Impact fatigue damage of glass/epoxy plates predicted from three parameters model

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Abstract

The objective of this experimental investigation is to obtain a detailed understanding of damage evolution of composite plates and its evolution with regard to impact energy and impact number. The investigation of new damage models is one of the ways to be explored, in order to explain the entire phenomenon accompanying impact fatigue loading on composite. In this study a comparison between two composite systems is carried out to determine the effect of impact energy and number of impacts on stiffness and damage parameter evolutions. A three coefficients damage model, proposed in a former work, is applied to the case of this study. It has been found that cross ply laminate can provide both an inherent capability to dissipate energy by developing large areas of delamination and greater perforation strength than glass/epoxy woven fabric system.

1. Introduction

Due to the demands of high performance materials, laminated composites with high strength to weight ratio and excellent mechanical properties have been developed. These materials are used in a wide variety of sporting equipment as well as in commercial and industrial structures. However, laminated composite materials are very susceptible to damage induced by impacts. The impacts may cause severe reduction in strength and stiffness, potentially leading to catastrophic failure of the whole structure. Until now, many attempts have been carried out to investigate damage caused by low velocity impact [1,2]. These attempts represented that the damage induced by an impact could be classified as matrix cracking, delamination, fibre breakage and debonding at the fibre-matrix interfaces [3]. Generally, in laminated composite materials, it is known that the delamination is a major damage mode and closely relating to the stiffness degradation of specimen. Therefore, considering a long-time usage of composite materials, the investigation of damage behaviours caused by low energy repeated impacts becomes important [4,5,6,7]. Often this damage may not be visible from the laminate surface, but the presence of this damage substantially reduces the composite mechanical properties, especially stiffness and strength [8,9,10,11,12,13].

In this study, low velocity impact fatigue tests have been carried out on Glass/Epoxy laminated composite at input energy of 4 Joules. The global bending stiffness of each plate was measured before and after each impact fatigue period through quasi-static bending tests. The scalar variable *D*, which characterises the material damage, was then calculated in function of impact number. The damaging modes and internal damage as a consequence of impact fatigue will also be investigated with two laminated specimens of Glass/Epoxy (woven fabrics and cross-ply laminates).

2. Materials and experimental techniques

2.1 Materials

The composites used in this study are: a Glass/Epoxy Woven fabric (GEW) and Glass/Epoxy Cross-Ply laminates (GECP). The GEW specimen is the Epoxy resin reinforced with E-Glass fibres at a nominal fibre volume fraction, V_f of 62%. It is constituted by eight layers of “taffeta” woven fabrics with a density of 920 g/m^2. The GECP specimen is made by the same resin and fibre than GEW. It is constituted of prepreg unidirectional layers of $\left(0/90/0/90/\overline{0}\right)_s$ lay-up. Specimens are plates of 280mm long by 180mm wide by 5.4mm thickness.

2.2 Impact testing conditions

The specimens are embedded on two edges, and are subject to the impact of a 5kg projectile of 35mm in diameter with a hemispherical head. The impact fatigue tests are stopped at regular time intervals in order to examine the variation in specimen global bending stiffness. In fact, the damages appearing in the material cause a loss in plate stiffness, due to the degradation of its mechanical properties. Therefore, the bending stiffness of the plate is controlled after each level of damage, while carrying out a static bending test on a conventional tensile machine (Instron ±10 kN). From the load-displacement curves (at the impact point), a damage parameter is calculated by using the ratio of load to displacement as an indicator of damage; hereafter we shall indicate it by stiffness in the remainder of this paper.

2.3 Impact fatigue testing

The impact fatigue apparatus (Fig. 1) used in our study is characterised by its crank-connecting rod mechanism which provides cyclic impacts. This mechanism which transforms a continuous rotational movement into an alternating translatory one is trained by an asynchronous motor, which permits to modify the impact frequency (until 10Hz) and the projectile velocity. The accessories used with the impact fatigue device are: a fixture system for the specimens and a projectile with hemispherical head of 35mm in diameter. The plate is clamped on two edges in the fixture system (Fig. 1) which is fixed on the device frame.

Fig. 1. Impact fatigue machine and specimen fixture system.

2.4 Static bending tests

Flexural properties of composites are measured before and after impact fatigue period using a static bending test. Flexural tests are performed in an Instron conventional tensile machine driven at a cross-head speed of 2mm/mn. The loading is transferred from the cross-head to the plates through a 35mm steel cylinder with a hemispherical head (like the projectile-cylinder). Specimens are clamped on two edges in the same fixture system than the impact fatigue testing.

