On the life time prediction of repeatedly impacted thermoplastic matrix composites

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A B S T R A C T
Impact-fatigue properties of unidirectional carbon fibre reinforced polyetherimide (PEI) composites were investigated. Low velocity repeated impacts were performed by using pendulum type instrumented impact tester (Ceast, Resil 25) at energy levels ranging 0.54–0.94 J. Samples were prepared according to ISO 180 and subjected to repeated low velocity impacts up to fracture by the hammer. Results of repeated impact study are reported in terms of peak load (F_{max}), absorbed energy (E_{max}) and number of repeated impacts. An analytical model to describe the life time of composite materials subjected to repeated impact loadings was presented.

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1. Introduction

Continuous fibre reinforced polymer composites with a high specific modulus and specific strength compared to other conventional materials have been used in large-scale structures such as aerospace, marine, automotive etc. [1]. Structural composites should be tested and analyzed under extreme loading conditions in order to determine their ultimate properties, such as static, impact and fatigue strengths etc. The composites may be subjected to low energy impact loadings during the service life [2]. These loads such as the drop of a handling tool, small impacts during the maintenance etc. may result in initial deformations and reduce the strength and life time of composite material.

There are many studies in literature report that material properties such as type of matrix and fibre, fibre orientation, volume fraction of fibre and matrix, interfacial properties, type and frequency of loading and service environment etc. closely affects the impact strength of the composites [3–5].

Because of their anisotropic nature, characterization of fracture behaviour and morphology of polymer composites are more complicated compared to conventional materials [6]. Fibre and/or matrix breakage, fibre debonding, fibre pull-out, shear failure of matrix and fibre and delaminations are common events not found on monolithic materials, and that can precede the ultimate failure of a composite [7–11].

Although many researchers have made efforts to analyze the impact behaviour of composite structures, there are limited studies about damage and life time prediction of composite laminates which are subjected to repeated low velocity impacts [12–15].

Azouaoui et al. [16] have presented the damage of a glass/epoxy laminated composite under impact-fatigue loading at low velocity and various incident energies. They have found that the damage history can be evaluated in three stages. In the first stage, the initiation and multiplication of delaminations are reported. The phenomenon of delamination saturation has been seen in the second zone and in the last zone an acceleration of the damage is observed due to the failure of fibres and cracking of the last layer. Hosur et al. [17] have investigated the impact-fatigue response of woven S2-glass/SC-15 stitched and unstitched composite laminates under single and repeated low velocity impact loading. They showed that under repeated impact loading, at lower energy levels peak load did not change significantly with number of impacts but at higher energy levels, peak load dropped suddenly after a certain number of impacts and absorbed energy also showed similar trend with respect to the number of impacts. Another impact-fatigue study have been designed to assess the behaviour of E-glass fibre reinforced vinylester composite material under repeated impact loads and to demonstrate the existence of a fatigue curve with an endurance limit by Roy et al. [8]. They have found that the composite samples showed progressive endurance with decreasing applied impact energy below the threshold fracture energy. Fernandez-Canteli et al. [18] were explored the possibility of applying the instrumented Charpy impact technique in order to determine the dynamic fracture toughness, K_{IC}, in carbon and glass fibre fabric composites for comparison with the corresponding static value, K_{IC}. The registered impact force and displacement at the specimen hammer contact point were used to evaluate Mode-I fracture energy and dynamic fracture toughness. The changes in fracture toughness due to impact velocity, crack size and stacking sequence of the specimen were investigated with different degrees of aging conditions. The results of the experiment showed that the dynamic and...
the static fracture toughnesses were increased with the crack growth for the two composite materials considered. Hosur et al. [19] determined the response of four different combinations of hybrid laminates to low velocity impact loading using an instrumented impact testing machine. The results of the study indicated that, there was considerable improvement in the load carrying capability of hybrid composites as compared to carbon/epoxy laminates with slight reduction in stiffness. The effect of repeated low energy impact on the performance of carbon–epoxy composites with three different stacking sequences was evaluated by de Morais et al. [2]. From the experimental results obtained, it was shown that the cross-ply and non-symmetric laminates have a better endurance against low impact events than unidirectional laminates. Dear and Brown [20] investigated the impact toughness of two grades of sheet moulding compound (SCM) and one grade of glass mat thermoplastic (GMT) material. Notable in the findings was that, the onset of through thickness damage occurred before there was visual evidence of surface damage at the point of contact between the striker and the specimen. Reis and de Freitas [21] determined the limit loading capacity and the damage growth mechanisms of impacted carbon fibre reinforced epoxy resin matrix composites when subjected to compression after impact. They had found that unstable damage growth was obtained by compression after impact due to a buckling mechanism in the delaminated area which was a function of the impact energy.

In this study, the composite material is subjected to low velocity repeated impact loadings with different impact energies. The main aim is to investigate the effect of the low velocity repeated impacts on the fatigue–impact properties of the continuous carbon fibre reinforced thermoplastic polyetherimide (PEI) matrix composites and to understand the impact–fatigue lifetime of this material. Results of low velocity repeated impact study were reported in terms of peak load, absorbed energy and number of impacts to failure.

