmetrically located.

#### 2. Stress intensity factor at bi-material interface

For a crack of 2a length located at the interface between two dissimilar materials subjected to a uniform tensile load, the complex relationship of the stress intensity factors are given by [Rice 1988] as:

$$K_1 + iK_2 = \sigma_{\nu} (1 + 2i\varepsilon)(2a)^{-i\varepsilon} (\pi a)^{0.5}$$
(1)

Bi-elastic constant is given by :

$$\varepsilon = \frac{1}{2\pi} \ln(\gamma) (2)$$

With

$$\gamma = \frac{G_1 + \kappa_1 G_2}{G_2 + \kappa_2 G_1} \tag{3}$$

Where  $\kappa_i = 3 - 4\nu_i$  in plane strain;  $\kappa_i = (3 - \nu_i)/(1 + \nu_i)$  in plane stress; and

$$G_j = \frac{E_j}{2(1+\nu_j)} \tag{4}$$

 $G_i, E_i$  and  $v_i$  are respectively shear modulus, Young modulus and Poisson ratio of material j.

For the case where the crack is at the interface (Fig.1), [Tan and Gao 1990], Emin Ergun & al [18] expressed SIF relationships from displacement correlation method.

From displacements values of nodes a, b, c, d, e obtained by finite element method, it is possible to express opening and shear fracture modes by the following equations given by references [Tan and Gao 1990], and [E. Ergun et al. 2008]:

$$K_{1} = \sqrt{\frac{2\pi}{s}} \left[ C_{1} \left( -v^{e} + 4v^{d} - 3v^{a} \right) - C_{2} \left( -v^{c} + 4v^{b} - 3v^{a} \right) \right]$$
(5)

$$K_{2} = \sqrt{\frac{2\pi}{s}} \left[ C_{1} \left( -u^{e} + 4u^{d} - 3u^{a} \right) - C_{2} \left( -u^{c} + 4u^{b} - 3u^{a} \right) \right]$$
(6)

s is the distance between nodes a and c or a and e.

 $u^i$  and  $v^i$  are respectively the node displacements with respect to x and y axis.



Fig. 1. Interface crack in bi-material specimen

$$C_1 = \frac{(1+\gamma)\zeta}{\cosh(\pi\varepsilon)} \frac{G_1}{\kappa_1 e^{\pi\varepsilon} + \gamma e^{-\pi\varepsilon}}$$
(7)

$$C_2 = \frac{(1+\gamma)\zeta}{\cosh(\pi\varepsilon)} \frac{G_1}{\kappa_2 \gamma e^{-\pi\varepsilon} + e^{\pi\varepsilon}}$$
(8)

with

$$\zeta = \left[\frac{1}{4} + \varepsilon^2\right]^{1/2} \tag{9}$$

#### 3. NumericalExamples

#### 3.1.Mismatch effect in mixed mode

To have a well understanding of mismatch effect, we have taken back the numerical example which was in analyzed in references[A. Cirello and B. Zuccarello 2006] and [N. Kazi Tani et al. 2009]. In our case, an inclined central crack of 2a length with an angle $\theta$  fromhorizontal axisxas shown in Figure 2 is studied. The cracked bi-material formed by polycarbonatePSM-1 (Material 1) and Aluminium (Material 2) which it's dimensions are W<sub>2</sub>/W<sub>1</sub>=1.5, H/W<sub>1</sub>=12.5, W<sub>1</sub>=12mm and the thickness is equal to 5mm. The bi-material plate is subjected to a tensile load in y

direction,  $\sigma_g$ =20MPa. It is possible to determine the applied stress on each material by applying the principle of Matrix-fiber system where the applied stress is given by [12] as follows:

$$\sigma_g = \sigma_{g1} \left[ v_1 + (1 - v_1) \frac{E_2}{E_1} \right]$$
(10)

If we suppose that both materials 1 and 2 behave elastically and the global deformation is the same for each side of material 1 and 2, then we can write:

$$\frac{\sigma_{g_1}}{\sigma_{g_2}} = \frac{E_1}{E_2} \tag{11}$$

From equations (10) and (11), we can split the total stress  $\sigma_Y$  into two components  $\sigma_{g1}$  and  $\sigma_{g2}$ .

