Progressive Crack Propagation in Bi-material Adhesive Bonding

Hamed Yazdani-Nejad [a] and Saeid Hadidi-Moud [b, 1]

Mechanical Eng. Department, Faculty of Engineering, Ferdowsi University of Mashhad, Iran

[a]h.yazdaninejad@gmail.com , [b]hadidi@ferdowsi.um.ac.ir

Keywords: Quasi-static, Crack Propagation, Bi-material Interface, Finite Element Analysis

Abstract

The extensive use of adhesive bonding has placed significant research interest in development of fracture prediction tools for bi-material interface problems. The focus of the research reported here is to address this issue for a specific adhesive bond problem. This has been achieved through the development of a comprehensive transformative numerical code in ANSYS. Fundamental hypotheses are presented in order to employ relevant singular elements on crack tip. Element type and size effects on results are discussed. The fracture criterion examined for modeling progressive growth of sharp crack in E27/steel interface is based on the maximum principal stress. Recent laboratory findings were used for Mode-I fracture data of CT specimen. Analyses have been implemented by modeling both linear elastic and nonlinear hardening behavior of E27 according to standard tensile test data for this epoxy. The results are discussed in details. Also a simple brittle failure predicting approach, based on near tip linear elastic interfacial fracture mechanics (LEIFM), is demonstrated and proposed to the specific bond problem. Final model affords to elaborate acceptable failure conditions for bi-material bonded structures with interfacial cracks.

Introduction

The industrial applications of adhesively bonded multi-layers alter from huge to nano structures. Typical applications include adhesive bonds in automotive and aerospace industries, fiber/matrix and interlaminar bonding in composites and protective and structural film adhesion in microelectronic components. The failure mechanisms of these structures may be different, including cohesive and adhesive failure, crack branching and cracks with oscillating paths. The characteristics of fracture through the interface are strongly influenced by the properties of the interface and of the materials on either side of the interface. Also the interface properties influence the advance of cracks throughout the bonded components.

The solutions to interfacial fracture problems were provided initially by Williams (1959), England (1965), Erdogan (1965), Rice and Sih (1965) and Malyshev and Salbanik (1965) [1-5]. Rice [6] introduced an angular measure of mixed mode fracture as the ratio of mode-II to mode-I stress intensity factor. Many researches have focused on the establishment of a numerical approach to present the failure behavior of bi-material interface cracked structures. Chen and Dillard [7] predicted the trajectory for directionally unstable cracks in adhesive bonds using FE analysis based on the energy model. Also Dwivedi and Espinosa [8] presented a dynamic crack propagation simulation in a unidirectional carbon/epoxy composite through finite element analyses of asymmetric impact (shear loading) of a rod against a rectangular plate. In their study crack propagation was simulated by embedding zero thickness interface element along the crack path. A simple step by step procedure was proposed by Shah *et al.* [9] based on near-tip fracture parameters to calculate the fracture toughness of bi-materials and also to predict the propagation behavior. The conclusion was based upon both the experimental evidence and FE analysis results. Hadidi-Moud *et al.* [10] introduced a new crack propagation approach based on element softening using interface

[1]Currently: Research Staff, Solid Mechanics Research Group, University of Bristol, UK; Saeid.Hadidi-Moud@Bristol.ac.uk

modeling. Their FE results based on progressively propagating rupture element model were in agreement with experimental data for both initiating and propagating behaviours. Shatil *et al.* [11] performed the numerical simulations on three point bend (3PB) specimens and studied the behavior of a crack lying perpendicular to the interface in a ductile/brittle bi-material.
The main objective of this work is to establish an appropriate numerical approach to highlight the practical importance of fracture parameters in the failure prediction of brittle adhesives; and also to introduce a simple approach to identify the appropriate criteria based on stress fields of the interface for a specific bonding adhesive (E27/Al). The experimental data used in this research has been derived from Hadidi-Moud *et al* [10].