3. Results

3.1 Damage evolution

We present in following the load-displacement plots of Glass/Epoxy woven fabrics (Fig. 2) and that of Glass/Epoxy Cross-Ply laminates (Fig. 3). Each load-displacement curve corresponds to a certain number of impacts. These curves show distinct slopes representing irreversible damage of materials.

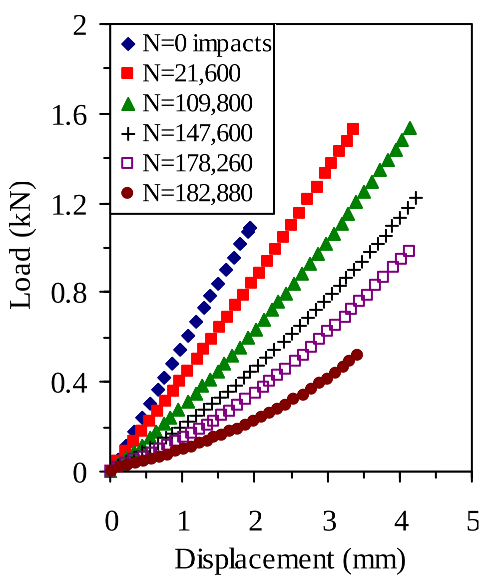


Fig. 2. P=f(d) diagram of GEW.

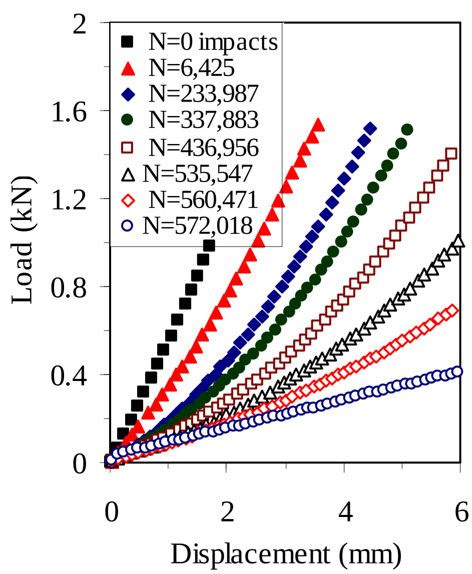


Fig. 3. P=f(d) diagram of GECP.

We characterise the material damage by the scalar variable D (Eq.1) which is defined as follows:

$$D = 1 - \frac{\tilde{R}_i}{R_0} \quad (1)$$

With $$\tilde{R}_i = \frac{P_i}{d_i} \quad (2)$$

Where R_0 is the initial bending stiffness of undamaged material, $\tilde{R}_i$ (Eq.2) is the bending residual stiffness of damaged material at a number of impacts N_i, P_i is the load at N_i, and d_i the corresponding displacement.

The curves of stiffness evolution (Fig. 4) and damage evolution (Fig. 5) with impact number of GEW and GECP at impact energy of 4 Joules reveal three distinct zones: initiation and multiplication of delaminations (zone I), saturation of delamination (zone II) and ply cracking with fibre breaking (zone III). In the first part of the curves (Fig. 4), the plate stiffness decrease moderately indicating an initiation and propagation of delamination at various interfaces. The second zone presents a horizontal stage which indicates a deceleration of delamination process. One notes thereafter an obvious decrease of the stiffness values until final rupture.

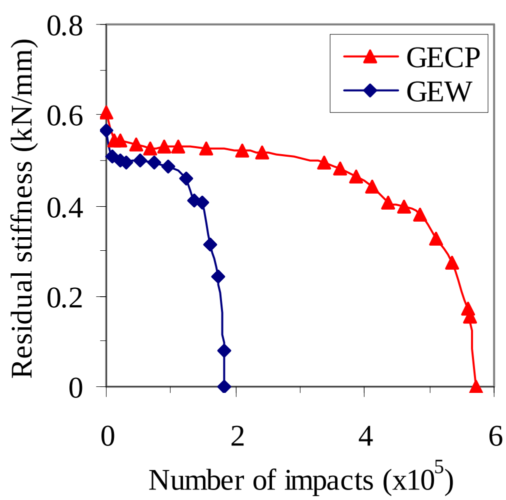


Fig. 4. Stiffness curves (4J).

