The influence of bi - material interface on crack propagation paths

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Abstract. This paper presents the particularities of crack propagation near an interface with emphasizing the possibilities of crack path. The crack paths are presented comparatively for homogeneous and non-homogeneous/interface case.

The results of fracture parameters and crack paths are influenced by the crack position and materials combination. For the case of a Three Point Bending specimen with a crack parallel to the interface the crack propagation paths obtained experimentally and numerically are in good agreement. Different materials combinations were considered for the two half's and the influence of the ratio between the two Young's modulus on the crack paths was numerically investigated. Other issues like applied mixed mode load, stress intensity factors for curved cracks, crack propagation criteria, crack increment are discussed.

Introduction

The presence of cracks has a major impact on the reliability of advanced materials, like fiber or particle reinforced composites or laminated composites. In the fabrication process of composite materials or in service interface cracks could appear in one of the constituents. These cracks growth and reach the interface and then can be deflected by the interface or can penetrate in the other constituent.

Many authors [1 - 4] suggested that the presence of interface leads to changes in the stress field and fracture parameters at the tip of a crack approaching the interface. Simha et al. [5] and Kolednik et al. [6] highlight the phenomena of shielding and anti – shielding produced by the bimaterial interfaces. Chapa-Cabrera and Reimanis [7] showed that plastic yielding at the crack tip could influence the stress concentration and the mode-mixity for cracks in layered materials. Kim et al. [8] examined the dependence of shielding and amplification effects on the thickness of interlayer, and on the distance of the crack tip to interlayer.

The Three Point Bend (TPB) specimen could be used for investigating the singular stress field in mixed mode conditions, [2] and was adopted for investigating of crack propagation.

A crack approaching an interface between two materials with different mechanical properties experiences changes in the stress field due to shielding or anti shielding effects and alter the stress intensity factors [9]. This will influence the path of the crack propagation.

Experiment

The crack path is influenced by the presence of bi-material interfaces. The Three Point Bend specimens made by PMMA (homogeneous) and half of Aluminum half of PMMA were adopted Fig. 1. Bonding of the two parts was done with Loctite Hysol 9461 epoxy based adhesive, after machining and cleaning of the surfaces (Loctite Cleaner 7061 and 7063). The notch was produced after the bonding by sawing with a razor-blade and diamond paste. Different values for the crack position *b* and crack length *a* were used. A MTS static and dynamic testing machine type 858 Table

Top System was used for bending tests. Tests were performed at room temperature and with a loading rate of 2 mm/min. Different crack paths were obtained for homogeneous and bi-material specimens, Fig. 2. The experimental crack paths were digitized with a microscope and by using an image processing software, were measured and plotted together with the numerical results, Fig.3.

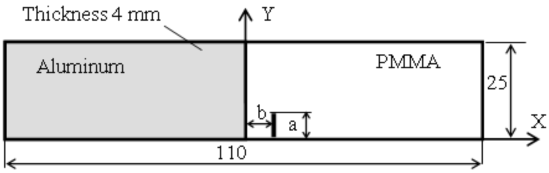


Fig. 1 Bi- material specimen dimensions

Comparison between crack path for homogeneous and bi-material specimens

a. Homogeneous PMMA crack path

b. Bimaterial Aluminum - PMMA crack path

Fig. 2 Cracked specimens

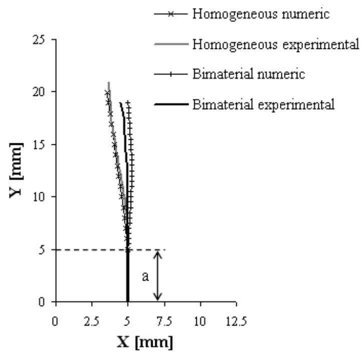


Fig. 3 Experimental vs. numerical crack paths

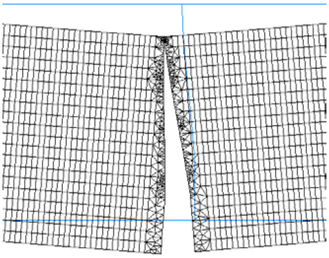
Numerical simulation

Simulation of crack propagation was done using Finite Element Method implemented in FRANC2D/L code, developed at Cornell University. An initial study for determining the crack propagation path for homogeneous case was carried out. Then the TPB specimen with an interface was numerically investigated. Eight node isoparametric elements were used to model the TPB specimen. Eight singular elements were placed around the crack tip as a common technique to model the stress singularity. The initial crack *a* length was considered 5 mm.

