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Damage characterisation of glass/polyester composite plates subjected to low-energy impact fatigue

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Abstract

This work reports and discusses an experimental method for characterising the damage behaviour of glass/polyester laminated composite plates at low-energy impact fatigue. Experimental tests are performed under increasing impact energy and increasing number of impacts conditions. The investigated energies are in the range of 3.5–7 J in order to describe the internal damage behaviour at different levels of incident impact energy. Diagrams are presented to show the effects of impact number, energy level and cumulative impact energy on delamination area evolution, and also on crater dimensions progress (diameter and depth). The delamination behaviour and crater dimension in the laminated specimens depend largely upon the level of incident energy. Well-defined impact fatigue (E–N_f) behaviour, showing an endurance limit at above 10^4 impact cycles, has been obtained.

1. Introduction

Application of composite materials in structural components of many fields in industry has resulted in an increasing need to develop improved analytical and experimental methods to characterise and predict the mechanical behaviour of these materials. Laminated composite materials are also very susceptible to damage induced by foreign object impacts. Studies [1,2] have shown that because of this impact damage, the mechanical properties of these materials can be severely degraded.

Due to the long-term usage of composite materials in structural components, the investigation of the damage behaviour caused by repeated impacts of low energy becomes important and useful [3,4]. However, the tests of impact fatigue are in developing stages. Only few authors were interested in the effects of impact fatigue on composites [5,6].

During repetitive impacts, microscopic cracks appear in the matrix, fibres break, and delaminations emerge at the interfaces, which make the prediction of the composite damage behaviour difficult. Considerable efforts were deployed to understand the single impact response of composites. However, impact fatigue on composite materials requires a greater consideration, since the effect of repeated impacts on composite damage is of

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a higher complexity. Because of this and because of the small number of machines producing cyclic impacts, this field was investigated only by few researchers. The analysis of the various studies performed to date on impact fatigue, shows that no standard configuration of specimens nor unified experimental device were adopted [3,5,6].

The influence of impact number on delamination growth is studied by some authors. Shin and Maekawa [6] determined by ultrasonic image scanning (c-scan) the plane distribution of the delamination, which occurs in the interfaces inter-layers. Delamination is preferentially propagated according to the fibre direction at 0° (last interface, elliptic shape) for the $[0_2/(+45/-45)_2]_S$ specimen, while in the case of the $[(+45/-45)_2/0_2]_S$ specimen the delamination shape is rather circular, which indicates that the delamination propagates according to $\pm 45^\circ$ directions (last interface). The authors showed that delaminated surface increases with number of impacts. However, the authors did not give an estimation of these surfaces. In addition, projected area of delamination grows rapidly at first with the increase of cumulative impact energy [6]. This growth soon becomes slowly thereafter, leading to a delamination area at a nearly saturated value.

In the same way, Found and Howard [7] and Wu and Shyu [8] showed the damaging effect of the impact number for various energy levels, on delaminated surfaces. The authors showed a significant growth of the internal damage during the repeated impact loading.

The accumulation of the damage resulting from the repeated impacts was studied by Mouritz et al. [9]. An observation under optical microscope shows the formation of a not very deep crater under the impact point after 5 impacts. Dimensions of these craters increase with impact number.

Hou and Jeronimidis [10] showed that there are two stages in the delamination propagation, one stable and the other unstable. Delaminated surface grows proportionally with the impact energy in these two stages, but with various growth rates.

Compressive and tensile residual strengths of carbon/epoxy composites subjected to repeated impacts were measured by Wyrick and Adams [3]. The authors showed that impact energy level and impact number are the principal factors, which influence the degradation of residual strength. Mittelman [11] was interested in the identification and characterisation of carbon/epoxy response under repeated impacts of low energy. Thus, the evolution of bending residual strength at various impact energies and variable impact numbers was studied. The reduction in residual strength of repeatedly impacted specimens was also noticed by Mouritz et al. [9]. These authors determine the bending and shearing post-impact properties, of laminated composites containing glass fibres and vinyl ester resin.