Numerical modelcarried out by using ANSYS software finite elementhave allowed us to determine the displacement field and stress intensity factors for mode I and mode II. The solution of the problem has been calculated by using 8 node quadratic elements in plane stress by computing  $K_1$ ,  $K_2$  from the nodal displacements on opposite sides of the crack plane[Madenci and Guven 2006] with singular element size around 5% of crack length.For symmetric configuration of the specimen, only the quarter of the plate considered in finite elements model (Fig. 2).



Fig. 2. Numerical model of bi-material plate containing a central inclined crack

The numerical results of stress intensity factors obtained in mode I and II are plotted Figure 3a and Figure 4. For well representing those results, thevalues of SIF are normalized by  $K_0 = \sigma_{g1}\sqrt{\pi a}$ . Results of  $\overline{K}_I$  in Figure 3-a are compared with the case of mode I, Figure 3-b obtained by [15].



Fig. 3-a. Evolution of normalized stress intensity factor  $\overline{K}_I$  with crack length and inclinaison angle  $\theta \Box$ ,  $E_1/E_2 = 0.047$ 



**Fig. 3-b.** Evolution of normalised stress intensity factor in mode I ( $\theta$ =0°) [15]



Fig. 4. Evolution of normalized stress intensity factor  $\overline{K}_{II}$  with crack length and inclinaison angle  $\theta \Box$ ,  $E_1/E_2 = 0.047$ 

According to the results plotted in Figure 3-a and Figure 4, we have noticed that for the most of  $\theta$  inclinaison angles of crack, the normalized stress intensity factors  $\overline{K}_I$  and  $\overline{K}_{II}$  are decreasing as the crack becomes longer. In the case of mode I, the decreased values are more significant when  $\theta$ varies between 0° and 30°. The values of  $\overline{K}_I$  seems constant for the case when $\theta > 45^\circ$ . This decreased curve is well described by [Kazi Tani et al. 2009] for a central crack in mode I. The same evolution has been noticed for mode II (Figure 4) except for the case  $\theta = 10^\circ$  where thenormalized SIF increases with crack lengths a/W>0.6.

In order to compare the numerical results with first mode of fracture mode I ( $\theta$ =0) [Kazi Tani et al. 2009], we have represented in Figure 5,the equivalent stress intensity factor for the mixed mode $\overline{K}_{eq}$ , which it is given by the following relationship:

$$\overline{K}_{eq} = \sqrt{\overline{K}_I^2 + \overline{K}_{II}^2} \tag{12}$$

In Figure 5, the equivalent stress intensity factor  $\overline{K}_{eq}$  decreases when inclination angle  $\theta$  varies between 0° and 45°. For angles  $\theta = 60^{\circ}$  and 75°,  $\overline{K}_{eq}$  values seem to be constant and do not depend on the crack length. This can be explained by the presence of mismatch effect which is more significant when the crack tip is nearthe interface. The presence of the crack in weakest material and mismatch effect yield a "closing" bridging stress intensity factor that decreases the stress intensity factor resulting from external loading, especially when the crack tip is close to the interface.

Elsewhere, we have taken back the same model by changing the position of materials where material 1 is Aluminium and material 2 is PSM-1.



Fig. 5. Evolution of normalized equivalent stress intensity factor  $\overline{K}_{eq}$  with crack length and inclinaison angle  $\theta \Box$ ,  $E_1/E_2 = 0.047$ 

The numerical results of stress intensity factors in mode I and II are shown in Figure 6 and Figure 7.

In Figure 6, the increasing curves of  $\overline{K_I}$  are more significant when  $\theta$  angles vary between  $\theta = 0^\circ$  and  $\theta = 45^\circ$ . For  $\theta = 60^\circ$  and 75°, the values of normalized SIF are very close.

In Figure 7, which represents the second mode, we notice that  $\overline{K_{II}}$  values increase with the crack length

for allangles except  $\theta = 10^{\circ}$  where  $\overline{K_{II}}$  data finishes by decreasing from a/W<sub>1</sub>>0.6.

To have a well understanding of the influence of the mixed mode (I+II), we have represent the  $\overline{K}_{eg}$  datain Figure 8.