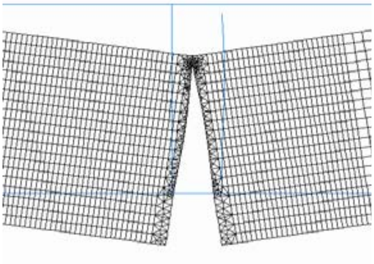
The aim of the initial studies, performed for homogeneous case, was to find the proper method for estimating the stress intensity factors, the mesh density around the crack tip, the method used for crack propagation and the crack propagation increment. The numerical results were compared with the experimental ones. All methods implemented in FRANC2D/L [10, 11] were considered for calculating the SIF's (displacement correlation, modified crack closure and J – Integral), and relatively close results were obtained. The displacement correlation method was used in the crack propagation analysis. Three methods were considered for the crack propagation: maximum principal stress [12], maximum energy release rate [13] and minimum strain energy density [14] as criteria for crack propagation. For the homogeneous case all these methods predict similar crack path, and the maximum principal stress method was adopted for the next investigations. Three different increments (as fraction of the initial crack *a*) were considered for the crack propagation equals with 0.1 *a*, 0.2 *a* and 0.5 *a*. The simulated crack paths were close for all crack increments and in good agreement with the experimental path. A 0.2 *a* crack increment was used for further investigations.

The remesh and fill algorithm was used for the crack propagation studies [10, 11].

The deformed meshes obtained after crack propagation in homogeneous and bi-material specimens are presented in Fig. 4.



a. Crack path for homogeneous case



b. Crack path for bi-material case

Fig. 4 The crack propagation paths starting from an initial crack with $a = 5$ mm and $b = 5$ mm

Results and discussions

Comparisons of the fracture parameters and crack propagation paths for homogeneous and bi-material specimens will be presented. Different parameters influencing the crack path were investigated. Fig. 3 shows the simulation and experimental results for homogeneous and bi-material specimens for an initial crack with $a = b = 5$ mm. Curvilinear paths were obtained for crack propagation in both experimental and numerical investigations. It could be observed that for homogeneous material the crack propagates in order to regain the symmetry, while when the interface is present the crack is push back by the interface, taking into account that the initial crack was placed in the compliant material.

A very good agreement between the simulated and experimental crack path was obtained for homogeneous case and fairly good agreement for bi-material case, Fig.3.

Interface influence on fracture parameters. The Stress Intensity Factors (SIF) K_I and K_{II} were considered as fracture parameters and were calculated using displacement correlation method. The variation of the crack tip mode-mixity:

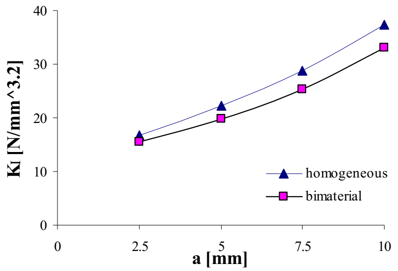
$$\psi = \tan^{-1} (K_{II}/ K_I) \, , \tag{1}$$

and the effective stress intensity factors:

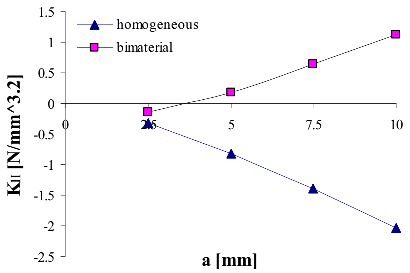
$$K_{eff} = \sqrt{K_I^2 + K_{II}^2} \, , \tag{2}$$

were also calculated.