In many studies, the influence of impact energy on impact fatigue lifetime was demonstrated. A theoretical impact fatigue lifetime analysis of PPS short fibre composites was carried out by Lhymn [12]. Ho et al. [13] showed that impact energy affects significantly the impact fatigue lifetime, represented here by the failure impact number. Ray et al. [14] like Roy et al. [15] examined the fatigue strength properties of composites by analysing the fatigue curves $E-N_f$ (impact energy–failure impact number). The results obtained by these works attest that energy level and number of impacts are the two major parameters, which govern the behaviour laws of composite materials subjected to impact fatigue.

This work reports and discusses investigations made to identify and characterise the response of laminated composite plates to low-velocity impact fatigue. Diagrams are presented to show effects of impact number, energy level and cumulative impact energy on delamination area evolution (inspected through high-intensity background light), either on process of crater development (diameter and depth of crater) at impact face. This work also deals with impact fatigue behaviour of glass/polyester composite laminates, showing classical fatigue behaviour by the plot of endurance curves.

2. Experimental procedures

2.1. Specimen

The material of the study is 8 layers of E-glass/polyester woven fabric composite, laminated by contact moulding process to the thickness of 3.5 and 1.8 mm. The volume fraction of E-glass fibre is 70%. Impact fatigue specimens were cut to the following dimensions $280 \times 180 \times 3.5$ and $280 \times 180 \times 1.8\,\mathrm{mm}^3$ from two plates of $2\,\mathrm{m}^2$ areas, with 3.5 and 1.8 mm thickness.

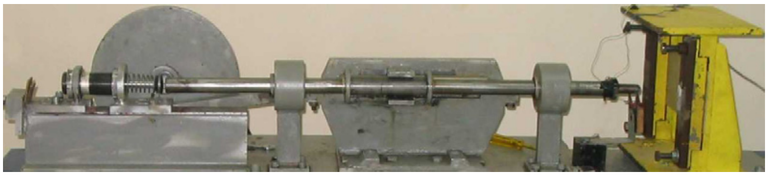

Fig. 1. Impact fatigue machine.

2.2. Impact fatigue device

The impact fatigue machine is constituted by a crank-connecting rod mechanism, which allow to produce cyclic impacts (Fig. 1), using an impactor with hemispheric head ($\varnothing$ 20 mm, 5.5 kg). The repeated impacts were obtained by transforming rotational motion into translatory one by the crank-connecting rod mechanism. The impact velocity was measured by using two parallel metallic blades located at a distance of 16 mm the one from the other, assembled on the impact fatigue machine frame, at a few millimetres of the impact point (in order to have a local measurement, right before the impact). An electrical contact between the impactor and these two metallic blades was ensured at each cycle by an electric wire fixed on the impactor. The interception by an oscilloscope of the two signals due to the electric contact wire-metallic blades, allows to measure the flight time between the two metallic blades (at the time of the passage of the impactor) and then to deduce the projectile velocity. Two edges of specimens were embedded and five impact energies were selected 3–7 J.

The impact number was determined by a cycle counter. It is equipment constituted by a photoelectric cell with proximity detection and of a digital counter giving the impact number at each cycle.

3. Experimental results and discussion

3.1. Evolution of delamination area with impact fatigue tests

A preliminary analysis of specimens damaged by impact fatigue reveals that for the same impact number, a whitish surface of circular form appears on the front and back faces, whose diameter increases with impact energy; it is the phenomenon of delamination. Indeed, the glass/epoxy being translucent, it becomes opaque while delaminating. In the neighbourhoods of this surface, cracks of few millimetres in length are observed; they are more obvious in the horizontal direction. During the impact fatigue tests, considerable damage was observed. Backlighting revealed a circular-shape pattern of internal delamination. The same circular-shape delamination pattern was apparent on the rear face. After a certain number of impacts (depending upon energy level), the delamination pattern was more developed, and the rear face showed signs of fibre fracture behind the impact site. Extensive matrix cracking had occurred, and the fibres appeared to have failed in tension-shearing. The dominant damage mechanisms for the laminates included delamination, matrix cracking, and tensile-shear fibre fracture.