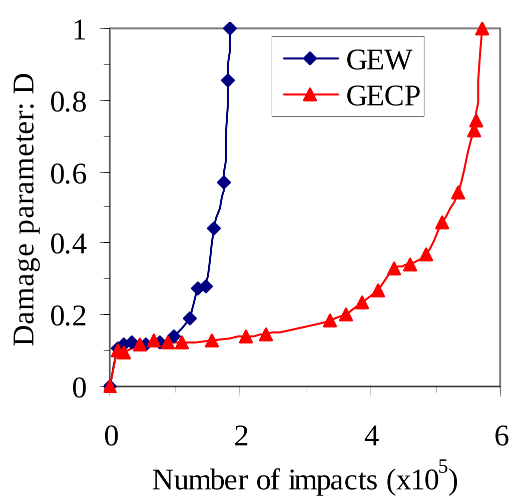


Fig. 5. Damage curves (4J).

In the first part of the curves (Fig. 5), damage parameter increases rapidly. The increasing evolution in this zone translates a damage of composite plates which appears by initiation and propagation of delamination in various interfaces. Delamination is the dominating damaging mode in this part of curves. The second zone presents a horizontal stage which indicates a deceleration of delamination process. Indeed, the supplied impact energy cannot propagate delamination any

more what keeps constant the damage parameter. One notes thereafter an obvious increase of the damage until final failure. This last zone is characterised, for each curve, by an increase of initial impact energy up to a sufficient value to create other delaminated surfaces and more than ever to break glass fibres. Additional energy was set experimentally at 150% of initial impact energy. This increase is justified by the insufficiency of initial energy to damage material more beyond zone II.
A comparison of damage evolution is carried out between two materials. In the first zone, Fig.5 shows that GEW presents rather greater values of damage parameter than GECP. The horizontal stage of GEW corresponding to the second zone is located at a value slightly higher than that of GECP. The last part relating to GECP is definitely longer than that of GEW, indicating by the way that GECP configuration resists better to the impacts. Indeed, a more significant impact number is necessary to damage GECP configuration. Thus the rupture of GECP occurs after an impact number much larger than that of GEW, the rupture impact number of GECP is equal to 572,423 whereas that of GEW is 183,285 (so approximately three times more).

The damage evolution is like an "S" shape curve and thus taking into account the damage early in life duration. The application of relationship (Eq.3), model proposed in former work [6], allows us to predict damage state of glass-epoxy woven fabrics (Fig. 6) and glass-epoxy cross ply laminates (Fig. 7) subjected to impact fatigue loading.

$$D = a \cdot \frac{\beta^b}{(a+1) - \beta^c} \qquad (3)$$

Where D is damage parameter, β is life fraction which is defined as the ratio between number of impacts N_i and failure impact number N_f, and finally a, b and c are experimental constants. This evolution law is described by three parameters that control each aspect of this development. The parameter "*a*" controls damage level during the period of relative stability, the parameter “*b*” controls the rate of initial damage and “*c*” controls the life fraction for which appear damages of final phase.

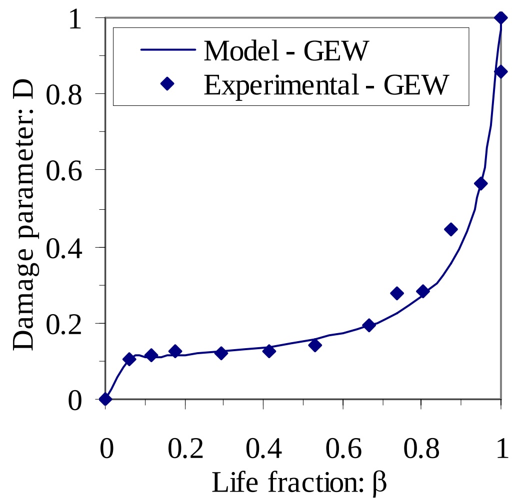


Fig. 6. Damage model for GEW (4J).