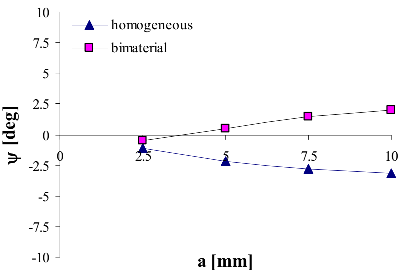
The fracture parameters for homogeneous (PMMA) and bi-material (Aluminum – PMMA) cases with the crack in the PMMA half are presented in Figs. 5 and 6 for a load of 100 N. Fig. 5 presents the results of K_I, K_{II} and ψ with increasing the initial crack length a ($b = 5$ mm). It can be observed that the influence of the interface is higher for longer lengths for both mode I and mode II SIF’s. The mode II SIF has different trend for the bi-material case comparing with homogeneous case. From Fig. 6 it can be observed that the influence of the interface is decreasing when the distance to the interface b is increasing ($a = 5$ mm). The SIF’s and mode-mixity values became closer for longer distances to the interface. For both studies the values of the K_I for interface case are lower than the homogeneous case, highlighting the shielding effect, which appears when the crack is placed in the compliant material [9]. A mixed mode stress field was observed at the crack tip but with lower values of the mode- mixitiy parameter ψ from -3^0 to $+5^0$.



a. K_I versus crack length

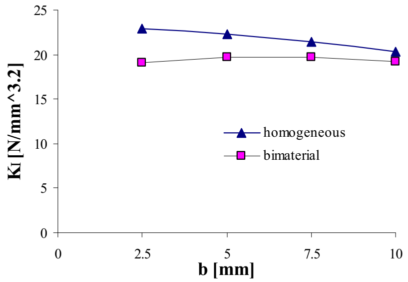


b. K_{II} versus crack length

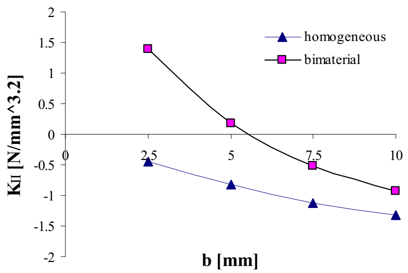


c. ψ versus crack length

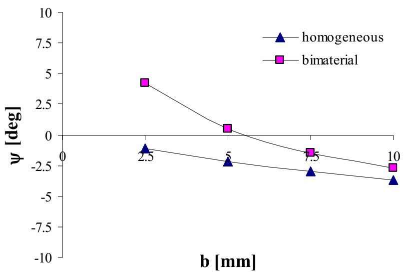
Fig. 5 Influence of crack length



a. K_I versus crack position



b. K_{II} versus crack position

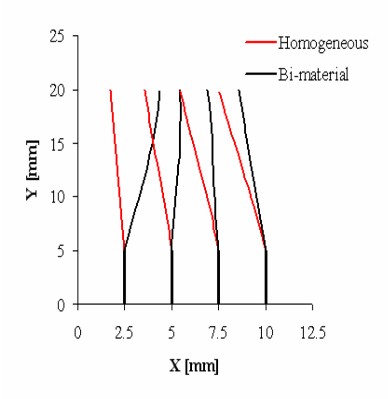


c. ψ versus crack position

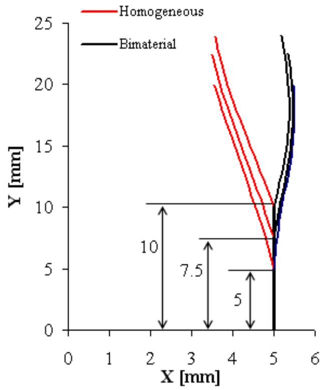
Fig. 6 Influence of crack position

Influence of crack tip position on crack path. Different crack distances to the interface and crack lengths were considered in order to investigate the influence of the bi-material interface on the crack path, Fig. 7. In Fig. 7.a the curvilinear crack paths for homogeneous and bi-material cases are shown for different crack distances to interface, *b*. It can be observed that for cracks close to the interface the difference between the paths is higher. This difference decrease with the increasing *b*, and practically the influence of the interface disappear for higher values of *b*.

The results for different initial crack lengths, with constant distance to the interface (b = 5 mm) are presented in Fig. 7.b. The crack paths are parallel for homogenous cases, respectively for the interface case. Crack propagation direction does not depend significantly by the crack length, which is in agreement with the results of Gunnars et al. [4] studies on different geometries and material combinations.



a. Influence of crack position



b. Influence of crack length

Fig. 7 Influence of crack tip position on the crack path

Influence of material properties. In order to study the influence of the material combination on the crack path four different material combinations, often used in engineering applications, were considered, Tab.1. The numerical analysis was performed using the maximum principal stress theory and the SIF's were determined using displacement correlation method.