At low energy level of 3.5 J, our attention was attracted by the slowness of delamination propagation, even with the increasing of impact number. In addition, the variation of delamination area is much more significant when the energy level is higher (Fig. 2).

As impact energy increases, the damaged area becomes larger. Fig. 2 shows that for increasing energies, delaminated surfaces are much more pronounced when the number of impacts is large. This indicates that projected area of delamination, resulting from the superposition of delamination in all the interfaces, is largely affected by the energy level. Indeed, increase in energy level induces shear stresses in the interfaces inter-layers, which lead to rupture of the interface and consequently formation and propagation of delamination. However, the evolution curves of delamination area A_d according to energy level E seem to follow a power law:

$$A_d = \alpha E^{\beta}, \tag{1}$$

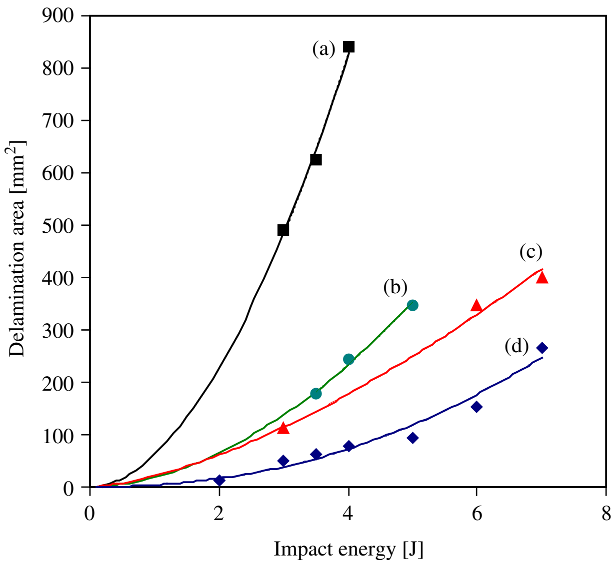

Fig. 2. Evolution of delamination area according to energy level: (■) $N = 50{,}800$ impacts, (●) $N = 5150$ impacts, (▲) $N = 1000$ impacts, (◆) $N = 100$ impacts. Curves fit: (a) $y = 62.45x^{1.86}$, (b) $y = 17.92x^{1.85}$, (c) $y = 21.28x^{1.53}$, (d) $y = 3.47x^{2.19}$.

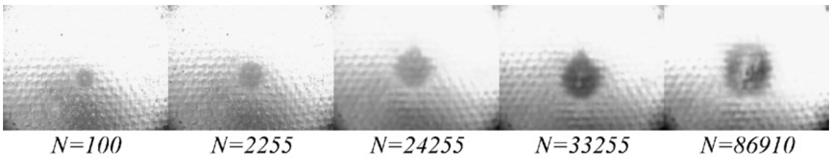

Fig. 3. Typical shape of projected area of delamination (at 3.5 J, back face).

where α and β can be determined by the plot of the curves: $\alpha = f(N)$ and $\beta = f(N)$, N being the number of impacts. This requires many experimental points in order to determine a quantitative tendency of the evolutions of these two parameters according to impact number N. The experimental points in our possession let to determine two empirical equations, which must be confirmed by other experimental points:

$$\alpha = 0.001\,N + 7.6 \quad \text{and} \quad \beta = 2.45N^{-0.03}. \tag{2}$$

The evolution of delaminated surfaces also depends on another significant factor, indeed the impact number also acts on the propagation of damage and more precisely on the variation of delamination area (Fig. 3).

