

Progressive Crack Propagation in Bi-material Adhesive Bonding

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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 this research project is to address this issue for a specific joint problem. Good agreement between numerical and experimental results has been obtained. This has been achieved through the development of a comprehensive transformative numerical code in ANSYS. Fundamental hypotheses have been 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 the maximum principal stress. Recent laboratory findings have been 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. These results have been discussed in details. Near tip analyses under mode-I loading predict a constant distance from tip that minimum mode mixity (ψ) corresponding to pure shearing can be seen. Also a simple brittle failure predicting approach, based on near tip linear elastic interfacial fracture mechanics (LEIFM), is demonstrated and proposed to the specific joint problem. Final model affords to elaborate acceptable failure conditions for bi-material interface cracked structures.

Introduction

The industrial applications of adhesively bonded multi-layers alter from huge to nano structures. Some common uses are 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 ways of these structures may be different, including cohesive and adhesive failure, crack branching, 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 influences the advance throughout this.

The solutions to interfacial fracture problems were provided initially by Williams (1959), Cherepanov, (1962), England (1965), Erdogan (1965), Rice and Sih (1965) and Malyshev and Salganik (1965). Also Rice [1] introduced an angular measure of fracture mode-mix as the ration of mode-II to mode-I stress intensity factors. Many researches have been focused on establishment a numerical approach to present the failure behavior of bi-material interface cracked structures. Chen and Dillard [3] have predicted the trajectory for directionally unstable cracks in adhesive bonds using FE analysis based on the energy model. Also Dwivedi and Espinosa [4] have presented a dynamic crack propagating simulation in a unidirectional carbon/epoxy composite through finite element analyses of asymmetric impact (shear loading) of a rod against a rectangular plate. Crack propagation is simulated by embedding zero thickness interface element along the crack path in their study. A simple step by step procedure is proposed by Shah *et al.* [5] based on near-tip fracture parameters to calculate the fracture toughness of bi-materials and also predict the propagation behavior. The conclusion was based upon both the experimental evidence and FE analysis. Hadidi-Moud *et al.* [7] also introduced a new cracking approach based on element softening using interface modeling. Their FE results based on progressive propagating model are in agreement with experimental data in both initiating and propagating behaviors. Shatil *et al.* [8] performed the

numerical simulations on 3PB specimens to study the behavior of a crack lying perpendicular to the interface in a ductile/brittle bi-material.

The aim of this paper 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 find the proper criterions based on stress fields of the interface for a specific joint (E27/A1). The experimental data has been used in this research has been derived from ref. [7].

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 propagating 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} .

