PROPAGATION OF A TRANSVERSE CRACK INSIDE THE INTERLEAF OF A CROS-PLY LAMINATE

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Abstract

The third generation of composite materials possesses a functional interphase between plies, which is reinforced by thermoplastic particles. Understanding the mechanism of matrix crack propagation through the interphase is an important prerequisite to the development of a robust code for the computation of damage resistance of cross ply laminates possessing an interleaf reinforced with plastic particles. The code will be derived from the existing damage mesomodel by introducing physics based model of crack propagation. The local phenomena that govern the damage behavior of the laminate are studied. The study focuses on the propagation of the transverse crack in the 90° ply that impinges plastic particles located in the interleaf between two cross plies. The stress intensity factor at crack tip (K) and the strain energy release rate (G) were computed using the Finite Element Method on a Representative Volume Element of cross-ply laminate. This RVE includes the transverse crack, the interleaf with different particles density/characteristics and the two associated cross plies. The changes in K and G were compared with local critical values available in the literature which allowed the propagation of crack in the interleaf to be determined. Various possible scenarios were discussed. It was shown that the path of crack is dependent on various factors including the respective elastic properties of matrix and particle, the tensile behavior of particle and its fracture properties. Trends in crack propagation were anticipated depending on particles key properties.

1 Introduction

Laminated composite structures have been largely used in aeronautic industries. In the newest models of Airbus and Boeing airplanes, more than 50 percent of their material are composite because of its excellent mechanical properties with a very low density. This requires indispensably a full comprehension on damage behavior of laminated composites up to the complete rupture in the design of aeronautical parts. Up to now, this question is still a scientific challenge. Most of current methods to characterize composite structures are experimental approaches because of their complexity in comparison with current calculation models. This pushes up the cost of aeronautic design and manufacture processes due to testing campaigns. The Virtual Structural Testing that is taking place, is a large change in the design and optimization process of composite structures ; the computer is supposed to replace the testing machine ([1, 2, 10, 15, 17]). Certainly there will always be experimental tests but their numbers will be greatly reduced. Openness to new materials such as the third generation of composites becomes a current issue. These composites incorporate functional interfaces whose purpose is to improve the resistance to dela-

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mination ([8, 9, 11, 22, 23, 29, 33, 34]). In literature, one can find experimental studies with an identical composite structure of Boeing named as T800H/3900-2.

The LMT-Cachan has developed for more than 30 years numerical models and calculation tools that provided an answer to the Virtual Structural Testing ([3, 6, 13, 16, 17, 19, 24]). Today, they are implemented or being implemented widely in industrial codes. Thus, the LMT-Cachan is one of the international laboratories "flagship" in this issue. In fact, the newest LMT-Cachan's mesomodel permits to describe, accurately in comparison with the reality, physical degradation mechanisms and their interactions during complex loading on both families of the first and second generations of composites. However, for the third generation of composite materials, matrix enriched interfaces between plies are replaced by a functional interphase, which is reinforced by thermoplastic particles. Thus, the physical phenomena up to the complete failure of the third generation have many different points regarding to both previous ones of composite structures. There have been a few works on characterizing these materials, but results on the effective of interphases using thermoplastic particles have not been cleared. Hojo et al. [11] have carried out DCB and ENF experimental tests in quasi-static and fatigue in order to compare the performance of composite with a certain functional particles-embedded interphase regarding to classical laminated composites. The effective of thickness of interphase was also analyzed. Groleau et al. [9] studied influence of ductility of matrix used in interphase. Three matrixes : CET-3 (epoxy of high ductility), DER 331(epoxy of medium ductility), MY720 (epoxy of low ductility) were used. In fact, this work showed that role of matrix in interphase depends on its ductility and its interaction with particles. S. Ogihara et al. [22] showed microscopic images of quasi-static tests on T800H/3900-2 composites of stacking $[0/90_m]_s$ using polyamide particles-embedded interphase. Not as classical composites, propagation of transverse cracks in 90° plies has not been ended by micro delamination mechanisms. They can continue to pass over interphases to access into adjacent plies. Their propagation paths are not also aligned, but inclined. This work was then developed for fatigue behavior in the case of quasi-isotropic stackings [23, 31]. In fact, it seems that particles in functional interphase of the third generation of composite have caused the change of transverse cracks propagation. Since transverse cracks are usually an intermediary damage mechanism between diffuse ones and delamination up to complete failure, it is indispensable to comprehend the mechanism of matrix crack propagation through the interphase of cross ply laminates possessing an interleaf reinforced with plastic particles. Several works have mentioned the effect of particles embedded in matrix on the path of cracks propagation for different cases using analytical approaches [7, 12, 25] or numerical methods [4, 18, 20, 26, 30, 32] and experimental campaigns [5, 21]. However, to the best of the author's knowledge, the propagation of transverse cracks inside thermoplastic particles-reinforced interphase at the micro scale has not been fully considered.