In order to quantify delaminated surface and its evolution according to the number of impacts during the impact fatigue test, we considered it useful to plot the curves of variations of this surface for various impact numbers, and this until total failure of the specimen, which corresponds to the plate perforation (Fig. 4).

Fig. 4 shows that between 1 and 1000 impacts, the variation of delamination surface grows gradually and in a quasi-linear way, whose slope is much more marked when the energy level is higher. The impact number is one of the principal factors ally to the impact energy, which influences considerably the damage and failure of composite materials subject to impact fatigue.

The projected area of delamination developed with increasing cumulative impact energy is shown in Fig. 5.

The cumulative impact energy added to the specimen is determined from multiplying impact number by the incident impact energy. In both specimens, although there are some differences depending upon the energy level, the projected area of delamination increased rapidly at first with increase of the cumulative impact energy.

The curves reveal two distinct behaviours: for low impact energies (3.5, 4 J) the propagation of delamination presents three zones; a rapid increase at first, followed by a slower growth of delamination area, followed by an acceleration of damage until the total failure of specimen. This evolution in three phases can be explained by

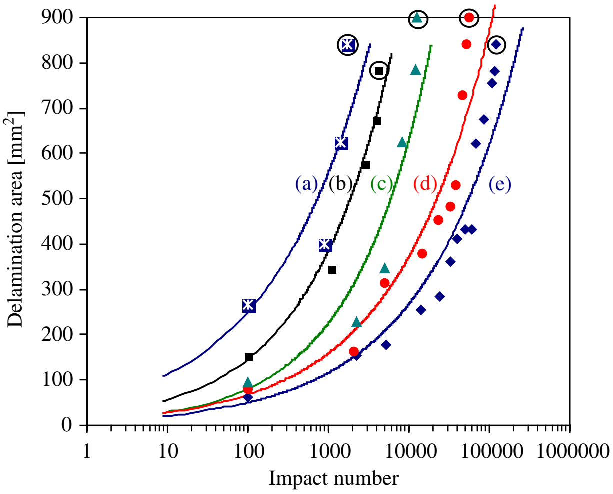

Fig. 4. Evolution of delamination surface according to impact number: (☒) $E = 7$ J, (■) $E = 6$ J, (▲) $E = 5$ J, (●) $E = 4$ J, (◆) $E = 3.5$ J. Curves fit: (a) $y = 50.58x^{0.35}$, (b) $y = 21.08x^{0.42}$, (c) $y = 10.19x^{0.45}$, (d) $y = 12.23x^{0.37}$, (e) $y = 9.32x^{0.36}$. (○) Failure point (perforation).

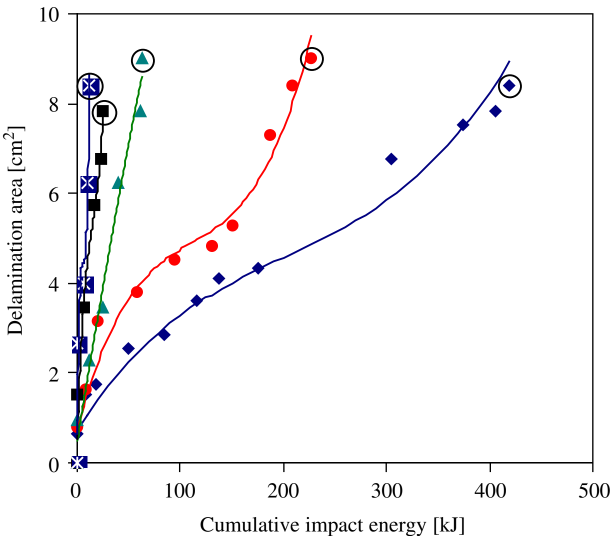

Fig. 5. Evolution of delamination area according to cumulative impact energy: (☒) $E = 7$ J, (■) $E = 6$ J, (▲) $E = 5$ J, (●) $E = 4$ J, (◆) $E = 3.5$ J, (○) failure point (perforation).

the fact that a great part of cumulative impact energy is absorbed in delamination in phases I and III, while the deceleration noted in the intermediate phase II indicates that the energy absorbed in delamination is less significant. That seems to be due to the fact that the other types of damage (mainly; punching of impact surface, growth of crater dimensions, matrix cracking at opposite face, etc.) as well as the bending elastic strain of the plate absorb the part of energy "lost" by delamination during the second phase (Fig. 5). For higher impact energies (5–7 J) the propagation of delamination grows rapidly in spite of the low impact number (Fig. 5).