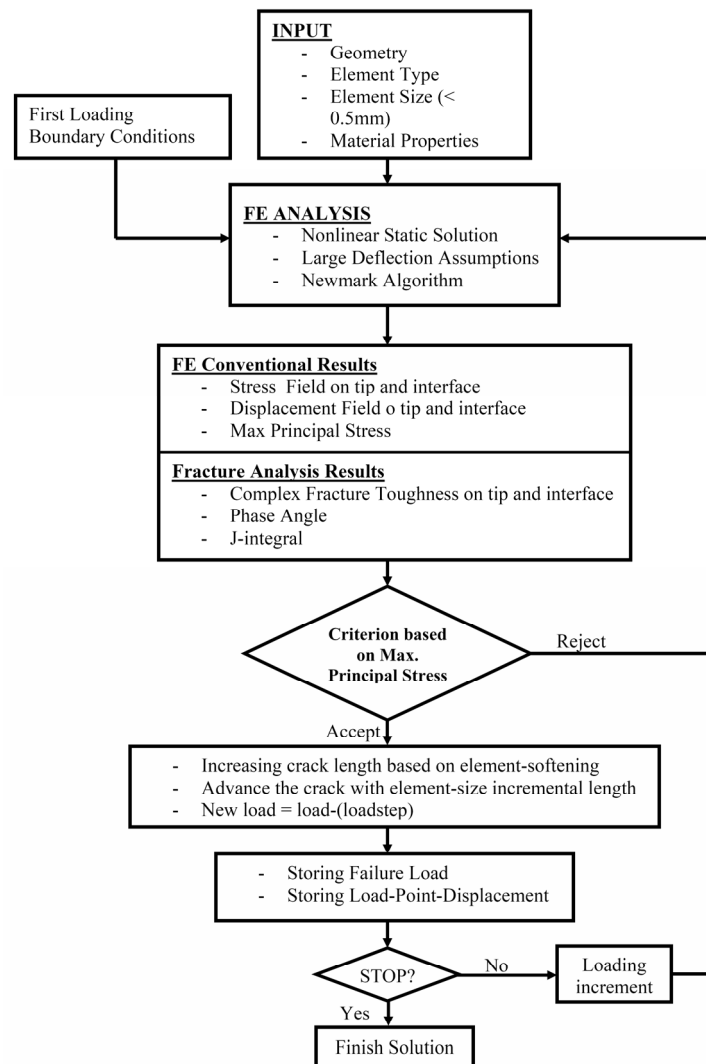


Fig.1. FE approach for simulation of progressive crack propagation in the interface

- 3- Crack path is just defined along and in the interface. Although the alternating crack trajectories in adhesive layer are shown in the other researches [3], by reducing local

peripheral thickness, anticipated crack direction in interface will be achieved in standard CT specimens [7].

- 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 including brittle behavior. Standard tensile test results have been used as inputs for material modeling [7].
- 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 consider material properties of the epoxy in modeling [7]. 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], $\nu = 0.395$, 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.

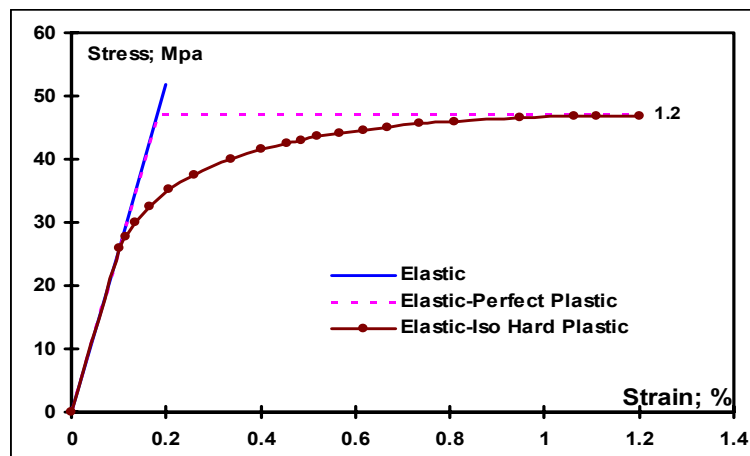


Fig. 2. Standard stress-strain curve for E27 [7].

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 [7]. Aluminum properties are considered elastic ($E = 70$ [GPa], $\nu = 0.333$) in simulations. Failure loads versus crack length have been measured in the opening mode for 34 specimens [7]. Fig. 3 shows these results. To determine zero-crack initiation loading, they have performed 12 additional tests. An average measured initiating load is 1436 [N].

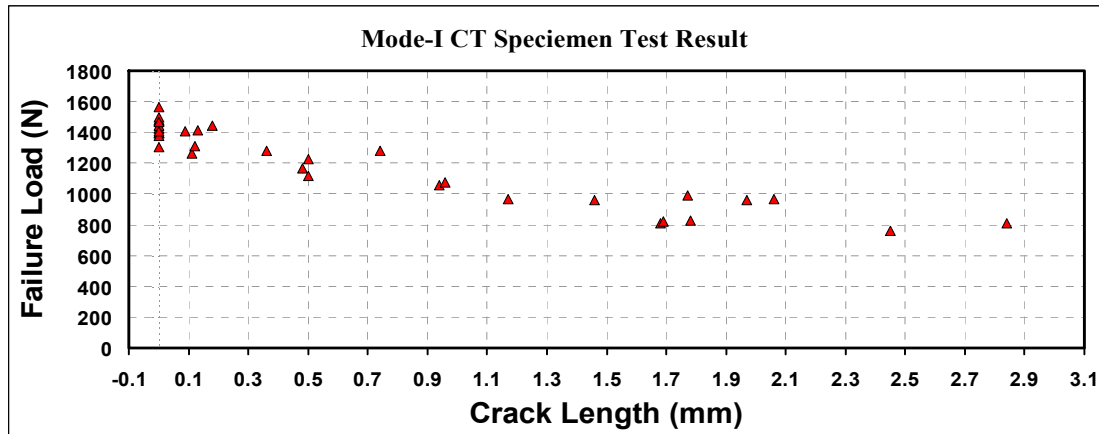


Fig. 3. Failure loading vs. crack length in standard fracture tests for opening mode [7].

