DEBONDING OF AN INTERFACE WHEN A CRACK APPROACHES PERPENDICULARLY TO IT

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ABSTRACT

In this paper, we studied the interface debonding when a crack perpendicularly approaches an interface between two dissimilar elastic materials. An interface toughness law was first defined according to an adhesive model governing the interface fracture. By analyzing the interaction between the normally approaching crack and the interface crack and by tacking account of the adhesive forces at ends of the interfacial crack, a model for studying the interface debonding and the debonding stability was established. It is observed that the interface debonding toughness depends strongly on the mixed mode locally produced over the plastic adhesive zone of the interface. These results agree with the experimental works gathered so far and can be used to explain the mechanism of « crack arrestor » formed by an interface.

1. INTRODUCTION

The debonding of an interface between two elastic materials when a crack approaches perpendicularly to it has been observed for long time. It can be schematically described by Fig.1. It may be found that the interface debonding occurs before that the crack tip reaches the interface. By increasing the front surface of the crack tip, the stress concentration decreases considerably when the crack tip touches the interface. This mechanism, so called « crack arrestor » in literature, may lead to delay or stop the crack propagation into the other side of the interface. The application of this mechanism can be found in many engineering domains such like the composite materials, ceramics, welded structures, road constructions etc. In all these structures, the crucial components of structures are the interfaces, which need a particular care in designs.

Even though one can find out numerous investigations concerning the stress singularities at the crack tip when it touches an interface between two elastic materials, the mechanism of the « crack arrestor » has not been thoroughly studied so far The principal interest of the « crack arrestor » is the interface debonding *before* arriving of the crack tip at the interface such that the stress concentration considerably decreases and the dynamic effects influence little on the reinitiation of the crack into the next layer. This possibility is studied in the present work. By using an adhesive model, the critical remote load, the debonding length of the interface and the debonding stability have been studied.

2. ASSUMPTIONS AND SUPERPOSITION SCHEME

Consider the plane elastic problem as shown in Fig.2. Two elastic bodies are bonded by an adhesive interface, both materials are assumed to be isotropic and homogenous. The material 1 occupies the upper half plane and the material 2 occupies the lower half plane. A crack is lain perpendicularly to the interface in the material 2 (hereafter refereed as *the normally approaching crack*). A Cartesian system *oxy* is attached to the interface and coincides with the crack axis. We suppose that the remote stresses only exist in the *x*-direction with $\sigma_x = \sigma^\infty$ in material 2 and $\sigma_x = \sigma^\infty E_1/E_2$ in material 1 with E_1 and E_2 being respectively the Young modules of the materials 1 and 2. The interface debonding is represented by an interfacial crack, with the two end closed by adhesive forces.