We can conclude that the impact number is the major damage factor for low energy levels (3.5 and 4 J). But, as soon as the impact energy takes greater values ($\geqslant 5$ J), this one becomes the dominating factor. Let us note that after plate perforation, delamination areas reach values ranging between 784 and 900 mm^2 and at any time these surfaces exceed a value higher than 900 mm^2 for the entire tested specimens with different energy levels. The relative delamination area (i.e. divided by specimen surface) shows values ranging between 1.5% and 1.8%.

3.2. Evolution of crater expansion with impact fatigue tests

The crater expansion characterised by the cyclic punching of impacted face (Fig. 6) seems to follow a linear evolution in the case of crater diameter, but a growth according to an exponential law is noticed for crater depth (Fig. 7). The same behaviour is observed for the other impact energies.

The increasing evolution of crater diameter according to impact number follows a linear straight line of slope much more remarkable when the energy level is higher. However, the crater depth presents a slowest growth to accelerate thereafter until the final failure. The crater absorbs energy according to the growth of its diameter. Indeed, the growth of diameter is accompanied by rupture in tensile-shearing of fibres at the impact face, around impact point. The higher the crack diameter value the larger the number of fibres to break, which requires a greater energy. This quantity of energy increases gradually with damage of plate, which induce a linear increase in crater diameter.

However, the crater depth absorbs in the first phase of curves a small energy in comparison with delamination and crater diameter that results in a weak growth of depth. In the second part of curves, a progression is noted. This rapid increase of depth appears by the failure of the composite layers, the ones after the others until the total failure of specimen.

In order to better understand the evolution of one of crater dimensions relatively to the other, we were interested in the variation of depth to diameter ratio according to impact number (Fig. 8). We note the existence of two different phases:

First phase: The growth of crater depth to diameter ratio is linear according to a weak slope. This means that crater diameter increases more rapidly than depth dimension.

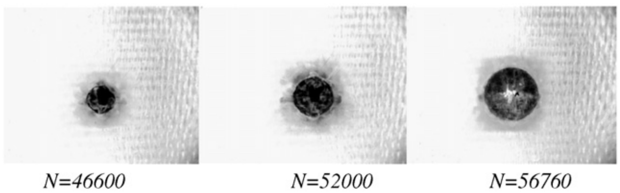

Fig. 6. Evolution of crater diameter according to impact number ($E = 4$ J).