Criterion adoption for E27/Al interface: Discussion on near-tip stress fields in failure loads

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 criterions 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; it means that 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. Also the experiments have been performed in terms of interfacial crack growth [7] and this research 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 [3]. The research has focused on seeking a way to verify experimental results based on criterion confirmation for a typical system in order to reach to an approach that can be generalized to the other bi-material interface cracked structures.

The tip values of the MPS have been checked in real failure loads and crack lengths. Those criterions 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 to their critical values on tip.

The failure points have been selected from the experiment of Hadidi-Moud *et al.* [7] as it is shown in fig. 3. FE analysis has been applied in each point by considering all fundamental hypotheses. Triangular element size on interface and around tip considered less than 0.15 [mm] and far from tip equal to 1 [mm].

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 [6]. The accurate model has been successfully established 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 properly have been loaded 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 through analyses:

1. The maximum principal stress on tip and failure criterion,
2. Element size effects on the results,

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

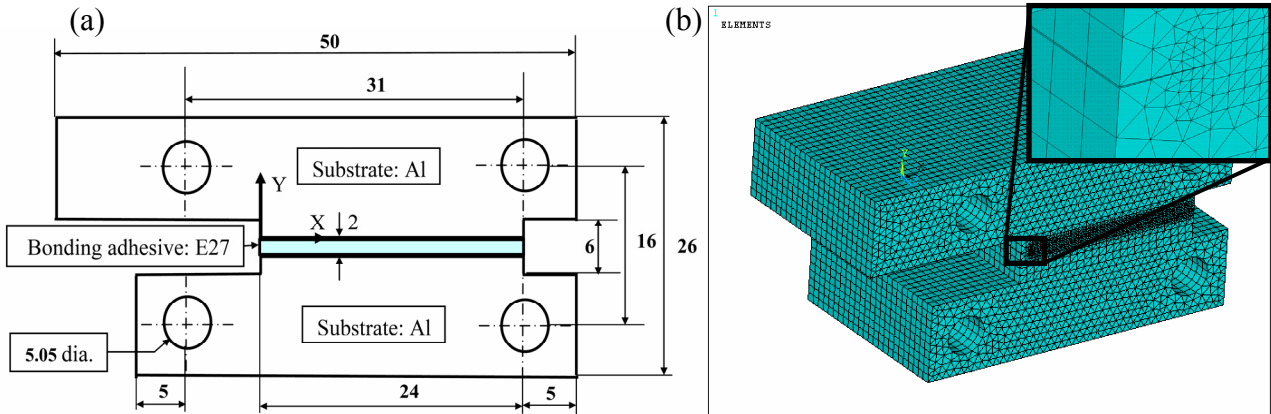


Fig. 4. CT specimen; a) dimensions (depth = 24 [mm]), b) Meshed model prepared by SOLID95.

1. The maximum principal stress on tip and failure criterion

The Study of 3D FE 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).

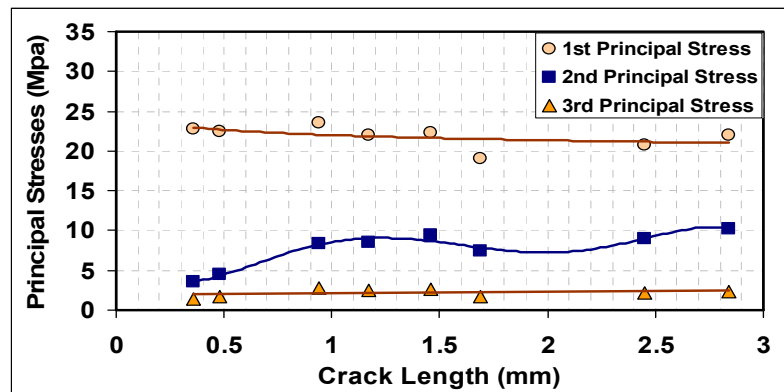


Fig. 5. Tip principal stress values vs. crack length (3D FE analysis).

Results reveal that the maximum ramp of MPS reaches to 1.452 [MPa/mm]. Before investigating fracture parameters and criterion based on MPS, mesh sensibility of the results will be presented.

2. Element size effects on results

The element size effects on principal stress and strain values have been investigated. Fig. 6 shows the tip results of some crack lengths (0.36, 1.46 and 2.84 [mm]) in different element sizes (0.1, 0.2, 0.4, 0.6, 0.8, 1 [mm]). The figure shows abrupt increase in very small element size (0.1 [mm]), but they remains constant in other element sizes. FE elements for all analyses are greater than 0.1 [mm]. In general, principal values are constant with element sizes between 0.1 and 0.8 [mm].