Fig. 6. Evolution of normalized stress intensity factor  $\overline{K}_I$  with crack length and inclination angle  $\Box \theta$ ,  $E_1/E_2 = 21.276$ 



Fig. 7. Evolution of normalized stress intensity factor  $\overline{K}_{II}$  with crack length and inclination angle  $\Box \theta$ ,  $E_1/E_2 = 21.276$ 



Fig. 8. Evolution of normalized equivalent stress intensity factor  $\overline{K}_{eq}$  with crack length and inclination angle  $\theta$ ,  $E_1/E_2 = 21.276$ 

Graphs in Figure 8 show the increase of normalized stress intensity factor with crack length and this, for all the inclination angles of the crack except for  $\theta = 75^{\circ}$  where  $\overline{K}_{eq}$  remains constant for all geometric ratios a/W<sub>1</sub>.

From the results, the influence of the interface on the evolution of  $\overline{K}_{eq}$  is significant for a/W<sub>1</sub>>0.3 and the slope evolution of graphs seems higher especially for inclination angles between  $\theta = 0^{\circ}$  and  $\theta = 60^{\circ}$ . This slope is less pronounced for  $\theta > 60^{\circ}$ .

These results show that the increase of  $\overline{K}_{eq}$  with the ratio of crack size to the distance to the interface depends strongly on the ratio of Young's moduli of the two materials: under uniform applied displacement,  $\overline{K}_{eq}$  decreases when the crack inclination becomes closer to the interface direction if the crack is located in the weakest material.

Also it is important to insist that the width ratio  $W_1/W_2$  has no effect on the  $\overline{K}_{eq}$  results and this is connected to the boundary conditions which states that  $\frac{\sigma_1}{\sigma_2} = \frac{E_1}{E_2}$ .

The mismatch effect concerns also the mixed mode of fracture and depends on crack inclinaison angle. It is important to established that normalized equivalent stress intensity factors values in mixed mode will never exceed the ones obtained for the case of the first mode of fracture, i.e  $\theta = 0^{\circ}$ .

The fact to consider geometric ratio of specimen  $W_1/W_2=1.5$  in mixed mode don't have any influence on the decreasing tendency of the stress intensity factor which is confirmed by [Kazi Tani et al. 2009] for geometric ratio  $W_1/W_2=1$  in mode I.

### 3.2. Symmetric cracks in bi-material ring specimen:

## 3.2.1. Influence of interface position on the stress intensity factors

Figure 9 shows a bi-material cracked ring specimen where the edge cracks are located symmetrically with a length and subjected to a compression load F. Mechanical properties of material 1 are (Young modulus  $E_1$ = 3050 MPa, Poisson ratio  $v_1$ =0.39) and for material 2, we have(Young modulus  $E_2$ = 64300 MPa, Poisson ratio  $v_2$ =0.33).

Geometric ratio of the crack is defined by  $a/(R_2-R_1)$  which varies between 0.1 and 0.7, radius ratio of ring is  $R_2/R_1 = 4.0$  and the thickness of the ring specimen is equal to 5mm.

Numerical model of the cracked specimen is considered with a flat edge where a pressure of P=F/S is applied (S is the flat cross section). The resolution is performed in plane stress using 8 nodes quadratic elements, (Figure 9). The global stress for this case can be expressed with the following relationship given by [20]:

$$\sigma_g = \frac{3F(R_2 + R_1)}{\pi B(R_2 - R_1)^2} \tag{13}$$

The calculation of the normalized stress intensity factors is done by using the formulation  $K_0 = \sigma_g \sqrt{\pi a}$  at crack tip A and B. Then, we obtain on the following graphs, Figure 10 and 11 respectively for mode I and mode II at crack tip A.

Figures 12 and 13 show the same factors for the crack tip B. In each case, the SIFdata decreasewhen the interface angle increases. A minimum appears more or less pronounced for a normalized crack length of 0.4.





a/ Compression loading of cracked specimen b/ FEMeshing of cracked specimen

Fig. 9. Numerical model of bi-material ring with symmetric edge cracks



Fig. 10. Evolution of normalized stress intensity factor in mode I (opening) at crack tip A,  $E_1/E_2 = 0.047$ 



Fig. 11. Evolution of normalized stress intensity factor in mode II (shear) at crack tip A



Fig. 12. Evolution of normalized stress intensity factor in mode I (opening) at crack tip B



**Fig. 13.** Evolution of normalized stress intensity factor in mode II (shear) at crack tip BThe Figures 14 and 15 show the evolution of normalized equivalent stress intensity  $\overline{K}_{eqA}$  and  $\overline{K}_{eqB}$ 



Fig. 14. Evolution of normalized equivalent stress intensity factor at crack tip A