Fig. 8 presents the results of the material properties influence on crack propagation path. For the same geometry and loading conditions different crack paths were obtained due to different material properties. For example the crack is attracted by the interface if is placed in the stiffer material (E_1/E_2 = 0.046 and 0.008) and is push back if is situated in the compliant material (E_1/E_2 = 21.54). It can be concluded that the mismatch between materials has a dominant influence on the crack propagation behavior.

Material combination	Material 1		Material 2		E_1/E_2 [-]
	E_1 [MPa]	ν_1 [-]	E_2 [MPa]	ν_2 [-]	
Homogeneous PMMA – PMMA	3250	0.40	3250	0.40	1
Bimaterial Al – PMMA	70000	0.33	3250	0.40	21.54
Bimaterial PMMA – Al	3250	0.40	70000	0.33	0.046
Bimaterial PMMA – Al_2O_3	3250	0.40	400000	0.22	0.008

Table 1. Material properties combinations

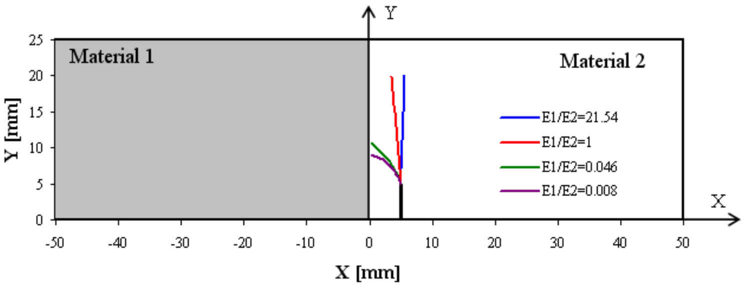


Fig. 8 Influence of material properties on the crack path

Fracture analysis

The fracture analysis was assessed using the normalized SIF's plane (K_I/K_{Ic}, K_{II}/K_{Ic}), with the fracture toughness of PMMA: K_{Ic} = 2 MPa $m^{0.5}$. The effective SIF and the mode–mixity were calculated for the maximum experimental load at which to unstable crack propagation starts. For example for the bi-material case with the crack placed in the PMMA and with dimensions $a = b = 5$ mm the maximum load was F_{max} = 335.1 N. Fig. 9 presents the failure envelope based on the maximum principal stress theory [12] together with the point 1 represented by the effective SIF and mode – mixity. It can be observed that point 1 is outside the failure envelope, and characterized by unstable crack propagation.

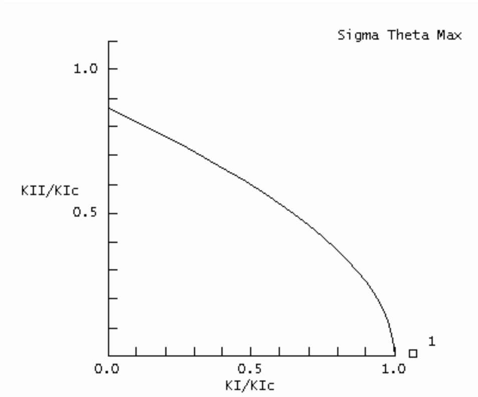


Fig. 8 Influence of material properties on the crack path

Conclusions

This work presents the experimental and numerical results of the influence of interface on the crack propagation path. Three Point Bend homogeneous and bi-material specimens were experimentally and numerically investigated. The following conclusions could be drawn:

- The presence of interface influences the fracture parameters and crack propagation paths.
- Similar crack paths were obtained experimentally and numerically. The displacement correlation method for calculating the fracture parameters, the remesh and fill algorithm and the maximum principal stress criteria implemented in the Finite Element Analysis accurately predict the curvilinear crack propagation path.
- Crack propagation paths are influenced by the crack position relative to interface.

- The material combination has a significant role on the crack propagation path. When the crack is in the stiffer material will propagates toward the interface, and when is situated in the compliant material is push back by the interface.
- Failure analysis was performed for assessment of the unstable crack growth.

Acknowledgments

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