3. 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).

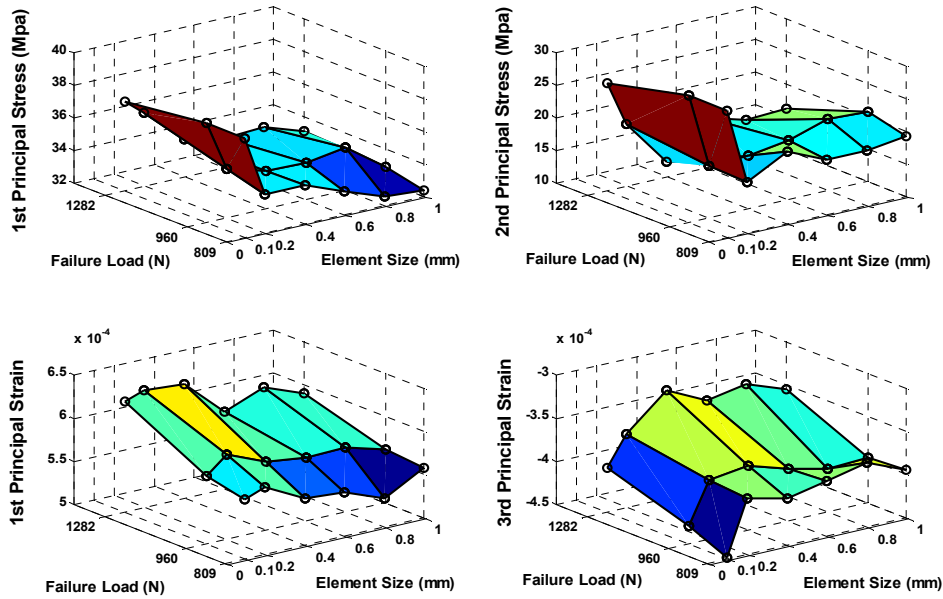


Fig. 6. Element size effects on principal stress and strain values.

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

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

that

$$\varepsilon = \frac{1}{2\pi} \ln \left[\frac{(3-4\nu_1)/\mu_1 + 1/\mu_2}{(3-4\nu_2)/\mu_2 + 1/\mu_1} \right] \quad (3)$$

In these relations μ and ν 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. 7a. 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 as a result of zero normal stress. More analyses have been indicated that in all crack lengths and failure loads, the distance which zero mode-I occurs at, is constant from tip. For this specific joint, this distance equals to about 9 [mm]. Figs. 7a to 7d, corresponding to experimental failure points of fig. 3, confirm that the pure shearing mode distance for various failure points is 9 [mm] for CT specimen (fig. 4). The origin is placed on outer crack edge (fig. 4a) not on tip. Due to inseparability of failure mode-I and II on the interface and singular effects on tip, the need to 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 determined distance. This observed phenomenon is valid only for brittle adhesives and elastic adhered materials in which LEIFM theories can be applied.

Near tip approaches can be also seen in the studies of Shah *et al.* [5]. They have 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. The near tip results are in good agreement with experimental data.