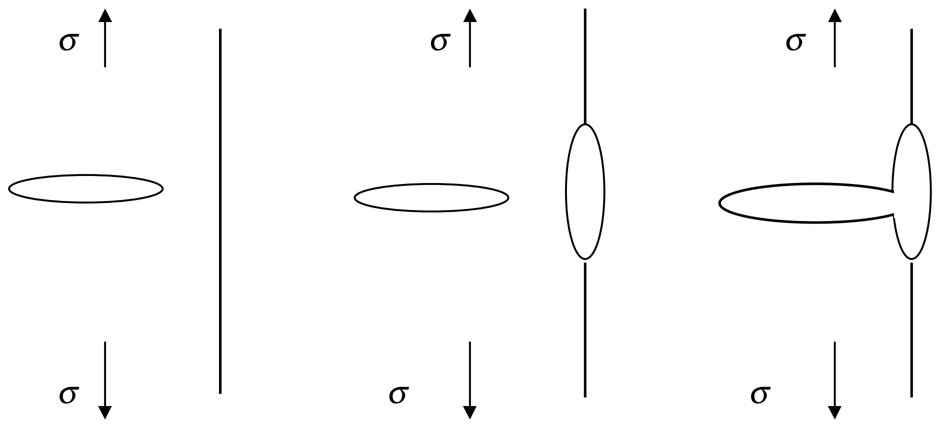

Fig.1: Crack arrestor formed by an interface

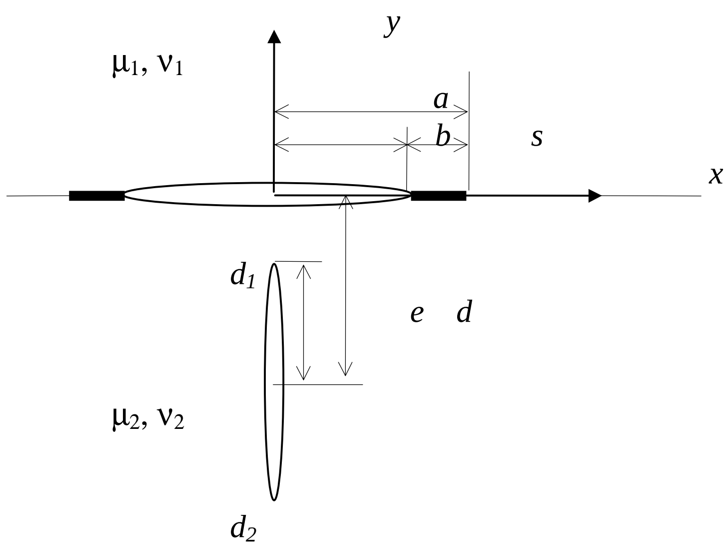

Fig.2: A crack normally approaching an interface and leading to interface debonding

The interface between the two materials is assumed to be perfectly elastic-plastic. The two bodies are bonded perfectly while the traction acting on the interface does not exceed a critical value. Let p and q be the normal and tangential components of the traction force acting on the interface, σ_c and τ_c be the critical values of the interface fracture strength under pure tension and shear loading respectively. We define a parameter λ to represent the interface fracture toughness under mixed loads:

$$\lambda = \sqrt{\left(\frac{p}{\sigma_c}\right)^2 + \left(\frac{q}{\tau_c}\right)^2} \qquad (1)$$

The interface transfers all stresses and deformations when λ < 1. However, the plasticity of the interface develops when λ=1. In this case, only the critical stresses satisfying λ = 1 are transferred by the interface. One can suppose that the interface debonding or the interfacial crack propagation occurs when the length of the plastic zone reaches a critical value s and over this length, the adhesive forces p and q are uniformly distributed. Therefore the condition for the interface debonding and the crack growth is

$$\lambda = 1 \text{ over the critical length } s \qquad (2)$$

The critical parameters s, σ_c and τ_c of an interface can be identified by carrying out a few well-chosen experimental tests. The validity of this interface toughness law will be discussed latter in this paper.

We assume that the condition of the interface debonding occurs before the conditions for crack reinitiation into material 1. The debonding of the interface can be defined as a interface crack at the ends of which the crack lips are closed by the critical value of the interface adhesive forces, i.e. λ=1. From this point of view, the interface debonding can be regarded as a Dugdale-Barenblatt interfacial crack ([1],[2]).

With these assumptions, the problem shown in Fig.2 becomes a problem of interaction between the normally approaching crack and the interfacial Dugdale crack (Fig. 3a). The solution of this problem requires the solutions of the following problems:

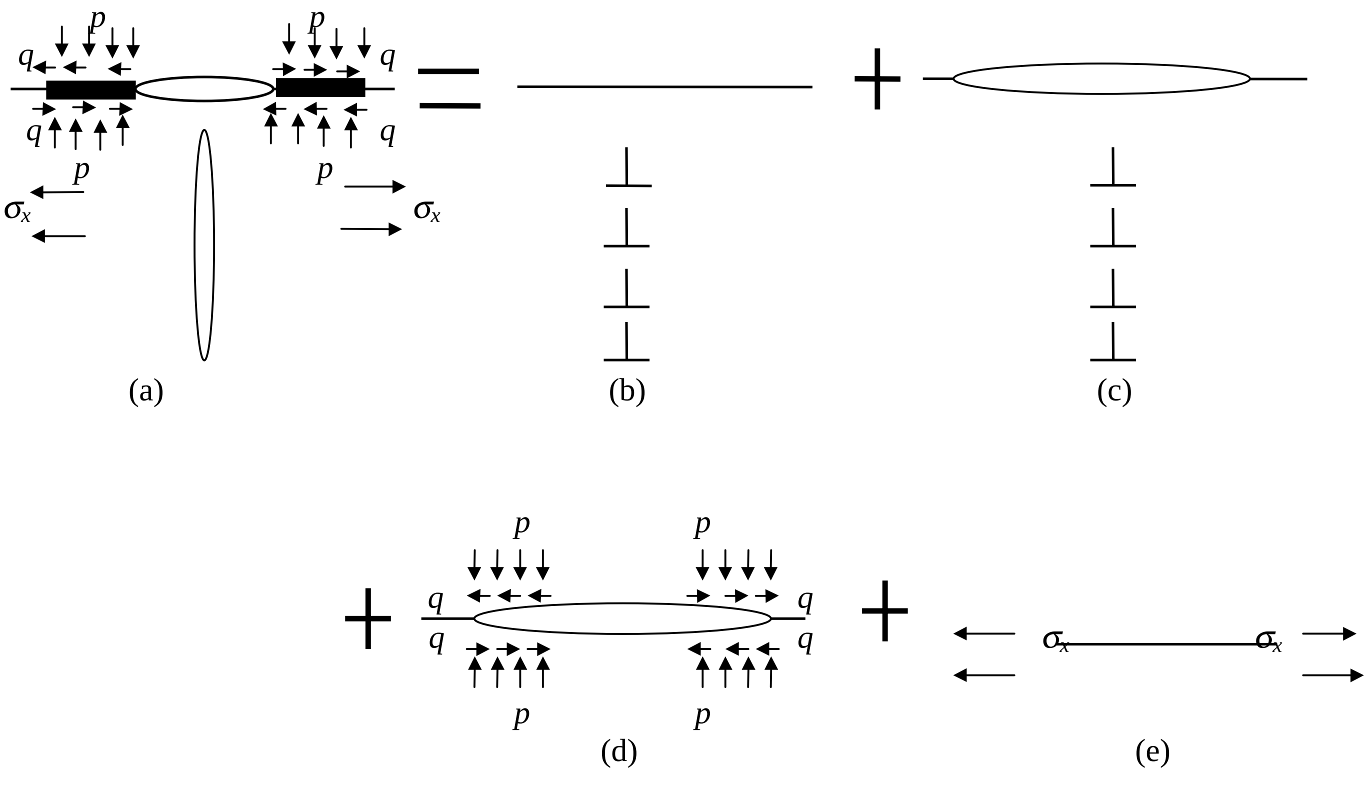

Fig.3: Superposition scheme.

(a) solution for a row of dislocations in material 2, occupying the place of the normally approaching crack, interacting with a bi-material interface (Fig. 3b);
(b) solution for a row of dislocations in material 2 interacting with an interfacial crack (Fig. 3c);
(c) solution for an interfacial crack under adhesive forces (Fig. 3d);
(d) solution for bi-material structure without cracks under remote loading (Fig.3e).

The superposition of the above solutions provides a singular integral equation. Its solution gives the distribution of the dislocations at the normally approaching crack, and then the stress intensity factors at each tip of the cracks can be readily obtained.

3. GROWTH CRITERIA OF THE INTERFACE CRACK

The solution of the interaction problem mentioned above allows the determination of the stress intensity factors at the tips of the interfacial crack:

$$K(a) = (K_I^{(1)} + iK_{II}^{(1)}) + (K_I^{(2)} + iK_{II}^{(2)}) \tag{3}$$

Roughly speaking, $K_I^{(1)} + iK_{II}^{(1)}$ is essentially due to the interaction between the interfacial crack and the normally approaching crack under remote tensile loading and $K_I^{(2)} + iK_{II}^{(2)}$ is essentially due to the adhesive forces acting on the ends of the interfacial crack. Under condition (2), i.e. when the adhesive forces and the length of the plastic zone reach their critical values, $K_I^{(2)} + iK_{II}^{(2)}$ represents the interface fracture toughness.

Now let us consider the following function:

$$G(a) = G^{(1)}(a) - G^{(2)}(a) = \frac{\left(K_I^{(1)}\right)^2 + \left(K_{II}^{(1)}\right)^2}{E'} - \frac{\left(K_I^{(2)}\right)^2 + \left(K_{II}^{(2)}\right)^2}{E'} \tag{4}$$

$$\text{where } E' = \frac{16\mu_1\mu_2}{(1+\kappa_1)\mu_2 + (1+\kappa_2)\mu_1}$$

where μ_i (i=1,2) are the shear modules, $\kappa_i=3-4\nu_i$ for plane stain and $\kappa_i=(3-\nu_i)/(1+\nu_i)$ for plane stress. For more convenience, $G^{(1)}(a)$ can be considered as the energy release rate of the interfacial crack tip due to the remote loading, while $G^{(2)}(a)$ the same quantity due to the adhesive forces. Under condition (2), $G^{(2)}(a)$ can also be regarded as a parameter of the interface fracture toughness, i.e. the work of separation per unit area of interface. Therefore, under condition (2), the growth criterion of the interface crack can be written as one of the following equations:

$$\mathrm{Re}[K(a)] \bullet 0 \quad \text{or} \quad \mathrm{Im}[K(a)] \neq 0 \tag{5}$$

or

$$G(a) \bullet 0 \tag{6}$$

Moreover, the criteria (2) and (6) can also be used for the prediction of the stability of the interface debonding. For a stationary position $G(a)$=0, the stability of the interface debonding may be evaluated by the following criteria:

$$\begin{aligned} \frac{\partial G(a)}{\partial a} > 0 \quad &\Rightarrow \text{ instable debonding} \\ \frac{\partial G(a)}{\partial a} < 0 \quad &\Rightarrow \text{ stable debonding} \end{aligned} \tag{7}$$

4. NUMERICAL RESULTS AND DISCUSSIONS

The calculations were carried out for a bi-material plane stress structure. The plane strain can be considered in the same manner. Different parameters are chosen in the calculations. Observation of numerical results by using these parameters will allow a reasonable evaluation of the trend about the bimaterial interface debonding when a normal crack approaches the interface.

4.1 Evaluation of the toughness law of the interface

Before presentation of the numerical results of the calculations, we first evaluate the assumption made for the toughness law of the interface, i.e. criteria (2). In general, the interface crack toughness depends on the mixed mode at tips of the interfacial crack. For a stationary interfacial crack, one defines the mixity parameter ψ as follows:

$$\tan\psi = K_{II}^{(1)} / K_I^{(1)} = K_{II}^{(2)} / K_I^{(2)} \qquad (8)$$

In the present model, the interface fracture toughness can be represented by $G^{(2)}(a)$ if condition (2) is satisfied:

$$G^{(2)}(a) = \frac{4\theta^2}{\pi E'} \frac{a\left(\sigma_c^2 + \tau_c^2\right)\left(1 + \tan^2\psi\right)}{1 + \left(\dfrac{\tau_c}{\sigma_c}\right)^2 + \left[1 + \left(\dfrac{\sigma_c}{\tau_c}\right)^2\right]\dfrac{a^2\theta^2}{a^2 - b^2}\tan^2\psi} \qquad (9)$$

where $\theta = \arccos\dfrac{b}{a}$

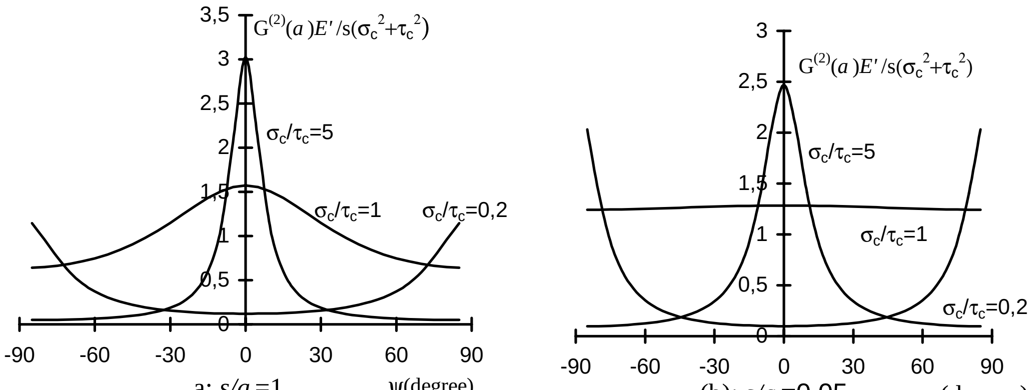

Figure 4 : Interface toughness as function of the mixed mode angle ψ

Fig.4 shows the variation of $G^{(2)}(a)$ as function of the mixity angle ψ and the ratio σ_c/τ_c for two interfacial cracks, s/a=1 and 0.05. $G^{(2)}(a)$ for s/a=1 corresponds to the toughness of interface debonding initiation, while $G^{(2)}(a)$ for s/a=0.05 corresponds to the interface fracture toughness when the interface crack is much longer than the plastic adhesive zone. From Fig. 4, a strong dependence of the interface toughness on the mixity measure ψ can be observed. Only when $s/a\to 0$ and σ_c/τ_c = 1, the interface toughness is mode-independent. If we define this limit case as the toughness of an « ideally brittle » interface, i.e.