The comprehensive transformative code development

A progressive code has been developed in ANSYS according to fig. 1. Loading based on incremental displacement-controlled has been considered for propagation modeling. Some fundamental necessities have been applied to FE framework to attain proper crack propagation:

1- The analysis performed by the code is a quasi-static analysis. As a consequence, kinetic energy and rate-dependent terms are ignored.
2- Element softening approach has been taken into consideration to simulate crack growth on the interface. It is achieved by multiplying tip element component in stiffness matrix by 10^{-6}.

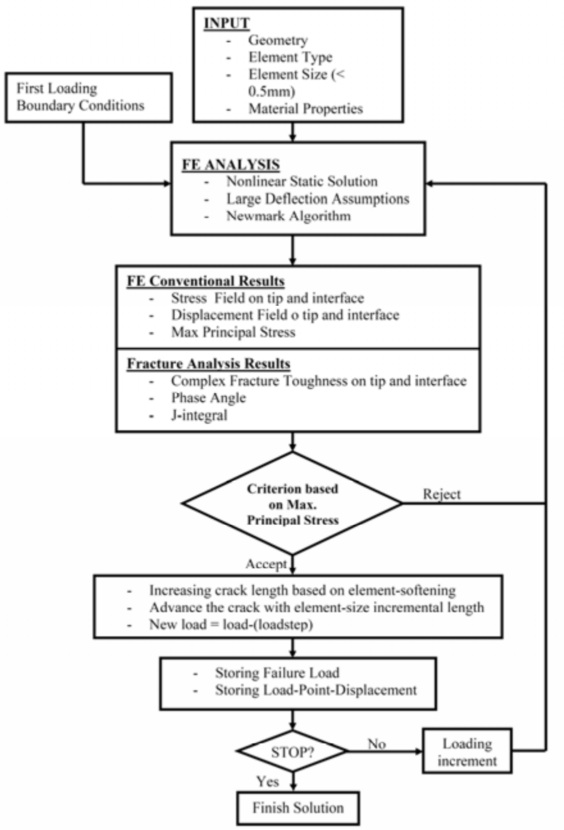


Fig.1. FE approach for simulation of progressive crack propagation in the interface

3- Crack path is just defined along and in the interface plane. Although the alternating crack trajectories in adhesive layer are shown in the other researches [7], by reducing local peripheral thickness, anticipated crack direction in interface will be achieved in standard CT specimens [10].
4- An internal loop has been used to resolve the new cracked interface, namely; another propagating step may occur due to the previous loading step and also a crack size difference more than one element size might be possible during one loading step. As a result, it is possible to reach to a requisite accuracy during crack propagating due to previous loading.
5- Interface element size for each simulation is lower than 0.3 [mm]. The accuracy of self-similar progressive simulation is handled by these values.
6- E27 is an adhesive exhibiting quasi-brittle behaviour. Standard tensile test results have been used as inputs for material modeling [10].
7- Criterion: As mentioned above, E27 is similar to brittle adhesives, so in spite of cohesive law, using maximum principal stress (MPS) and maximum shearing stress (MSS) as the criterion is also admitted in the framework of LEIFM.

Case study

CT fracture specimen under quasi-static displacement loading will be investigated numerically and experimentally in this section.

Standard Tensile Test results for epoxy E27

A set of standard tensile test results on E27 has been used to extract the material properties of the epoxy in modeling [10]. Fig. 2 shows the linear elastic and nonlinear plastic stress-strain curves for E27 emerged from tensile test. It can be measured that E = 25.956 [MPa], ν = 0.395, Tensile Yield Stress = 25.96 [MPa] and Ultimate Tensile Stress = 47.0 [MPa]. Two methods have been used for material definition in FE code: Elastic and stress-strain values.

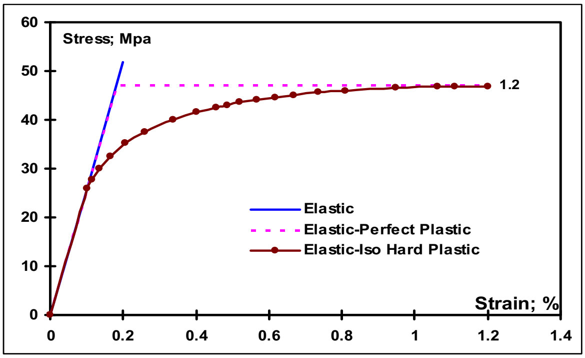


Fig. 2. Standard stress-strain curve for E27 [10].