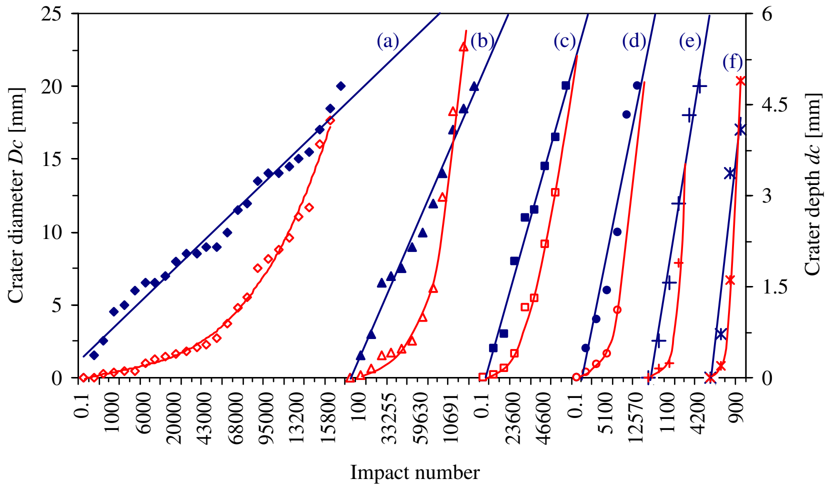

Fig. 7. Evolution of crater dimensions according to impact number: crater diameter (◆) Dc at $E = 3$ J. (▲) Dc at $E = 3.5$ J. (■) Dc at $E = 4$ J. (●) Dc at $E = 5$ J. (+) Dc at $E = 6$ J. (✱) Dc at $E = 7$ J. Crater depth (◇) dc at $E = 3$ J. (△) dc at $E = 3.5$ J. (□) dc at $E = 4$ J. (○) dc at $E = 5$ J. (+) dc at $E = 6$ J. (✱) dc at $E = 7$ J. Curves fit (a) $y = 0.68x + 0.75$. (b) $y = 1.63x - 43.98$. (c) $y = 2.50x - 100.39$. (d) $y = 3.50x - 173.43$. (e) $y = 4.34x - 244.22$. (f) $y = 6.20x - 385.20$.

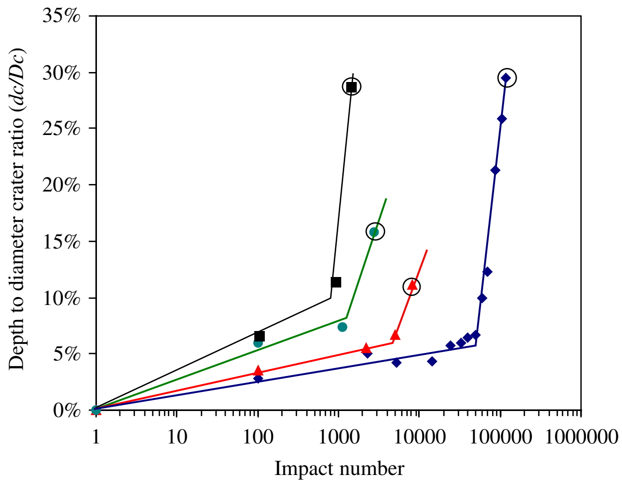

Fig. 8. Evolution of crater depth to diameter ratio according to impact number: (■) $E = 7$ J. (●) $E = 6$ J. (▲) $E = 5$ J. (◆) $E = 3.5$ J. (○) Failure point (perforation).

Second phase: The linear evolution of crater depth to diameter ratio according to a high slope (relative to first phase) indicates that crater depth increases more rapidly than diameter, which explains that perforation of plate is imminent.

3.3. Endurance curves

One of the principal objectives of this study is to plot impact fatigue curves. That consists of carrying out the impact fatigue tests until the total failure of composite plates. One notes then, for each energy level, the failure impact number or lifespan. The fatigue curves are obtained while carrying in x-coordinates; the failure impact number and in ordinates; the energy level.

The lifespan is measured by the cycle number to failure N_f. The application of N cycles ($N < N_f$) involves a certain damage in the material, which is important to quantify because it determines its remaining lifetime and thus can indicate if it is or not necessary to replace the defective part to avoid any accident.

Each specimen is perforated after a certain number of impacts and under a well-defined energy. The results obtained are represented in the form of a curve characterising the rupture of material (perforation) according to energy level and impact number, thus, to each specimen corresponds a point of the plan (E, N_f) (Fig. 9).

One can generally distinguish on this curve three distinct phases: for an energy level higher than 6 J (specimen thickness of 3.5 mm) and higher than 4 J (specimen thickness of 1.8 mm), the damage is very fast and the duration of repeated impacts until the perforation of specimens is very short. The higher is the energy level, the more the perforation is imminent; case of low cycle fatigue.