$$G_c = G^{(2)}(s/a\to 0,\ \sigma_c/\tau = 1) \qquad (10)$$

the fully shear-shield toughness, i.e. when $\sigma_c/\tau_c \to 0$, is, according to (9) and (10):

$$G_c = G^{(2)}(s/a\to 0,\ \sigma_c/\tau_c = 1)/\cos^2\psi \qquad (11)$$

The strong mode dependence of the interface toughness has been reported by many experimental studies ([3-6]). These studies shown that near mode II toughness in some systems is as much as a factor of 10 higher than near mode I toughness (measured in units of energy per unit area). With the toughness law used in this paper, a small ratio of σ_c/τ_c can fit well the experimental results above mentioned. Fig.5 show that the choice of σ_c/τ_c = 1/7 gives a reasonable fit to the experimental data of Cao and Evans [3] when s/a<0.1.

The mixed mode dependence of interface fracture toughness were modeled by numerous authors ([7-8] among others). The interface toughness law used in this work is approaching to that of Evans and Hutchinson [7]. They proposed a model of asperity interaction behind the crack tip to account for the mixed mode dependence. They produced a family of criteria for mixed mode interface fracture in which the tip is partially or fully shielded from shearing effect. Their family of criteria reduced to (10) for a perfectly smooth interface and to (11) in the limit of a very rough interface.

4.2 Critical remote tensile stress for interface debonding

Under the critical remote stress, the interface begins to debond. The transcendent equations (5) and (2) were solved by using iteration techniques in order to evaluate the critical remote tensile stress.

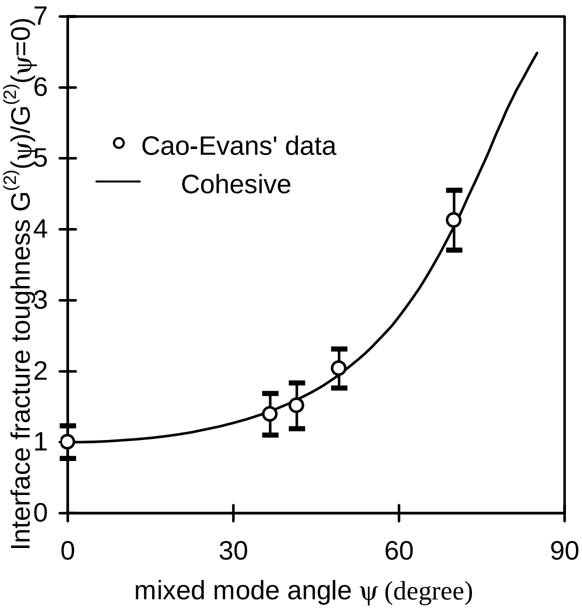

Figure 5 : Comparison of the Cao-Evans data for an epoxy/glass interface with the adhesive model for σ_c/τ_c =1/7

Results of these calculations are represented in Figures 6, 7 and 8 which group together results respectively for σ_c/τ_c = 0.2, 1 and 5. The relative critical remote load $\sigma^\infty/(\sigma_c^2 + \tau_c^2)^{1/2}$ is plotted against $d/e - 1$, the relative position of the normally approaching crack with respect to the interface, for different bimaterial combinations and plastic adhesive lengths. From these figures, one can observe the influences of different parameters on the interface debonding toughness:

(a) The critical remote stress increases when the Dunduns parameter α decreases. This means that the interface debonding is easier when the crack lies in the less stiff material;

(b) In general, the critical remote stress increases when the relative distance of the normally approaching crack becomes far away from the interface. This is normal because the interaction interface-crack decreases when they are situated far away from each other. When this distance is large enough, the critical remote stresses for different values of s converge to the same values. However, if s is long enough, the critical load can reach an extreme value for a certain distance of d/e-1. This extreme value may be locally maximum or minimum according to the ratio σ_c/τ_c. At this distance, the interface is more resistant for large σ_c/τ_c and less resistant for small σ_c/τ_c.

(c) The influence of σ_c/τ_c on the interface toughness is more complicate. For large distances *d/e*, the critical loads increase with σ_c/τ_c. However, this trend is not true when $d/e \rightarrow 1$. The role of the ratio σ_c/τ_c in the interface debonding can be explained more clearly by considering the mixity at the interfacial crack tip. It is seen that the mixity angle ψ pass from positive values to negative values when the crack approaches to the interface. At a certain distance, ψ becomes zero, thus we have a pure mode I interfacial crack.. For a pure mode I interfacial crack, the interface toughness reaches a minimum value for small ratio σ_c/τ_c and a maximum value for large ratio σ_c/τ_c. This is exactly the trend shown in figures 6-8.

