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Jarosław BIENIAŚ
Barbara SUROWSKA
Patryk JAKUBCZAK

INFLUENCE OF REPEATED IMPACT ON DAMAGE GROWTH IN FIBRE REINFORCED POLYMER COMPOSITES

WPŁYW UDERZEŃ WIELOKROTNYCH NA ROZWÓJ USZKODZENIA KOMPOZYTÓW POLIMEROWYCH WZMACNIANYCH WŁÓKNAMI*

The study presents the problems of the influence of repeated low velocity and low energy impacts on damage growth in carbon and glass fibre reinforced high strength polymer composite. The laminate response to impacts was analyzed, the types of damages and their interrelations were identified as well as damages mechanisms were described for tested laminates subjected to repeated impacts. The following conclusions have been drawn on the basis of completed tests: (1) composite materials with polymer matrix reinforced with continuous glass and carbon fibres demonstrate limited resistance to repeated impacts. The laminates resistance to impacts depends mainly on the properties and type of components, particularly in case of reinforcing fibres, orientation of layer under the influence of external impact; (2) tested laminates with carbon fibres are characterized by lower resistance to repeated impacts than laminates with glass fibres. This is proved by the curves of laminate response to impacts, wider damage area and tendency to laminate structure perforation as a result of repeated impacts; (3) repeated impacts lead to damage growth mainly through propagation of damage initiated in initial impacts phase. Delaminations and matrix cracks belong to the basic mechanisms of damages in composite materials; (4) composite damage propagates with increasing number of impacts in fibres orientation direction, particularly in lower composite layers. Further impacts may result in higher stress concentration and higher initiation energy causing the damage growth in various areas of the material. Further impacts increase the damage leading to gradual growth of damages initiated before.

Keywords: *composites, repeated impact, NDT, damage.*

W pracy przedstawiono problematykę wpływu powtarzających się uderzeń o niskiej prędkości i niskiej energii na rozwój uszkodzenia wysokowytrzymałych kompozytów polimerowych wzmacnianych włóknem węglowym oraz szklanym. Dokonano analizy odpowiedzi laminatu na uderzenia, zidentyfikowano rodzaj i relacje pomiędzy uszkodzeniami, a także przedstawiono mechanizmy uszkodzenia w badanych laminatach poddanych wielokrotnym uderzeniom. Na podstawie przeprowadzonych badań wykazano że: (1) materiały kompozytowe o osnowie polimerowej wzmacniane ciągłymi włóknami szklanymi i węglowymi wykazują ograniczoną odporność na wielokrotne uderzenia. O odporności laminatów na uderzenia decydują głównie właściwości i rodzaj komponentów, w szczególności włókien wzmacniających, orientacja warstw pod wpływem oddziaływania zewnętrznego; (2) badane laminaty z włóknami węglowymi charakteryzują się niższą odpornością na wielokrotne uderzenia w porównaniu do laminatów z włóknem szklanym. Świadczą o tym charakterystyki odpowiedzi laminatu na uderzenia, większy obszar uszkodzenia oraz skłonność do perforacji struktury laminatu w wyniku wielokrotnych uderzeń; (3) uderzenia wielokrotne powodują rozwój uszkodzenia głównie przez propagację uszkodzenia inicjowanego w czasie początkowych uderzeń. Do podstawowych mechanizmów uszkodzenia materiałów kompozytowych należą rozwarstwienia oraz pęknięcia osnowy; (4) wraz ze wzrostem liczby uderzeń uszkodzenie kompozytu propaguje w kierunku ułożenia włókien, szczególnie dolnych warstw kompozytu. Kolejne uderzenia mogą powodować większą kumulację naprężeń oraz energii inicjacji odpowiedzialnej za rozwój uszkodzenia w różnych obszarach materiału. Kolejne uderzenia powodują zwiększanie uszkodzenia prowadząc do stopniowego rozwoju wcześniej zainicjowanych uszkodzeń.