In a previous work [27, 28] the damage of the interphase between adjacent 0° and 90° plies in a composite structure $[0/90_n]_s$ was studied based on a homogenization method using the micro-meso bridge built in LMT [13, 14, 16]. In fact, the development of transverse cracks was homogenized in the thickness of interphase as evolution of damage by using damage variables. In this paper, propagation of transverse cracks inside the interphase is numerically analyzed at the microscopic scale. In fact, particles are described in a Representative Volume Element (RVE) assuming their bonding with matrix around is perfect. The part 2 of this paper presents calculation conditions in 2D with Finite element methods as material parameters and geometrical configurations chosen for a RVE. A remotely imposed deformation is proposed so that all constituents behave only in linear and elastic phase. The method for calculating Stress Intensity Factor (K) and Energy Release Rate (G) is also introduced. The next part performs discussion on obtained results in validation with experimental data in the literation. Five scenarios are analyzed based on evolution of control variables of crack propagation K and G in function of its length. Effects of diameter and elastic modulus of particles are also discussed. The part 3 is followed by conclusions on critical effects decided by modulus, toughening and plastic properties of particles.

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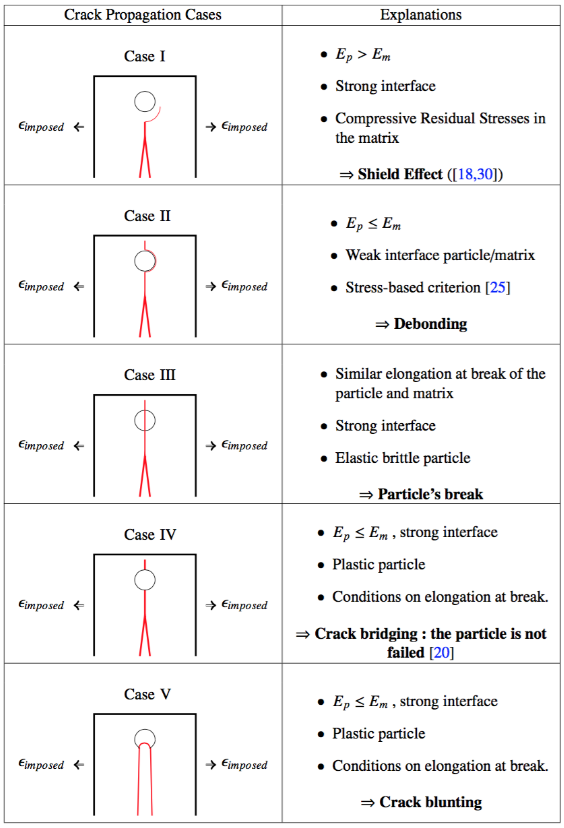