Fracture experiments on CT-specimens in opening mode

Aluminum-based CT specimens adhered by E27 (Fig. 4a) have been tested in opening and mixed modes [10]. Material properties in simulations for the Aluminum were considered as elastic (E = 70 [GPa], ν = 0.333). Failure loads versus crack length have been measured in the opening mode for 34 specimens [10]. Fig. 3 shows these results. To determine zero-crack initiation loading, 12 additional tests have been performed. The average measured initiating load was 1436 [N].

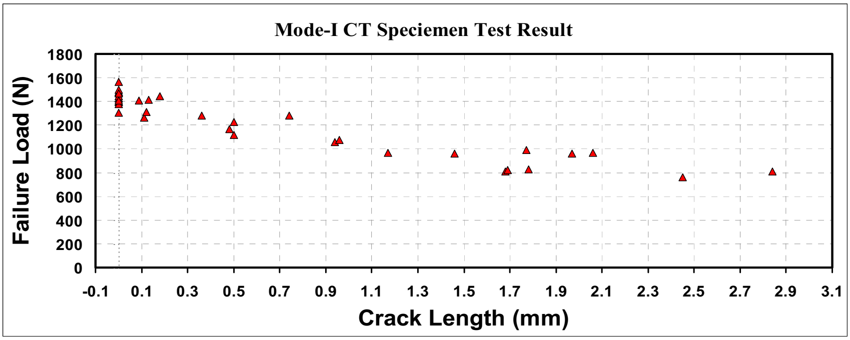


Fig. 3. Failure loading vs. crack length in standard fracture tests for opening mode [10].

Adoption of criterion for E27/Al interface: Discussion on near-tip stress fields

The purpose of this section is to pursue and confirm the practical criteria for crack initiation and propagation in E27/Al interface due to the real failure loads achieved by experiments based on previous mentioned general criteria like MPS. The purpose is to introduce detailed evidence to confirm the known criterion, appropriate for this special interface cracked system. First of all, the main assumption supports this idea that crack growth happens in the interface only; i.e. both adhered materials are tougher than adhesive. In other words, the maximum toughness of adhesive layer can be considered less than the minimum toughness of two layers. This can be an admissible pre-supposition because E27 is a brittle adhesive. All the experiments have been performed in terms of interfacial crack growth [10] and hence the model is also formed based on bi-material interface cracking. Therefore it would be in vague to consider other failure types like kinking or reciprocating crack path [7]. The research has focused on seeking a way to verify experimental results based on criterion confirmation for a typical system in order to reach an approach that can be generalized to address a range of bi-material interface cracked structures.

The tip values of the MPS have been checked in real failure loads and crack lengths. These criteria are applicable if their critical values in real failure loads and cracks are constant. And vice versa, namely, by reaching to critical values, crack grows upon determined failure loadings. The simplest but not necessarily the most valid criterion for brittle adhesives is that principal tensile stresses approach their critical values near the crack tip.

The failure points have been selected from the experiments reported by Hadidi-Moud *et al.* [10] as shown in fig. 3. FE analysis has been applied in each point by considering all fundamental hypotheses. Triangular element size on interface and around the tip is refined to less than 0.15 [mm] and far from tip it does not exceed 1 [mm]. Mesh sensitivity analysis showed that this level of mesh refinement was sufficient for the FE analyses.