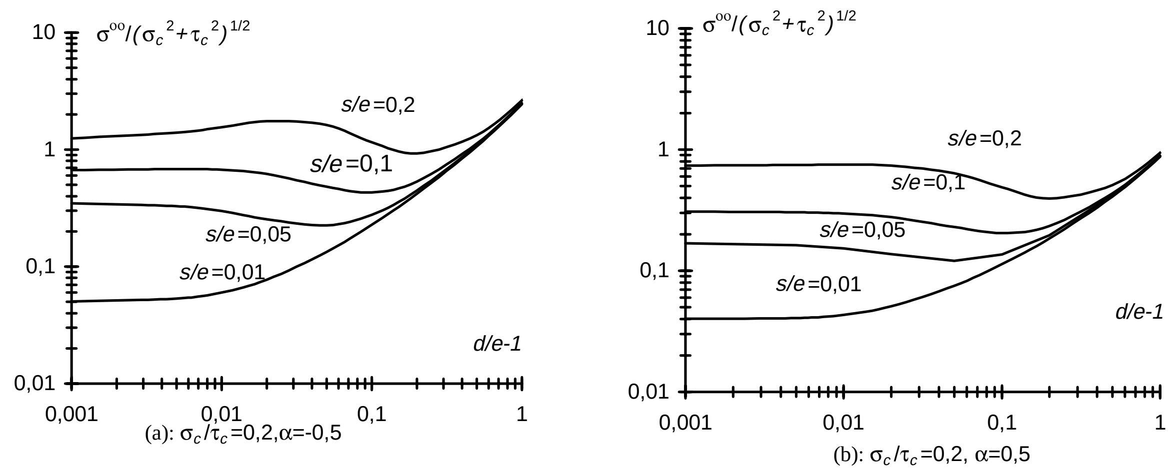

Figure 6: Critical remote tensile stress for interface debonding, $\sigma_c/\tau_c = 0.2$

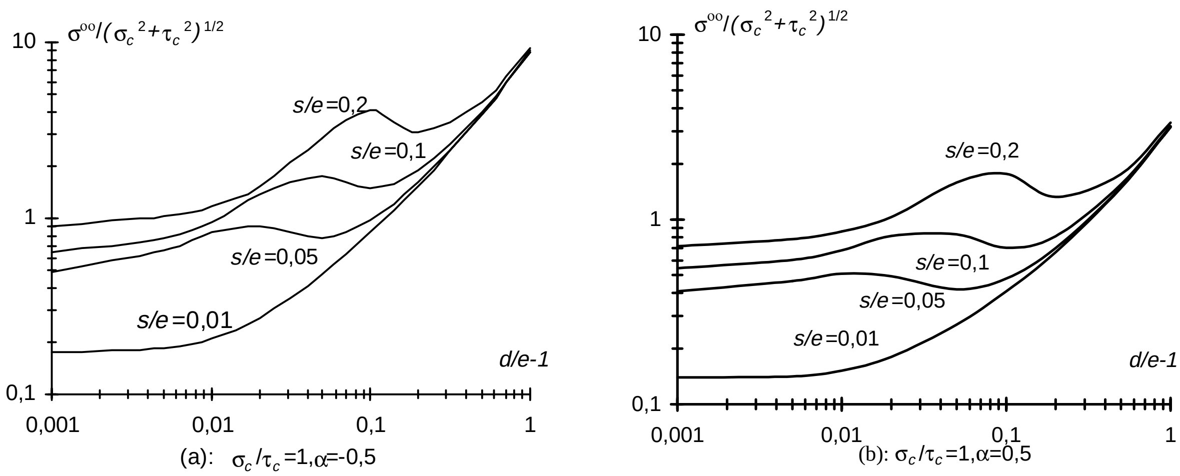

Figure 7: Critical remote tensile stress for interface debonding, $\sigma_c/\tau_c = 1$