2. Experimental procedures

Unidirectional carbon fibre reinforced Polyetherimide (PEI) composites were kindly supplied by TenCate Advanced Composites (Nijverdal/Netherlands) in the form of hot pressed plaques. Fibre volume content was 60%. Plaques manufactured from 14 plies with a ply thickness of 0.14 mm and the areal weight of ply was 222 g/m². The commercial code of the laminate was CD5150.

Impact tests were performed by pendulum type instrumented impact tester (CEAST Resil 25). The test samples were prepared according to ISO 180 standards. Un-notched samples were used with the dimensions of 10 × 2 × 65 mm. Fig. 1 illustrates the sample insertion procedure.

Preliminary experiments were performed in order to find the optimum drop angle. This angle was found as 70°, which has minimum inertial oscillations in the contact load between striker and sample during the impact. The sample was fractured with single impact at 70°. The maximum available impact energy of the striker was 2.65 J for 70°. Hammer length and mass were 0.327 m and 1.254 kg, respectively. Sampling time was chosen as 8 μs. At an angle of 70° (2.65 J) the hammer hit the sample with the velocity of 2.05 m/s.

Instrumented impact test parameters are shown in Fig. 2. Results of low velocity repeated impact study were reported in terms of peak load, absorbed energy and number of impacts. It is important to understand the approach used in the analysis of force–time curves, which is critical in determining the impact characteristics of materials. Upon impact of the pendulum, the force rises sharply to a maximum value \( F_{\text{max}} \) and gradually decays to zero due to catastrophic failure (fracture). The total area under the force–time curve gives the impact energy of the system \( E_{\text{Fmax}} \). These curves can be divided into two regions. The 1st region is the crack initiation and the second is the crack propagation regions. The areas under each region give the energy for these processes, which are defined as energy for crack initiation \( E_{\text{i}} \) and energy for crack propagation \( E_{\text{p}} \). The spikes in the 1st region are due to inertial oscillations of the sample. The amount of deformations \( (X_{\text{e.v.}}) \) is illustrated in Fig. 1, which corresponds to the maximum deformation of the composite sample.

3. Results and discussions

At first step of this study, preliminary observations were done in order to understand the impact response of the composite samples. Fig. 3 represents the instrumented impact test results of these
preliminary observations. In this group, the force–time (F–t) curves of impacts at energy levels ranging 0.14–2.65 J are illustrated. As seen in Fig. 3, up to 0.54 J (Fig. 3a–d) totally elastic deformations were observed. Achieved maximum forces ($F_{\text{max}}$) were increased by increase in impact energy. The symmetrical F–t
curves represent the typical elastic deformations. At 0.94 J (Fig. 3e) the symmetry of the F–t curves disappeared. Small sudden drop in F value was observed at around 2 μs after it reaches its maximum. Up to impact energy of 1.44 J composite samples were not fractured with single impact, but they were plastically deformed. The impact energies of izod hammer were chosen as 0.14, 0.24, 0.38, 0.54, 0.94, 1.44, 2.01 and 2.65 J. With the same sequence of the impact energy of the hammer, the striking velocity changes as 0.47, 0.62, 0.78, 0.93, 1.23, 1.51, 1.79 and 2.05 m/s. The hammer struck each sample only once. The samples were preserved from additional strikes of the hammer. The fracture time was remarkably decreased while the impact energies were around 2.01 and 2.65 J. Not surprisingly, at impact energy of 2.65 J the highest F_max and minimum fracture time was observed.

Fig. 4 represents the variation of F_max and E_max values of this group. There was a linear increment in F_max and E_max values by the increase in impact energy of the hammer.

At the second step of this study, the parameters of impact-fatigue experiments are chosen from the results of preliminary observations. As illustrated in Fig. 3b, the highest impact energy of 0.54 J is observed which results in totally elastic deformations. On the other hand, the impact energy of 0.94 J did not fracture the sample but cause elastoplastic deformations. As a result of these preliminary observations, it was decided to chose the energy range of impact-fatigue experiments between 0.54 and 0.94 J. The impact energies of izod hammer were chosen as 0.54, 0.57, 0.61, 0.65, 0.69, 0.73, 0.77, 0.81, 0.85, 0.90, and 0.94 J. With the same sequence of the impact energy of the hammer, the striking velocities were changed as 0.93, 0.96, 0.99, 1.02, 1.05, 1.11, 1.14, 1.17, and 1.20 m/s, respectively. During these impact-fatigue experiments the composite samples were inserted into the sample holder and hit by izod hammer repeatedly. The composite samples were subjected to single impacts repeatedly up to fracture at each impact energy level.

Fig. 5 represents the force–time curves of the second group experiments. Each illustration in Fig. 5 represents the F–t curves of impact-fatigue experiment results between the first and the final impacts. As expected, the maximum impact number for fracture was observed at minimum impact energy level of 0.54 J. The composite sample was fractured after 3580 repeated impacts. At higher impact energy levels, composite samples were fractured after lower number of impacts. The minimum impact number for fracture was observed as 21 at highest impact energy of 0.94 J.