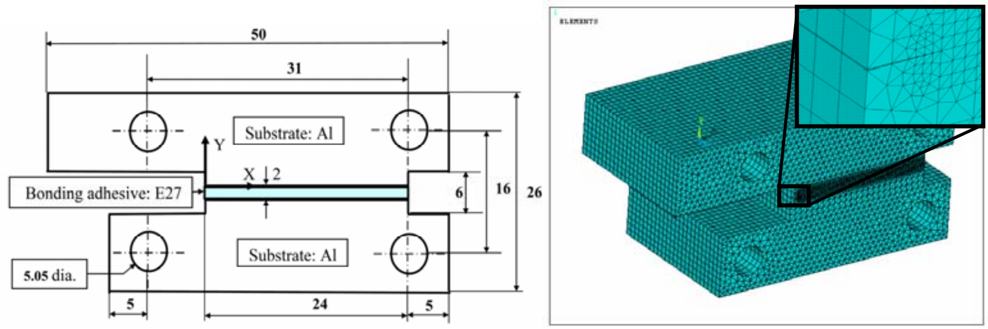
FE analysis of real bi-material specimen with E27 adhesive layer

Different 3D analyses have been performed in order to extract fracture parameters in mode-I loading. A high-order 20-node element (SOLID95) has been used for meshing of 3D model [10]. The accurate model has been successfully developed in ANSYS using SOLID95 elements. Fig. 4b shows the model with three layers.

Crack face has been simulated in upper E27/Al interface like real specimens. Loading pins have been loaded properly in loading directions. Displacement-controlled loading has been modeled on half of the nodes. Refined elements have been applied on loading points. Five sets of FE results have been derived from the analyses:

1. The maximum principal stress on tip and failure criterion,

2. Complex stress intensity factors, Mode mixity and the characteristic distance,
3. Near tip energy release rate (G) and the J-integral around the tip.



(a) (b)

Fig. 4. CT specimen; a) dimensions (depth = 24 [mm]), b) Meshed model prepared by SOLID95.

1. The maximum principal stress on tip and failure criterion

The Study of FE analysis results demonstrates that MPS values obviously remain invariable with respect to crack length as it can be assumed constant in an extensive range of crack lengths (fig. 5).

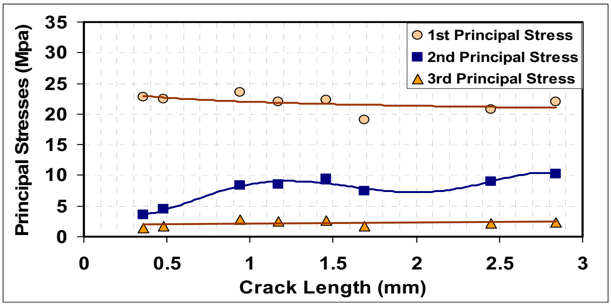


Fig. 5. Tip principal stress values vs. crack length (3D FE analysis).

Results reveal that the maximum ramp of MPS reaches to 1.452 [MPa/mm]. Prior to determination of fracture parameters and examination of fracture criterion based on MPS, a mesh sensibility analysis was performed to validate the FE data.

2. Complex stress intensity factors (K_I, K_{II}), mode mixity and the characteristic distance

The stress components on the interface can be used to assess fracture parameters near tip and on tip using LEIFM. Therefore, it is possible to recognize interfacial behavior during various crack lengths. Also some key results emerge that are beneficial for the criterion. In this section, near tip analyses have been used that will predict a constant distance from tip in which minimum mode mixity (pure shearing) can be seen. The stress intensity factors can be given by eqs. (1) and (2).

$$K_I = \frac{\sigma_{yy}\sqrt{2\pi\ r}}{\cos(\varepsilon \ln r)} \tag{1}$$

$$K_{II} = \frac{\sigma_{xy}\sqrt{2\pi\ r}}{\cos(\varepsilon \ln r)} \tag{2}$$

where

$$\varepsilon = \frac{1}{2\pi}\ln\left[\frac{(3-4v_1)/\mu_1 + 1/\mu_2}{(3-4v_2)/\mu_2 + 1/\mu_1}\right] \tag{3}$$