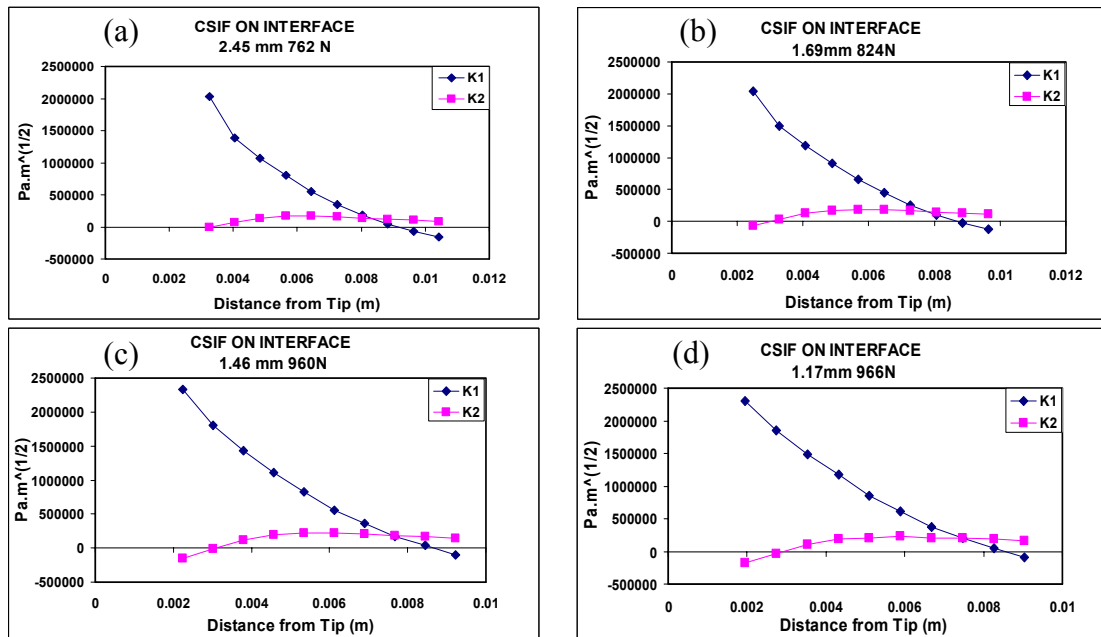


Fig. 7. Interfacial stress intensity factors vs. distance from tip for various failure points; a) 2.45 [mm], 762 [N], b) 1.69 [mm], 824 [N], c) 1.46 [mm], 960 [N], d) 1.17 [mm], 966 [N].

At the 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. 7, through the distance from tip to the characteristic distance, mode-I values decreases. Therefore the mode mixity angle will increase upon the relation: $\psi = \text{atan}(K_{II}/K_I)$. It is obvious that at the characteristic distance, $\psi = 90$ (pure shearing). Near tip mode-I of 2.84 mm-crack has been presented in fig. 8a.

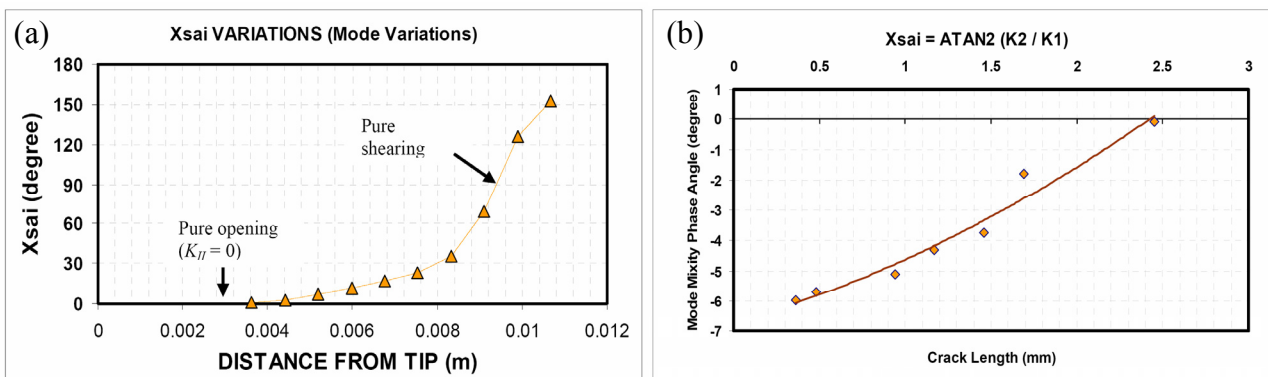


Fig. 8. Mode effects; a) Mode mixity angle near tip on interface of a 2.84 mm-crack, b) Mode mixity angle on tip of various crack lengths.

Furthermore, according to mode mixity values near tip, very small shearing mode exists on the tip and it does not entirely vanish. This can be seen in figs. 7a to 7d in which very small negative shearing mode appears on tip. This effect occurs due to the non-similarity of crack location in bi-material 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. 8b. Higher shearing effect will participate in failure of smaller crack lengths.

4. Near tip energy release rate (G) and J -integral around tip

According to ref. [5], 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 shows that the ERR values (G) near tip (not exactly on tip) are in agreement with J -integral values around tip in various crack lengths and failure loads. Therefore, near tip G can be used to explain the failure moment of E27/Al interface. G can be given by

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

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. 9 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 J -integral.