Fig. 15. Evolution of normalized equivalent stress intensity factor at crack tip B

For  $\alpha \Box$  inclination angles between 0° and 85° (Figure 14), we notice that normalized equivalent SIF $\overline{K}_{eqA}$  data are very small and present an overlap when the crack tip A grows in the material with lower young modulus. For the case of crack tip B which is located in the material 2, the values of normalized equivalent stress intensity factors  $\overline{K}_{eqB}$  (Figure 15) are very high and their evolution is on progress especially for crack lengths  $a/(R_2-R_1)\geq 0.4$ . When $\alpha$  varies between 95°

and 165°, the crack tip A is located in the most stiffener material (aluminium) and  $\overline{K}_{eqB}$  values are closeand quite small.

Also, it is very interesting to represent in  $\Box$  Figure 16 and Figure 17 the evolution of the same stress intensity factors  $\overline{K}_{eqA}$  and  $\overline{K}_{eqB}$  with inclination angle  $\alpha$ .



Fig. 16. Effect of interface angle  $\alpha$  on normalized equivalent stress intensity factor at crack tip A



Fig. 17. Effect of interface angle  $\alpha$  on normalized equivalent stress intensity factor at crack tip B

Figures 16 and 17 show the both zones of crack tip evolution where the interface is marked by a vertical dashed line which corresponds to  $\Box \alpha = 90^{\circ}$ . For the case where  $\alpha$  is below 90° (Fig.16), the crack tip A is located in the material 1 and thestress intensity factor values  $\overline{K}_{eqA}$  are low and looks the same until $\alpha$  is near 85° where the tendency to decrease is more significant.Near $\alpha = 90^{\circ}$ , wenotice that  $\overline{K}_{eqA}$  increase due to the higher stiffness. This evolution is even more significant with crack size  $a/(R_2-R_1)$ . Figure 17 shows the opposite evolution for crack tip B.This is due to fact where the crack tip is located in the weakest material.

#### 3.2.2. Influence of material properties on stress intensity factors

The influence of material properties on normalized stress intensity factorshas been study for  $\alpha = 75^{\circ}$  and  $120^{\circ}$ , and material ratio  $E_2/E_1=2$ , 4 and 6 (see Fig.18-a and Fig18-b). For the case where  $\alpha = 75^{\circ}$ , the graphs seem very close for any material ratio.

When  $\alpha = 120^{\circ}$ , the crack tip A is located in the stiffer material,  $\overline{K}_{eqA}$  increases more significantly as crack length ratio increase. The growth tendency has been presented in the paper of [Madani et al. 2007] for the case of bi-material plate with an edge crack in term of energy release rate variation with crack length and material ratio  $E_2/E_1$ .



Fig. 18-a. Evolution of normalized equivalent stress intensity factor with crack length and material ratio  $E_2/E_1$  for  $\alpha=75^\circ$ 



Fig. 18-b. Evolution of normalized equivalent stress intensity factor with cracklength and material ratio  $E_2/E_1$  for  $\alpha=120^{\circ}$ 

Finally it is interesting to study the variation of  $\overline{K}_{eqA}$  according to  $E_2/E_1$  for different values of  $\alpha$  and for a fixed crack length  $a/(R_2-R_1)=0.4$  (Fig.19). In this Figure, the corresponding values to  $\alpha = 90^{\circ}$  have been calculated using Excel program based on node displacements obtained by finite element method and equations (1) to (9). The results show that some of the graphs follow a growthevolution when  $\alpha > 90^{\circ}$  and the crack tip A is located in the stiffermaterial. For  $\alpha \le 90^{\circ}$ , the  $\overline{K}_{eqA}$  values decrease especially when  $\alpha = 0^{\circ}$ ,  $\alpha = 30^{\circ}$  and  $\alpha = 85^{\circ}$  where the  $\overline{K}_{eqA}$  values are very close.



Fig. 19. Variation of normalized equivalent stress intensity factor at crack tip A with material ratio  $E_2/E_1$  and  $\alpha$  for  $a/(R_2-R_1)=0.4$ 

Most of the numerical results show that compression test on the cracked ring specimen formed by bi-material presents a continuity of normalized equivalent stress intensity factors volution in term of orientation angle, stiffness ratio and normalized crack length. Then, it is much easier to characterize the fracture strength of cracked interface.