In these relations μ and v are shearing module and Poisson's ratio, respectively. Indices 1 and 2 are related to two joined materials. The dominant effect of mode-I in near tip distances can be seen in fig. 6a. The shearing mode after increasing in a short distance takes a constant trend through interface with a steady effect on stress intensity factors. Opening mode's variations have more effect on these coefficients. Pure shearing occurs at 9 [mm] from tip that corresponds to zero normal stress. More analyses indicated that for all crack lengths and failure loads the loci at which pure shear (zero mode-I) occurs is a constant distance from the tip. For this specific joint, this distance equals to about 9 [mm]. Figs. 6a to 6d, correspond to experimental failure points of fig. 3, confirm that the pure shearing mode distance for various failure points is approximately 9 [mm] for the CT specimen (fig. 4). Due to inseparability of failure mode-I and II on the interface and singular effects on tip, the need for a new approach to evade the singularities is unavoidable. It can be found that crack initiation occurs in Mode-I loading in which small pure shearing mode is produced at a specified distance. This observed phenomenon is valid only for brittle adhesives and elastic adhered materials in which LEIFM may be applied.
Near tip approaches have been also offered by Shah *et al.* [9] who proposed a new method in order to predict failure point for a 3PB-PMMC/PC bi-material based on near tip (not exactly on tip) parameters. They found that the near tip results were in good agreement with experimental data.

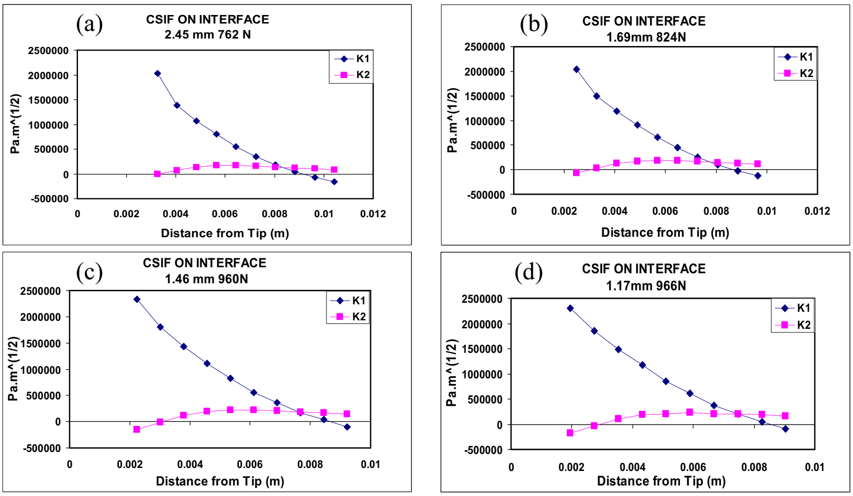


Fig. 6. Interfacial stress intensity factors vs. distance from tip for various failure points; a) 2.45 [mm],762 [N], b) 1.69 [mm], 824 [N], c) 1.46 [mm], 960 [N], d) 1.17 [mm], 966 [N].

In presence of linear equations in the framework of LEIFM, the calculation of characteristic distance is possible by finding of CSIF minimum values. In addition, based on fig. 6, along the crack from tip to the characteristic distance, mode-I values continuously decrease. Therefore the mode mixity angle will increase upon the relation: ψ = atan (K_{II}/K_I). It is obvious that at the characteristic distance, ψ = 90 (pure shearing). Near tip mode-I results for 2.84 mm-crack are presented in fig. 7a.

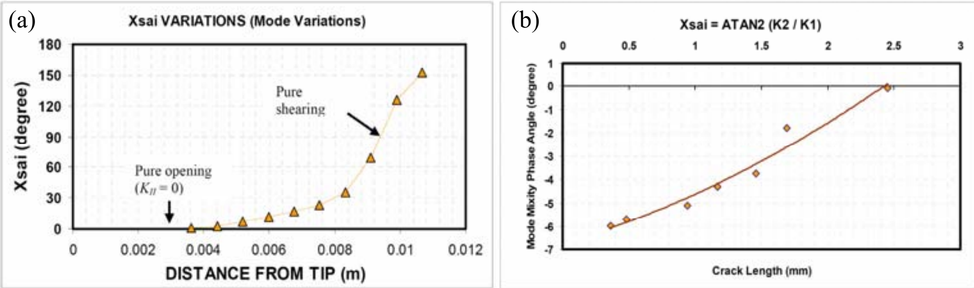


Fig. 7. Mode effects; a) near tip mode mixity angle on interface of a 2.84 mm-crack, b) Mode mixity angle for various crack lengths.