Słowa kluczowe: *kompozyt, uderzenia, badania nieniszczące, uszkodzenie.*

1. Introduction

Fibre reinforced polymer composites (FRP) are widely used in many sectors, mainly in aeronautical engineering for the elements of aircraft, including the skins. Due to the trends towards maintenance costs reduction and towards the reduction of aircraft structure weight, the demand level for durable and damage resistance materials is high [25]. These requirements are met by the composite structures characterized i.a. by high level of static and fatigue strength, low density and corrosion resistance. However they are characterized by limited resistance to impacts with concentrated force [19].

The resistance to impacts is particularly important in the scope of aircraft operation and their reliability. The aircraft are required to perform determined functions at determined time and operation conditions. The impacts may lead to degradation of individual structural elements and consequently to the reduction of their service life and finally affecting the safety level [21].

The dynamic loads may be generated in course of flight and ground handling of aircrafts e.g. by falling tools, collisions with load-

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** ing and technical support trucks, foreign bodiesthrust by the engine and aircraft wheels and tyres damage [22, 25]. As can be drawn from technical literature [25], completed repairs of critical elements of airframes in passenger aircrafts (Boeing 747) in course of their scheduled service life were caused by three types of damages i.e. mainly fatigue cracks, corrosion processes and damages caused by impacts; the latter encompassed about 13%. The impacts may lead to complete perforation of composite structure and to generation of invisible damages with numerous delaminations, cracks in composite matrix and in reinforcing fibres [1, 8, 11, 24].

At the moment several published research papers relate to the evaluation of the influence of the impacts on damage growth in composite aircraft structures. Richardson et al. [19] described the influence of low velocity impacts on fibre composites damage degree vs. impact velocity and energy. From the conclusions presented by the authors it appears that the damages of composite structures caused by the impacts can be subdivided into damages propagating inside the structure and external damages e.g. in the form of perforations. The type of matrix and reinforcement material belong to the factors determining the character of damage as well as the damage initiation and propagation mechanisms at the impact. The carbon fibres, due to their higher brittleness and lower deformation in comparison with glass fibres or aramid fibres, are characterized by the lowest resistance to impacts [19]. The composites reinforced with carbon fibres are characterized by degradation of fibres as prevailing form of damage. But fibre glass reinforced composites are characterized by extensive delaminations in composite structure [3]. Other authors [11, 20, 21, 23, 26] evaluated the influence of fibres orientation in the form of reinforcement on composites damage growth, the influence of damage on their static and fatigue strength as well as the influence of environment conditions on the resistance of composite materials to impacts.

There are only a few studies describing the evaluation of the influence of repeated impact on damage growth in composite materials which may be found in the literature [10, 17, 18]. The authors indicate that repeated impact may contribute to significant damage growth in composite structures through the cyclical growth of originally initiated damages [9]. The influence of repeated impact is tested mainly in the low energy range in order to evaluate the damage growth progress from insignificant material degradation level [23]. It is justified in case of airspace materials exposed to this type of damages and difficult diagnostics thereof. Aymerich et al. [5] demonstrated that even an insignificant internal structure degradation after single impact may lead to the reduction of composite strength even by several tens of percent. However in case of repeated impact, the influence of damage growth on the reduction of mechanical properties has been not evaluated yet.

The article presents the problem of the influence of repeated impact with low – velocity and low energy on damage growth in high strength polymer composites reinforced with carbon and glass fibres. The laminate response to impacts was analyzed, the types of damages and their interrelations were identified as well as damages mechanisms were described for tested laminates subjected to repeated impacts.

2. Materials and methods

Two types of composites were tested. Carbon fibre reinforced composites (CFRP) and glass fibre reinforced composites (GFRP). The FRP panels examined in this study were made of AS7J carbon/epoxy prepreg (0.13 mm of thickness, Hexcel, USA) and R-glass fibres with epoxy resin prepreg (0.25 mm of thickness, Hexcel, USA). The nominal fibre content was about 60 vol.%. The lay-up scheme of both laminates was ($0_6/90_6$) for CFRP and ($0_3/90_3$) for GFRP. Total thickness of laminates was 1.5 mm.

The composite laminates were produced in the Department of Materials Engineering - Lublin University of Technology by using autoclave method (Scholz Maschinenbau, Germany**)**. The cure cycle was carried out at a heating rate of 2°C/min up to 135°C and held at this temperature for two hours. The pressure and the vacuum used were 0.4 and 0.08 MPa, respectively.