For a range of energy ranging between 4 and 6 J (specimen thickness of 3.5 mm) and between 1.5 and 4 J (specimen thickness of 1.8 mm) the degree of damage go less quickly than previously, in an interval of repeated impacts located between 5000 and 60,000 impacts. The more the energy level decreases, the more the propagation of damage slows down; case of high cycle fatigue.

For an energy level lower than 4 J (specimen thickness of 3.5 mm) and lower than 1.5 J (specimen thickness of 1.8 mm) the impact fatigue curves (Fig. 9) show that the damage of plates is very slow until the rupture. Indeed, this phase is located in an interval ranging between 60,000 and 170,000 impacts, described by a slope angle value tending towards 0 when the impact number is very high; case of endurance fatigue, which one calls also safety zone. This result enables us to conclude that below a certain value of threshold impact energy, the impacted material never reach the rupture, result established also by Lhymn [13].

The curve represented by Fig. 10 can be compared to Wöhler curve.

The effect of impact energy on failure impact number is shown in Figs. 9 and 10, it indicates that the failure impact number varies inversely with impact energy. This result is extremely interesting, since one can a priori

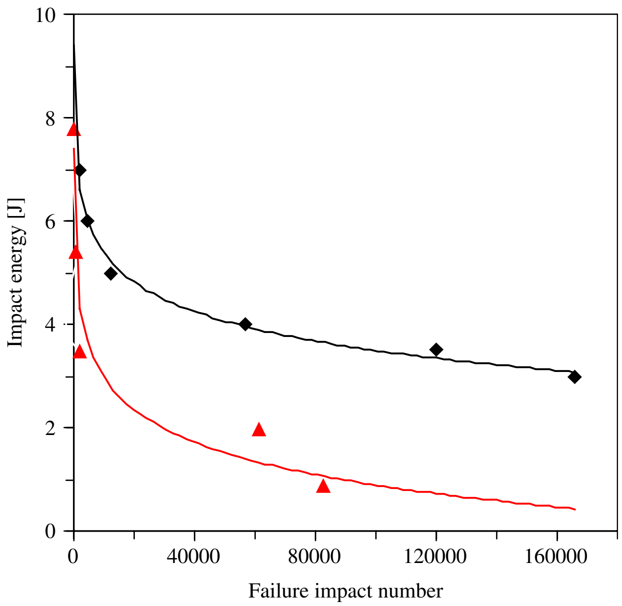

Fig. 9. Impact fatigue curves for two different thickness: (◆) 3.5 mm. (▲)1.8 mm.

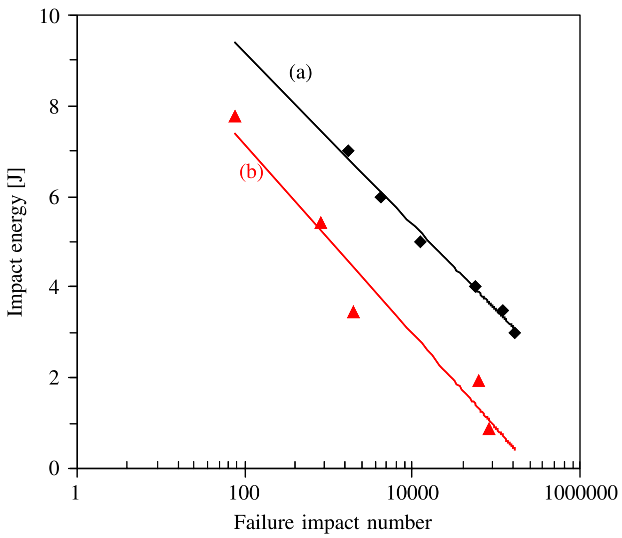

Fig. 10. Impact fatigue curves for E-glass/polyester woven fabric composite (logarithmic scale): (◆) 3.5 mm. (▲) 1.8 mm. Curves fit (a) $y = -0.82\mathrm{Ln}(x) + 12.94$. (b) $y = -0.90\mathrm{Ln}(x) + 11.31$.

apply what is known on classical fatigue to the case of impact fatigue, by taking into account the specificities of this particular type of test.