Figure. 1. Possible scenarios of crack propagation under controlled deformation

2 Parameters of the study

The simulations used Abaqus on a 2D Representative Volume Element (RVE) which represents two 0° plies in the outside and one 90° ply inside (see figure 2). The plies were homogenized and had classical thickness H=125 µm. They are seperated by an interleaf, composed of matrix and spherical particles. The thickness of the interleaf is h=25 µm. The length L=180 µm of the RVE in the tensile direction 1 has been chosen to represent the classical transverse crack density at saturation ($\rho_s = \frac{H}{L} \approx 0.7$). The RVE is loaded in tension along the 1 direction. Deformation $\epsilon_{imposed} = 2\%$ is imposed and stays constant as the crack is propagated step-by-step. The crack (in red on figure 2) is represented by the "SEAM-Tool" in Abaqus. A quasi-static analysis of crack propagation was carried out. The crack length was increased iteratively after a computation of K_I and G. The propagation of the crack is along a straight line through the particle. As the interface particle/matrix is supposed to be perfect, the debonding case is not studied. The values of Stress Intensity Factor (K) and Energy Release Rate (G) are computed using the Rice-Integral. The size of the mesh (composed by CPE4R plane-strain elements) has been chosen in order to have a converged value of K. All the constituents are considered having an elastic behaviour (see figure 2). As the particles are made of thermoplastic resin, this assumption has to be explained. The stress/strain tensile curves found in the litterature for this kind of thermoplastic ([21]) show a yield strain of about 5%. As the imposed strain was less than 2%, the particle's material can be considered as elastic.

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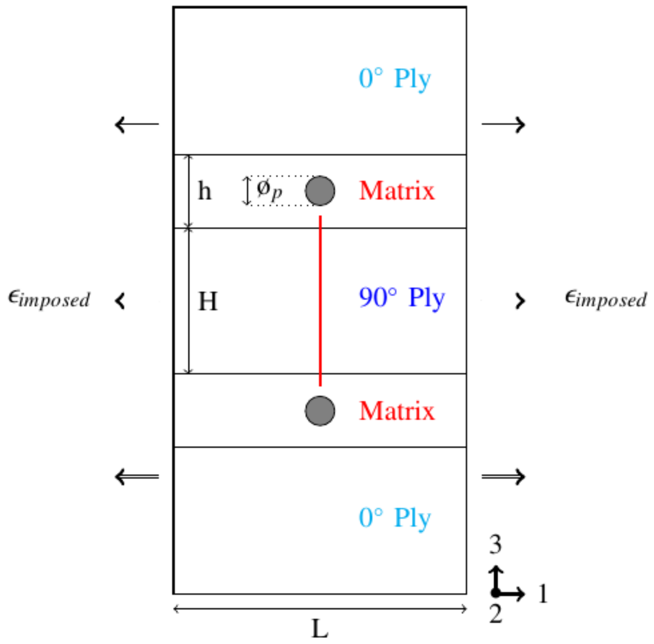

		Characteristics	Properties
Material	0 Ply	Orthotropic	E_1=294GPa E_2=E_3=9.7GPa
	90 Ply	Isotropic	E_1=E_3=9.7GPa E_2=294GPa
	Matrix	Elastic Isotropic	E_m=3.76GPa
	Particle	Elastic Isotropic	E_p=[1-10]GPa
Geometry	H		125 µm
	h		25 µm
	L		180 µm
	$\epsilon_{imposed}$		2%
	$ø_p$		10-15µm

Figure. 2. Geometry and properties of the RVE

3 Results

3.1 Effects of diameter and Young modulus of particles

The effects of diameter and Young modulus of particles on the values of K_I are studied. The crack will be forced to move according to the third scenario (inside the particle). The particle will have the following diameters : 10 and 15 µm and Young modulus of 1 and 10 GPa. These values have been chosen to have both the cases of a particle softer and stiffer than the matrix. The different cases are studied in figure 3 where K_I and G are plotted as a function of the length of crack. The dotted lines represent results for the Young modulus of 10 GPa and the solid lines for those at 1 GPa. Each color corresponds to a different diameter.

The black line is a case without any particle. It can be seen that K_I and G decrease with increasing crack length which means that the crack propagation is stable if there is no particles. This is due to the imposed displacement on the RVE and the local constrained effect due to the proximity of the 0° ply. If there is a particle, the evolution of K_I and G will change. For a soft particle, there is slight increase of K_I as the crack approaches the particle. When the crack reaches the particle, the low value of K_I prevents it from propagating : more energy is needed to go through the particle. On the opposite, a stiff particle will have a shielding effect on the crack as shown by the significant decrease of K_I in front of the particle. It can be explained by the local stress field around the particle which decreases for stiff particle (and increases for a soft one). After the particle, the curves tends to the case without particle. These results are similar to those reported in the literature for polymer toughening ([18]) and discussed in the introduction.