The low-energy impact test were performed at room temperature using a drop-weight impact tester (InstronDynatup 9340) with possibility of recording force-time curves. Impact tests were carried out according to ASTM D7136 standard [17]. Samples dimension was 150x100 mm. A hemispherical impactor tip with a diameter of 38.1 mm and mass of 1.4 kg was used. Impact with 5 J energy were conducted one, three and five times in the same point.

Laminates after one, three and five impacts were tested with macroscopic observations and NDT methods for damage area evaluation. As NDT the ultrasonic pulse-echo method were used (OmniScan MX, Olympus, Japan).

3. Results and discussion

The typical force-time (*f-t*) and force-deflection (*f-d*) curves recorded during impact are shown in Figure 1.

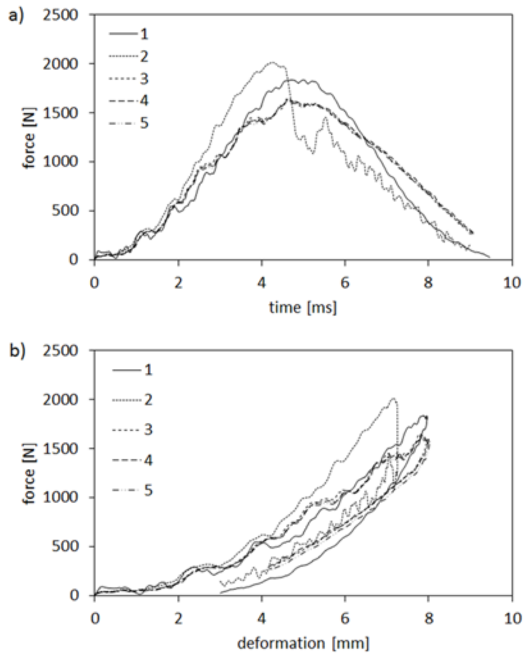

Fig. 1. Force - time (a,c) and force - deflection (b,d) curves of fibre reinforced polymer composites after multiple impact

There are four specific phases of force change on force vs. time curves as a result of impact: the initial stage of system stabilization, force increase stage, time of reaching the maximum force, *Fm* (Fig. 1a,c) and force decrease stage thereafter. Described force-time stages gradually represent the material reaction to the influence of the impactor, regardless of the successive impact number. The first stage of the force value variations is responsible for the system stabilization. The force fluctuations in this stage represent the vibration of the material – impactor system [16]. The force fluctuations observed in the next force increase stage are insignificant and mainly associated with local degradation of composite structure [16]. The matrix degradation and propagation of delaminations, particularly on the boundaries of layers with different orientation of reinforcing fibres occur in case of low impact energies [11]. The smoothest force curve is observed at the first impact. Therefore it can be found that an insignificant and local damage is observed. Such circumstances are observed in case of glass

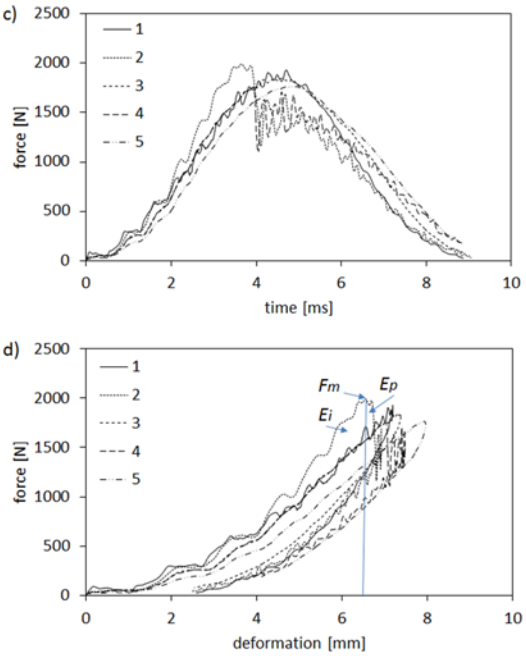

Fig. 1. (continued) Force - time (a,c) and force - deflection (b,d) curvesof fibre reinforced polymer composites after multiple impact