The two curves seem to follow a power function (see Eqs. (3), (4) and (5)), as it is the case of Whöler curves:

$$E = AN_f^b, \tag{3}$$

where A and b are the material constants. b can be determined by the plot of the curve: $\mathrm{Log}(E) = \mathrm{Log}(N_f)$, which designate a straight line and the intersection with y-coordinate is equal to $\mathrm{Log}(A)$.

The lifetime relationship for specimen of 3.5 mm thickness is given by

$$E = 25.57N_f^{-0.173}. \tag{4}$$

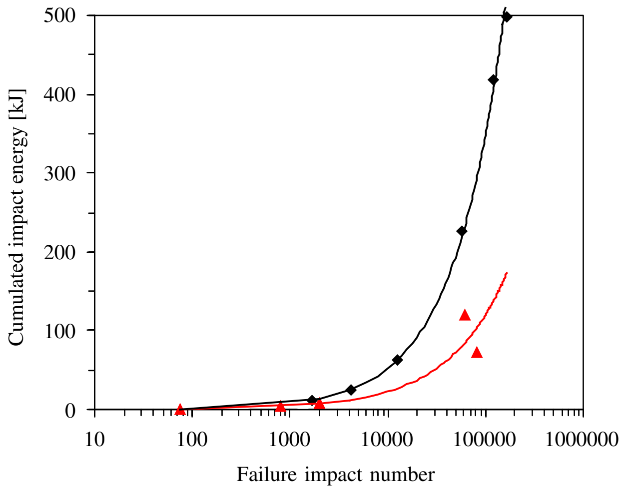

Fig. 11. Evolution of cumulative impact energy with failure impact number: (◆) 3.5 mm. (▲) 1.8 mm.

The lifetime relationship for specimen of 1.8 mm thickness is given by

$$E = 28.82 N_f^{-0.276}. \tag{5}$$

It is judicious to plot the curve of cumulative impact energy according to failure impact number (Fig. 11), in order to study the combined effect of impact number and energy level on lifespan N_f.

Fig. 11 shows that for high energy levels weak cumulative impact energy is sufficient to break material corresponding to a lower impact number. For low impact energy, the composite plates tend never to break, in spite of the great energy cumulated by material. This zone of endurance is represented by the asymptote at the end of the curve.

4. Conclusion

The principal results of this study are as follows:

The impact number is the major damage factor for low energy levels (3.5 and 4 J). But, as soon as the impact energy takes greater values ($\geqslant$5 J), this one becomes the dominating factor. Indeed, delamination area grows considerably for high values of impact number when the energy level is low. For higher impact energies (5, 6 and 7 J) the propagation of delamination grows rapidly in spite of low impact number.

With increase of cumulative impact energy, the projected delamination area increase rapidly at first, after which it showed a relatively slight increase, followed by an acceleration of damage. This evolution in three phases can be explained by the fact that a great part of cumulative impact energy is absorbed in delamination in phases I and III, while the deceleration noted in the intermediate phase II indicates that the energy absorbed in delamination is less significant. That seems to be due to the fact that the other types of damage (mainly; punching of impact surface, growth of crater dimensions, matrix cracking at opposite face, etc.) as well as the bending elastic strain of the plate absorb the part of energy "lost" by delamination during the second phase.

The delamination behaviour and crater dimensions in the laminated specimens depended largely upon both the level of incident impact energy and impact number. The higher cumulative impact energy, the larger the delamination area and crater dimensions generated, respectively, in the interior and at the impact face of specimen.

In our study, classical fatigue behaviour is demonstrated. Indeed, the plot of fatigue curve; impact energy according to failure impact number (representing the lifespan) emphasised a curve similar to the Wöhler curves, following a power law.

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