3.2 Scenario of crack's propagation

The curves shown in figure 3 have to be compared to critical values of stress intensity factor. Comparison was made for a particle softer than the matrix with a diameter of 10 µm. The values of K_{I_c} for classical thermoset (for the matrix) and thermoplastic (particle) were selected. In the literature, these values show variation and the conclusion can depend on the choice. For the matrix, $K_{I_c}^m = 400kPa\sqrt{m}$ was taken and

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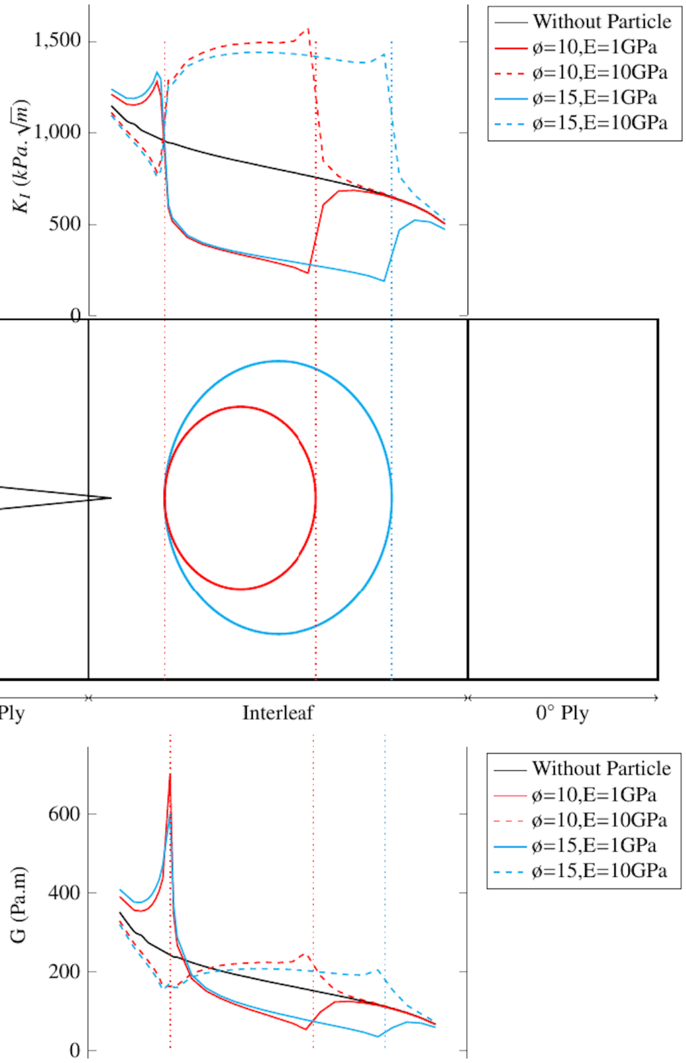
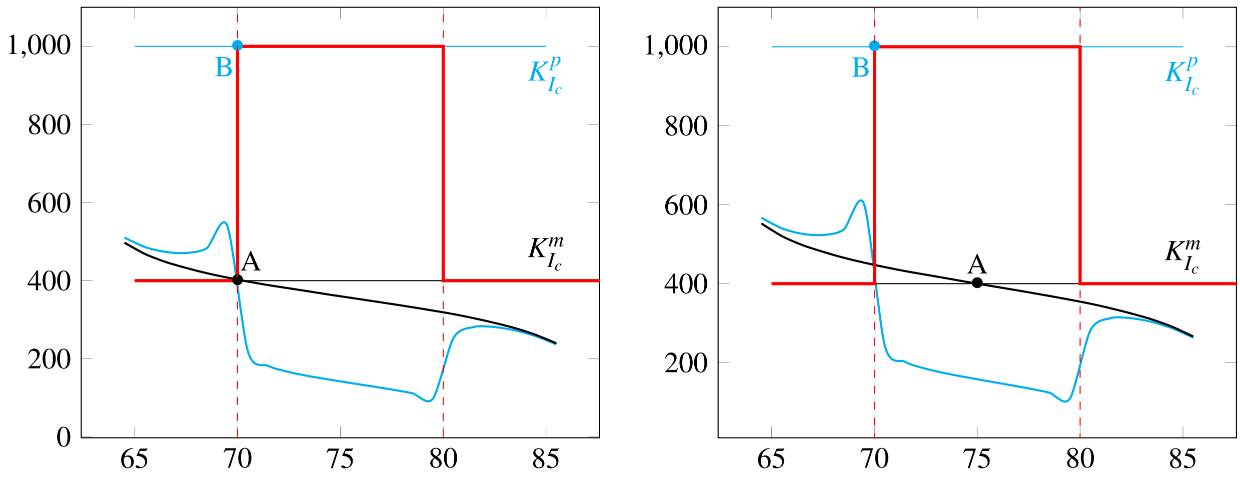