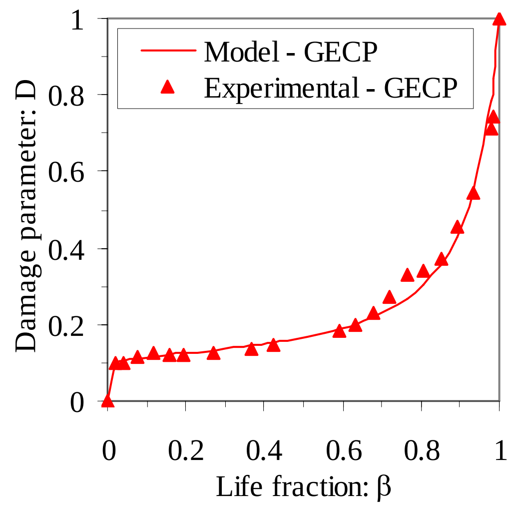


Fig. 7. Damage model for GECP (4J).

Model parameters are determined using Excel solver software (Table 1).

Laminate	GECP	GEW
a	0.170	0.152
b	0.107	0.078
c	2.200	2.354

Table 1. Model coefficient values (*a*, *b* and *c*).

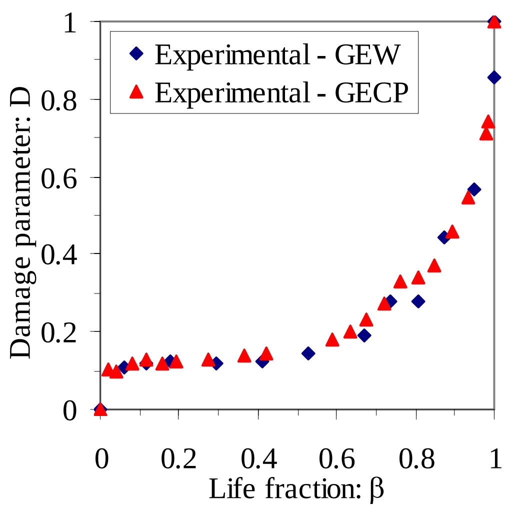


Fig. 8. Damage parameter against life fraction diagram.

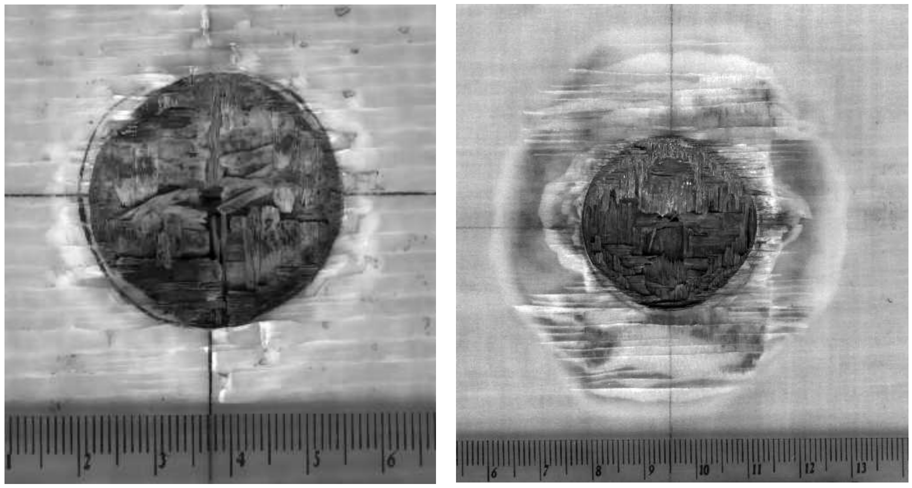
A preliminary analysis shows that parameter "*a*" for GECP laminate is slightly greater than that of GEW configuration, but values are quite similar each other, which explain the same level of second zone for both configurations (Fig.8). GECP laminate presents somewhat higher rate value of initial damage (representing by "*b*" parameter), and equivalent value of "*c*" parameter, indicating that damages of final phase appear at rather the same life fraction for both laminates (Fig. 8).

The main damage modes are found to be matrix cracking in every ply and delamination within the lower interface, even though small areas of delamination in the other interfaces. We notice most important delamination areas for GECP specimens. Indeed, in the case of GECP, delamination propagates easily following fibres without meeting any resistance. On the other hand, in GEW configuration the weaving obstructs the delamination propagation; this is due to the fact that crack path gets around woven fibre bundles which make delamination progression difficult. Delaminations are detected visually by using high intensity background light (Fig. 9).

Fig. 9. Delamination area by high intensity background light.