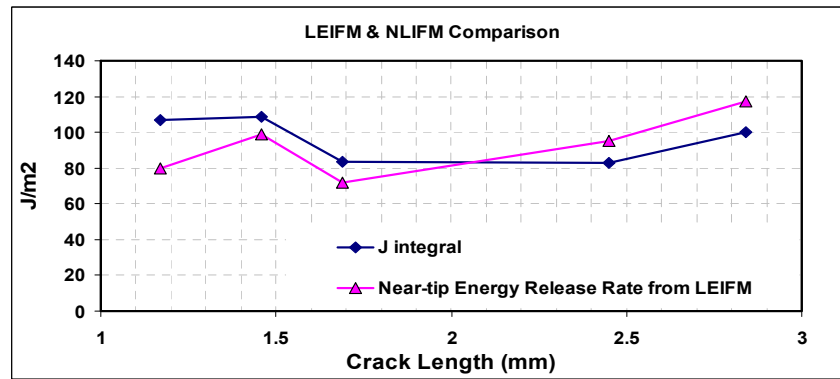


Fig. 9. comparison between near tip G and J -integral in various crack lengths.

Experimental verification: Progressive crack propagation in E27/Al interface

Maximum difference between loading steps is about 0.3 [μm]. These very small loading increments handle the accuracy of analyses. Also an internal loop resolves the new cracked interface on previous loading step (fig. 1): Another propagating step may occur due to the 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. 10 shows the simulation's results upon described assumptions. The figure shows that using MPS as the criterion has been successfully performed. Two material modeling have been applied for E27: elastic-work hardening and perfectly elastic. Both performed analyses are in agreement with experimental crack growth however it is obvious that elastic-work hardening modeling for E27 is more appropriate. Also predicted failure loads for zero-crack length by numerical analyses are different from experimental data.

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 interfacial cracking in similar crack length.

In crack lengths smaller than 0.15 [mm], sudden drop can be seen in fig. 10. These values in smaller cracks relate to the errors in FE analyses. While the element size approaches to 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.

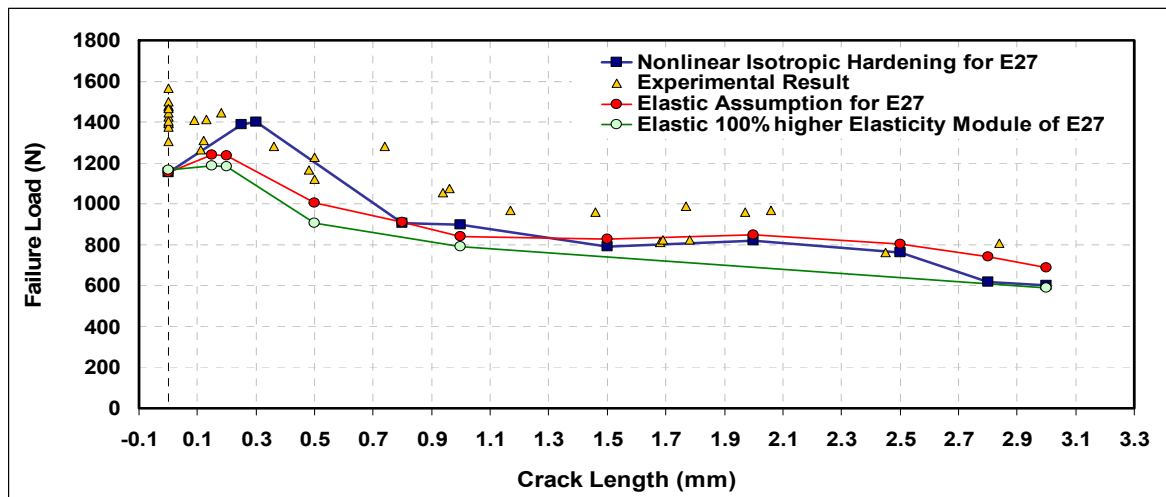


Fig. 10. Comparison between numerical and experimental results in different material modeling.

Concluding Remarks

In accordance with the numerical results presented in fig. 10 and discussions on stress fields and fracture parameters, it can be concluded that the established code is able 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. 7). A simple brittle failure predicting approach, based on near tip LEIFM, instead of J -integral, can be applied to the specific joint problem (fig. 9). Also failure mode results show that non-similar dimensions cause the shearing mode effects on interfacial cracking even in similar loadings (fig. 8b). Final model and the approaches used to find the proper criterions afford to elaborate acceptable failure conditions for bi-material interface cracked structures.

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