The fracture toughness of a brittle biomaterial can be evaluate from Figure 19 according to Young's modulus ratio  $E_2/E_1$  and inclinaison angle  $\alpha$ . Due to the fact that we are in elastic case, fracture toughness is given by multiplying  $K_{eqA}$  by the ratio  $F_c/F_{comp}$  where  $F_c$  is the critical load and  $F_{comp}$  the computing load.

### 4. Conclusion

This study has extended the mismatch effect analyses for the mixed mode of fracture as the published results were only concerningthe case of opening mode. In this paper, it has been noticed that the mismatch effect can be present in the mixed mode of fracture for both cases such as: bi-material plates with inclined crack under tensile loading and bimaterialcracked ring specimen subjected to compression loading.

The results show that the mismatch effect depends on the crack length for bothopening mode and on the crack inclination angle i.e the bimodality crack loading. This effect is characterized by the tendency to decrease of the equivalent SIF in mixed mode when the crack tip is located in the weakestmaterial. Hence, we confirm the results obtained by [Kazi Tani et al. 2009] and experimentally by [Cirello et al. 2006] whohaveused the same specimen in the first mode of fracture with different width ratio.

In order to develop toughnesstests for cracked bi-materialspecimens, we have studied the mismatch effect by using a cracked bi-material ring. The choice of this specimen is based on the

fact that its manufacture is easy and cheaper. Furthermore, its shape allows us to change the bimodality by a simple rotation of the interface to loading direction.

The results show that it can be easy to obtain specimen calibration function in order to determine the critical stress intensity factor. The low cost of the test specimen and the execution celerity can allow easily getting the intrinsic curve of the interface fracture for bi-material.

## Nomenclature

**K** [MPa.m<sup>1/2</sup>]: Stress intensity factor. **K**<sub>1</sub> [MPa.m<sup>1/2</sup>]: Stress intensity factor for the first mode of fracture.

 $\mathbf{K}_{2}$  [MPa.m<sup>1/2</sup>]: Stress intensity factor for the second mode of fracture.

ε: Bi-elastic constant of material.

**E**<sub>i</sub>: Young modulus of material*j*.

 $v_i$ : Poisson ratio of material*j*.

 $G_i$ : Shear modulusof material *j*.

 $\mathbf{u}^{i}$ :Displacement of node*i* with respect toxaxis.

 $\mathbf{v}^{i}$ : Displacement of node *i* with respect toyaxis.

s: distance between nodes a and c or a and e.

**a** [m]: Crack length.

W [m]: Plate wide.

 $\mathbf{K}_{eq}$ [MPa.m<sup>1/2</sup>]: Equivalentstress intensity factor.

 $\overline{\mathbf{K}}_{eq}$ [MPa.m<sup>1/2</sup>]: Normalized equivalent stress intensity factor.

 $\overline{\mathbf{K}}_{eqA}$  [MPa.m<sup>1/2</sup>]: Normalized equivalent stress intensity factor at crack tip A.

 $\mathbf{\overline{K}}_{eqB}$ [MPa.m<sup>1/2</sup>]: Normalized equivalent stress intensity factor at crack tip B.

 $\mathbf{R}_{1}$ [m]:Internal radius of cracked ring specimen.

 $\mathbf{R}_{2}$ [m]:External radius of cracked ring specimen.

 $\sigma_{g}$  [MPa]: Global applied stress

 $\sigma_{g1}$  [MPa],  $\sigma_{g2}$  [MPa]: are respectively the applied stress in y direction for material 1 and 2

 $\alpha$  [°]:Inclination angle of interface with respect to x axis.

 $\theta$  [°]:Inclination angle of the crack with respect to x axis.

SIF: Stress Intensity Factor

**RGB: Red Green Blue** 

PSM1/Al: Polycarbonate/Aluminium

## Извод

# Еволуција фактора јачине напона у мешовитом режиму уз присуство ефекта неподударања

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## Резиме

У овој студији, нумерички модели засновани на методи коначних елемената су развијени за неколико примена механике лома. Употреба узорка са прслином формираног од различитих материјала је омогућила анализу ефекта положаја прслине разумевање неподударања ефекта за случај мешовитог режима лома. Са друге стране, веома је занимљиво анализирати ефекат положаја интерфејса и оптерећења за случај прстенасте симетричне узорка са прслином под притиском.

**Кључне речи**: Пукотина, интерфејс, би-материјал, мешовити режим, фактори јачине напона, ефекат неподударања

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