3.2 Damages in front and rear faces

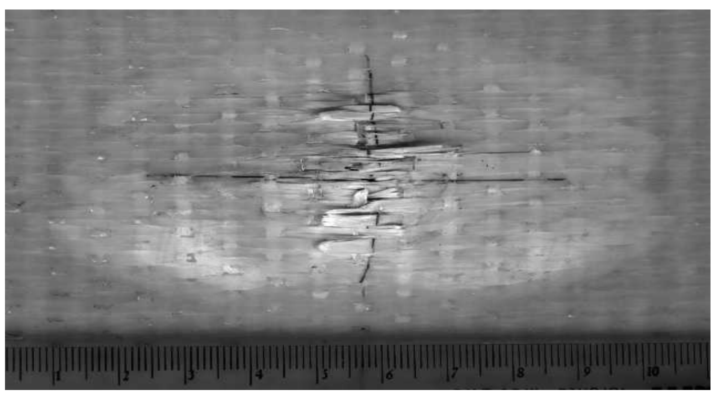
One observes on impacted face (Fig. 10) formation of a spherical crater, which is due to the contact projectile-plate. Its diameter increases with number of impacts. Under impact point, we observe matrix cracking and fibre breaking. This zone is damaged in compression where it is difficult to distinguish the various damaging modes. The punching of plate surface leads to a heating located under impact point. Indeed, the crushing of this zone, under the effect of repeated impacts, induces an increase in temperature which burns the resin and consequently blackens the surface of contact projectile-plate (burned resin powder). For GECP we notice the presence of intralaminar longitudinal cracks (in the first layer) around the impact point. Moreover, Fig. 10 shows delaminations located at the interfaces close to impact surface. Delamination area for GECP configuration is much more pronounced than GEW one.



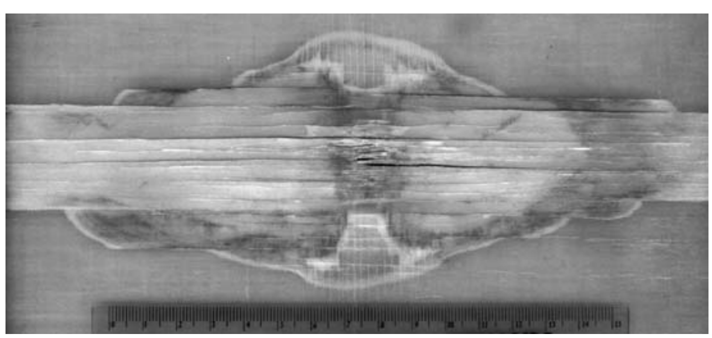
a)- GEW b)- GECP

Fig. 10. Spherical crater and typical shape of delamination on impacted face.

On non impacted face, we distinguish delaminated surface corresponding to the interface of last layer (Fig. 11). It can be seen fibre bundle broken according to width direction, in GEW case, forming thus a transverse crack. This one is formed by the tensile-shearing rupture of fibre bundles at weaving level. GECP configuration reveals multiple cracks propagating longitudinally.



a)- GEW



b)- GECP

Fig.11. Fibre failure and delamination typical shape on non impacted face

4. Conclusion

This work presents an experimental method for the study of impact fatigue effect on composite plates. A test protocol was set up in order to facilitate and to determine efficiently the problem of impact fatigue tests. Investigation of composite laminates is carried out in this study in order to characterise the effect of impact fatigue tests on damage parameter of composites: Glass/Epoxy Woven fabrics (GEW) and Glass/Epoxy Cross-Ply laminates (GECP). It is noted however that GECP resists to impacts better since more significant impact number is necessary to increase its damage parameter and thus to reach final stage of plate perforation. The greatest part of energy is consumed in delamination for GECP, while for the GEW the weaving obstructs the delamination propagation and hence make that essential of incidental energy is consumed to break fibres and consequently to accelerate plate failure.

Moreover, this study permits to highlight the damaging modes which characterise GEW and GECP. The damage appears by formation of a spherical crater on the impacted face, formation of delamination in different interfaces and appearance of cracks in the last layer. GECP has a delaminated surface (last interface) more important than GEW. Indeed, in the case of GECP delamination propagates easily following fibre direction of last layer without meeting any resistance. On the other hand, in GEW configuration the weaving obstructs delamination propagation; this is due to the fact that the crack path gets around woven fibre bundles which make delamination progression difficult. The cracks appearing at back face are longitudinal for GECP (cracking of the resin according to fibre direction of last layer) and transversal for GEW according to plate width.

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