Furthermore, according to near tip mode mixity values, very small shearing mode exists at the tip and it does not entirely vanish. This can be seen in figs. 6a to 6d in which very small negative shearing mode appears at the tip. This effect occurs due to the non-similarity of crack loci in bi-material interface structure: As can be seen in fig. 4a, the notch has been created in upper interface of adhesive layer; therefore some shearing effects influence the crack initiation and propagation under similar opening loads. This phenomenon on tip has been presented in fig. 7b. Higher shearing effect will participate in failure of smaller crack lengths.

3. Near tip energy release rate (*G*) and *J*-integral around the tip

According to ref. [9], near tip analyses can be applied in order to find the failure point of a sharp crack on the interface. But the application of this theory is confined to LEIFM framework. Another observation in this research suggests that the ERR values (*G*) near the tip (not exactly at the tip) are in good agreement with *J*-integral values around the tip and this is the case for various crack lengths and failure loads. Therefore, near tip *G* can be used to predict failure for the E27/Al interface. *G* is given by:

$$G = \frac{(1/E_1 + 1/E_2)(K_I^2 + K_{II}^2)}{2\cosh^2(\pi\varepsilon)} \tag{4}$$

Eq. (4) is only valid when LEIFM can be applied but *J*-integral relation can be used in all linear or nonlinear problems due to its relation to the strain energy density. Fig. 8 shows the approximate equality of *G* and *J*-integral for the specific problem of E27/Al. Therefore, because of simple measurement of *G*, it is possible to use *G* for crack growth simulation instead of the *J*-integral approach.

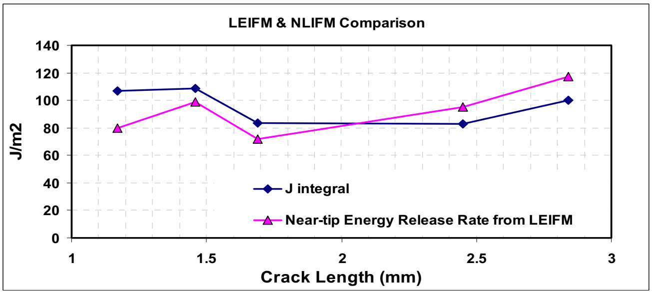


Fig. 8. Comparison between near tip *G* and *J*-integral in various crack lengths.

Experimental verification: Progressive crack propagation at E27/Al interface

The maximum difference between loading steps in the Fe analyses was set to about 0.3 [μm]. These very small loading increments handle the accuracy of analyses. Also within each increment an internal loop is used to resolve the new cracked interface on previous loading step (fig. 1). This means that an additional propagation step is allowed and may occur due to a previous loading step.
MPS has been considered as failure criterion and its critical value for this cracked problem has been considered as 21.860 [MPa]. Fig. 9 shows the results of simulations based on the described assumptions. The figure shows that MPS has been successfully implemented as the failure criterion. Two material modeling; elastic-work hardening and perfectly elastic were examined for E27. Both performed analyses agreed well with the experimental crack growth however it is recommended that elastic-work hardening model is more appropriate.
Another analysis has been performed by double elastic modulus of E27. The results show reduced failure loads in the same loads. Therefore the consideration of higher elastic modulus for E27 (in perfectly-elastic modeling) leads to smaller failure loads due to displacement-controlled loading. Consequently, an important outcome will emerge: in a CT single-material specimen from Al with the same dimensions, smaller loading leads to cracking in similar crack length.
In crack lengths smaller than 0.15 [mm], sudden drop can be seen in fig. 9. These values in smaller cracks relate to the errors in FE analyses. While the element size approaches the crack length, this effect appears. Therefore, smaller element size is needed to improve the results in very small cracks. The average real failure loading for zero-crack equals to 1436 [N] whereas the analyses predict the value of 1152 [N] for crack initiation.