Figure. 3. Effect of diameter and Young modulus of the particle : K_I and G as a function of the crack's length



(a) $\epsilon_{imposed}$ = 0.9% : Crack has propagated till the particle's edge

(b) $\epsilon_{imposed}$ = 1.0% : Crack arrested at particle boundary (B). In the absence of particle, the crack reaches A

Figure. 4. K_I ($kPa.\sqrt{m}$) as a function of the crack length (µm) for different values of imposed strain $\epsilon_{imposed}$ of the VER ($\o_p$ =10 µm and E_p = $1GPa$)

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for the particle $K_{I_c}^p = 1000kPa\sqrt{m}$. In figure 4, K_I is plotted as a function of the length of the crack for different values of the imposed strain. The black curves correspond to the cases without particle and the red one is critical stress intensity factor. The point A represents the crack tip if there is no particle and the point B in the case of the particle. Up to $\epsilon_{imposed} = 0.9\%$, $K_I < K_{I_c}$. Then, for $\epsilon_{imposed} = 1.0\%$ due to the decrease of K_I and the high value of $K_{I_c}^p$, the crack should not propagate in the particle.

To make a distinction between the cases IV and V of figure 1, the critical tensile strains ϵ_{c_m} and ϵ_{c_p} of the matrix and the particle have to be considered. In the situation of figure 4a, the crack tip is situated at the edge of the particle. As shown on figure 4, when the deformation on the RVE increases, the blue curve goes up. Crack blunting will occur if the value of K_I at the point A does not reach $K_{I_c}^p$. If the particle is tough enough, this condition will be fulfilled before the failure of the matrix. Then, when the deformation on the RVE reaches $\epsilon_{c_m} < \epsilon_{c_p}$, the matrix will crack while the particle is not failed and it bridges the crack : this is crack bridging.

4 Conclusion

In order to characterize the transverse crack propagation through an interleaf reinforced with a particle, numerical simulations were carried out for a RVE composed of one inner 90° ply and two 0° outer plies and subjected to remote uniaxial and uniform tensile deformations. The reinforcing particle was characterized by various Young modulus and diameter values. The stress intensity factor K and the stress energy release rate G at the tip of a series of stationnary cracks having increasing lengths were computed. Plots of K and G as functions of the crack length were found in agreement with the trends reported in the literature for infinite media and showed shielding effect from a stiff particle and an amplification from a soft one. To emphasize the positive effect of a soft particle by arresting the crack, the values of K were compared to the critical values K_c. It was shown that the toughening effect of the particle would be enhanced by plasticity, as a result local increases of G_c and K_c. Then, two main scenarios can occur depending on the Young modulus E_p and the toughening properties of the particle. For a very high K_c and low E_p , the crack will jump over the particle and restart in the matrix beyond the particle : bridging effect. Otherwise, the crack will propagate slowly through the particle but its tip will be blunted due to plastic deformation of the particle : blunting effect.

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