At first impacts for each energy level, the hammer-sample contacts were recorded along 5–6 μs. On the other hand after impact-fatigue loadings, at the final impacts samples were fractured in 2.5–3.5 μs. During the impact-fatigue experiments at each energy levels F_max values were decreased progressively by the impact numbers. Also the impact modules of the samples are decreased which results in lower “slopes” in F–t curves during the experiments.

Fig. 6 illustrates the variation of F_max values during the impact-fatigue experiments at different energy levels. It was observed that at each energy levels the changes in F_max values were realized in three regions. At 1st region F_max values were dropped sharply due to the fibre fractures in the compression zone. During the impact-fatigue experiments, deformation morphology of the materials was also investigated visually and by optical microscope. The results of these investigations are reported in detail previously [22]. As it is well known, the compressive strength of the C/PEI composite is lower than the tensile strength. This is why, during the impacts, composite material initially deformed in compression zone (Fig. 1). The carbon fibres in compression zone forced the microbuckling and shear deformations. There were many kinked fibres were observed at the compression zone. As a result of this loading, at first step due to the fractured fibres in compression zone there is a sudden drop in F_max values during the impact-fatigue experiments. These sudden drops in F_max values called as 1st region in Fig. 6. 2nd region can be called as “plateau region” where the F_max values endured around a certain value. In this region, initiation and multiplication of delaminations occurred which was also reported by Azouaoui et al. [16]. Delaminations in laminated composites are of major concern because there is significant loss of stiffness. This region was followed by 3rd region. At this region, after a certain impact number the F_max values were decreased sharply again because of the fibre fractures in the tensile zone. Finally the samples were totally fractured at the end of this region with a minimum F_max values.

Unlike F_max, E_max has shown a different behaviour and changed in two regions. During the experiments, up to a certain impact number for each impact energy level, the E_max values remained constant. This region was called as 1st region. At the end of the 1st region, the E_max values showed remarkable decrease and this region was called 2nd region. The 2nd region in Fig. 7 started at approximately the same impact number with the starting of 3rd region in Fig. 6. This situation can be explained as “cumulative energy balance”. During the experiments at 1st and 2nd regions, the crack initiation energy (E_i) was decreased by the increase in impact number. On the other hand, the crack propagation energy (E_p) increased. As a result, in 1st region the total energy (E_max) remained approximately constant (Fig. 7).

In order to see the relationship between the impact number and F_max values for all impact energy levels, each curves are re-illustrated at the same scale in Fig. 8. In Fig. 8 it is possible to see the all changes in F_max values for each energy levels. Not surprisingly, the larger 2nd regions were observed during the impact-fatigue

![Fig. 4. F_max and E_max values respect to the impact energies.](image-url)
experiments at lower energy levels (e.g., 0.57–0.61 J). On the other hand at higher energy levels the regions in $F_{\text{max}}$ values realized in a narrow bands. Samples in high energy level fractured after limited impact numbers.

Fig. 5. $F$–$t$ curves of impact-fatigue experiments for different impact energy levels.
Fig. 9 illustrates the variation of $E_{\text{max}}$ values during the impact-fatigue experiments. $E_{\text{max}}$ values systematically changes with respect to energy levels and impact numbers. Especially for the aircrafts that subjected to many small impacts during the service life, it is important to know the possible cumulative damage on the body. Is this damage big enough to
be evaluated as a risk for catastrophic failure or not? In order to have an idea about this situation, the authors investigated the energy levels, number of impacts and residual impact strength relationship. There is not a satisfactorily good model for prediction of impact-fatigue life for composite materials. On the other hand it is possible to find different models for fatigue loading.

In Fig. 10, the experimental results are re-illustrated which give information about low energy impact-fatigue life of composite material. As seen in Fig. 10, up to 0.57 J, the impact number up to fracture show a parabolic variation. Lower than this impact energy value, the impact number up to fracture increased suddenly. If we called impact energy as “$y$” and impact number as “$x$” the equation of the impact-fatigue life curve can be expressed as:
4. Conclusion

The impact properties and the effects of the repeated impacts on the impact-fatigue properties of carbon fibre reinforced PEI composites were studied. It was observed that, as expected, the impact energy of the hammer and the number of repeated-impacts were main parameters. In impact-fatigue loading, decrease in impact energy resulted in an increase in the number of impacts to fracture. It is observed that at each energy level, the changes in $F_{\text{max}}$ values were realized in three regions. Unlike $F_{\text{max}}$, $E_{\text{max}}$ changed in two regions.

The maximum impact number for fracture was observed at minimum impact energy level of 0.54 J. At higher impact energy levels, composite samples were fractured at lower number of impacts. The minimum final impact number is observed at impact energy of 0.94 J. A model for prediction in impact-fatigue life for composite material is also presented.

References