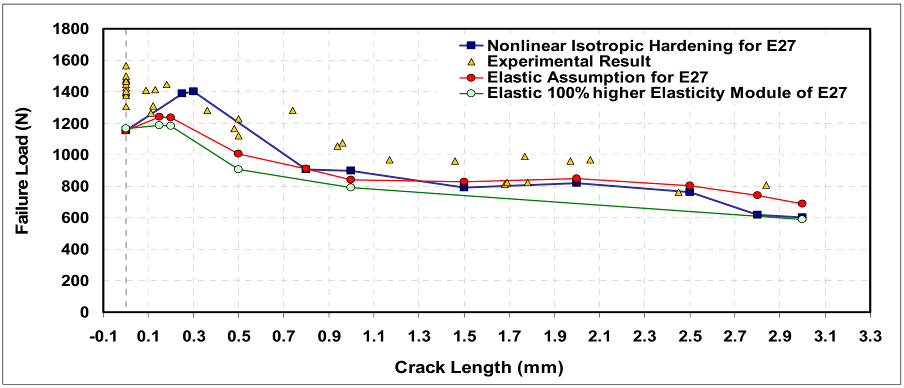


Fig. 9. Comparison of numerical and experimental results for different material models

Concluding Remarks

- According to the numerical results presented in fig. 9 and discussions on stress fields and fracture parameters, it can be concluded that the established code is capable to explain the proper behavior of progressive crack propagating in isotropic elastic bi-material layers adhered by brittle adhesives. Also the criterion used for modeling (MPS) is appropriate for this case of multi-layers.
- In addition, near tip analyses under mode-I loading predict a constant distance from tip in which minimum mode mixity angle corresponding to pure shearing can be seen (fig. 6). A simple brittle failure predicting approach, based on near tip LEIFM, instead of J-integral, can be applied to the specific joint problem (fig. 8). Also failure mode results show that non-similar dimensions cause the shearing mode effects on interfacial cracking even in similar loadings (fig. 7b).
- Final model and the approaches used to find the proper criterion afford to elaborate acceptable failure conditions for bi-material interface cracked structures.

References

[1] J. G. Williams: The stress around a fault or crack in dissimilar media, Bull. Seismol. Soc. Am., No. 49, pp. 199-204 (1959).

[2] A. H. England: A crack between dissimilar media, Journal of Applied Mechanics, No. 32, pp. 400-402 (1965).

[3] F. Erdogan: Stress distribution in bonded dissimilar material with cracks, Journal of Applied Mechanics, No. 32, pp. 403-410 (1965).

[4] J. R. Rice and G. C. Sih: Plane problems of cracks in dissimilar media, Journal of Applied Mechanics, No. 32, pp. 418-423 (1965).

[5] B. M. Malyshev and R. L. Salbanik: The strength of adhesive joints used the theory of cracks, International Journal of Fracture Mechanics, No. 36, pp. 199-217 (1965).

[6] J. R. Rice in: Elastic fracture mechanics concepts for interfacial cracks, Journal of Applied Mechanics (1988).

[7] B. Chen and D. A. Dillard in: Numerical analysis of directionally unstable crack propagation in adhesively bonded joints, International Journal of Solids and Structures, No. 38, pp. 6907-6924 (2001).

[8] S. K. Dwivedi, H. D. Espinosa in: Modeling dynamic crack propagation in fiber reinforced composites including frictional effects, Journal of Mechanics of Materials, No. 35, pp. 481-509 (2003).

[9] Q. H. Shah, M. Azram, M. H. Iliyas in: Predicting the crack initiation fracture toughness for a crack along the bimaterial interface, Journal of Applied Sciences, No. 5, pp. 253-256 (2005).

[10] S. Hadidi-Moud, A. D. Crocombe, G. Richardson in: Modelling interfacial failure in adhesively bonded structures, Proceeding of 5th European Conference on Adhesion (EURADH'2000), Lyon, France (2000).

[11] G. Shatil, A. Saimoto, X. J. Ren in: Ductile-brittle fatigue and fracture behavior of aluminium/PMMA bimaterial 3PB specimens, Journal of Engineering Fracture Mechanics, No. 75, pp. 674-681 (2008).