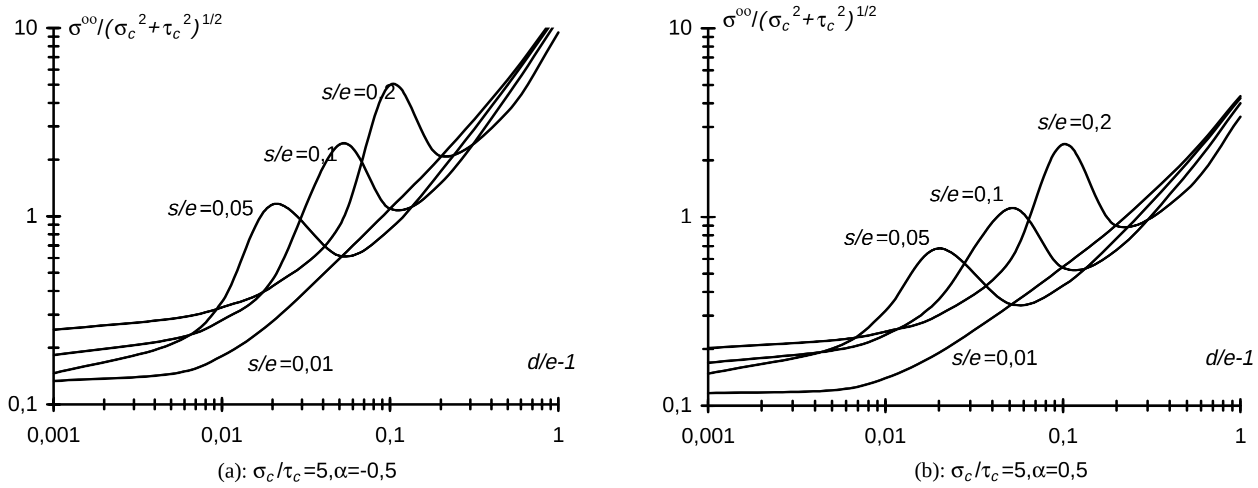

Figure 8: Critical remote tensile stress for interface debonding, $\sigma_c/\tau_c = 5$

5. CONCLUSIONS

In this paper, we have studied the interface debonding for a crack normally approaching an interface between two elastic materials. The interface was considered as perfectly elastic-plastic. An interface fracture toughness law has been defined. This model fits well the experimental data reported in the literature if the critical parameters are appropriately chosen. By analyzing the interaction between the normally approaching crack and the interface crack and by tacking account of the adhesive forces at the interfacial crack tips, the interface debonding has been studied.

In the case when the interface debonding occurs before the crack reinitiation into the next layer, the critical remote tensile stress has been calculated. It is observed that the interface debonding toughness depends strongly on the mixed mode locally produced over the adhesive zone of the interface. These results show that the interface fracture toughness (characterized by σ_c, τ_c and s) plays an important role in the interface debonding. The relative bimaterial stiffness seems fewer determinants. These results agree with the experimental works gathered so far. We believe that the present model is useful to explain the mechanism of « crack arrestor » and provides an analytical method for interface designs in engineering applications.

REFERENCES

[1] DUGDALE, D. S. (1960). Yielding of steel sheet containing slits. *Journal of Mechanics and Physics of Solids* **8**, 100-104

[2] BARENBLATT, G. I. (1959) On the equilibrium cracks dues to brittle fracture. Straight-line cracks in flat plates. *Journal of Applied Mathematics and Mechanics* **23**, 434

[3] CAO, H. C. and EVANS, A. G. (1989). An experimental study of the fracture resistance of bimaterial interfaces. *Mechanics of. Materials* **7**, 295-304

[4] LIECHTI, K.M. and CHAI, Y. S. (1992). Asymmetric shielding in interfacial fracture under inplane shear. *J. Appl. Mech.* **59**, 295

[5] THOULESS, M. D.(1990). Fracture of a model interface under mixed-mode loading. *Acta Met. Mater.* **38**, 1135-1140

[6] O'DOWD, N. P., STOUT, M. G. and SHIH, C. F. (1992). Fracture toughness of alumina/niobium interfaces: experiments and analysis. *Phil. Mag.* **A66**, 1037

[7] EVANS, A. G. and HUTCHINSON, J. W. (1989). Effects of non-planarity on the mixed mode fracture resistance of bimaterial interfaces. *Acta Metall.*. **37**, 909-916

[8] BELTZ, G. E. and RICE, J. R. (1991) In *Modeling the Deformation of Crystalline Solids* (eds LOWE, T. C. and ROLLETT, A.) The Minerals, Metals and Materials Soc. p.457. TMS, Warrendale, PA.