and carbon composite.The local damages are initiated in the material without significantly reducing the composite rigidity but simultaneously reducing the whole energy of initial impacts. However the successive impacts lead to the occurrence of higher force fluctuations at the time of impact. Particularly the second and the third impact lead to the sudden reduction of force after *Fm* is reached (Fig. 1a,c). The sudden reductions of force after the achievement of the maximum value of force have been also observed by other authors [16, 21, 22]. They concluding that such variations of the force values rather indicate to more extensive and advanced material damage, finally reducing the rigidity and strength of the material. The reduction of force was higher after the second impact in glass composite (about 50%) (Fig. 1a).The reduction in carbon composite (force reduction by about 40% after *Fm* is reached) was lower but characterized by greater number of fluctuations (Fig. 1c). Probably observed difference was caused by various degradation mechanisms in these composites under the influence of impact.The next impacts (i.e. fourth and fifth impact) are not characterized by intensive force fluctuations at the time of impact (Fig. 1a,c). It may mean that the next impacts do not initiate any new areas of significant structure degradation any more. However the damages initiated before are gradually growing and absorbing most energy in course of the next impacts. Simultaneously the measured time of material – impactor contact is similar for all the impacts. Chakraborty [9] found that the nucleation of the new delamination locations occurs in carbon composites as a result of repeated impacts. However the area damage previously is also an intensively growing area. Nevertheless the shape of force curve in course of further impacts indicates that the damage growth is rather stable and relatively uniform without any further drastic loss of material cohesion. Morais et al. [17] and Found et al. [10] obtained similar results in their evaluations of the damage growth vs. number of impacts, indicating the stable growth of composite damage vs. increased number of impacts. The interrelations between the successive *f-t* curves are similar in the both types of materials, which indicates their similar trends in the scope of damage propagation as a result of repeated impacts.

The analysis of relationship between the initiation energy (E_i) and degradation propagation energy (E_p) is possible on the basis of the force – deflection (*f-d*) curves for the material in course of successive impacts [2, 13, 22]. Among others Sohn et al. [22] described that the point of reaching maximum force (F_m) determines the areas of damage initiation energy until the maximum force point is reached, as well as the area of damage propagation energy after reaching the maximum force point (Fig. 1d). All absorbed energy during impact (E_a) is the sum of initiation energy (E_i) and propagation energy (E_p). The aggregate energy absorbed (E_a) by the material during the dynamic impact is the sum of the initiation (E_i) and propagation energy (E_p). Similar energy relationships have been found in these curves *(f-d)* for glass and carbon composites (Fig. 1b,d). From among all the impacts, the second and third impacts maintain noticeably different relationships between E_i and E_p. The value of force which may be observed in these cases is slightly higher at similar deflection and the value of propagation energy field is lower. It can be caused by the significant damage growth at these impacts. The shape of the force – deflection (*f-d*) curves does not indicate to any laminates perforations. It has been denoted that the value of the impactor deflection at the total force reduction after the impact is close to the initial value of the deflection observed for the force stage (after the system stabilization stage). This relationship is similar for the both materials cases. Similar values of the deflections after each next impact indicate to the lack of permanent deformation of composites. Higher values of the material deflections in case of impact have been recorded for fibre glass composites because, among others, the elongation to break for glass fibres (R type) is about two times higher than in case of high strength carbon fibres. Brittle and highly durable materials will be characterized by higher initiation energy and lower propagation energy. Carbon fibre reinforced composites can be matched to this group. On the other hand, more plastic but less durable materials will have lower initiation energy and higher propagation energy. This may also concern composites containing glass fibres [6]. Higher deformation may result in higher interlayer delaminations in composites due to higher values of lateral shear stresses [11]. Higher susceptibility to bending strains in case of impact is associated with lower rigidity characterizing GFRP composites in comparison to CFRP composites.

In order to distinguish responses to repeated impacts in CFRP and GFRP composites, the analysis of their damage was carried out after the successive impact. The macroscopic image of tested samples is shown in Figure 2, where invisible macroscopic damages (BVID), cracks and delaminations were found.

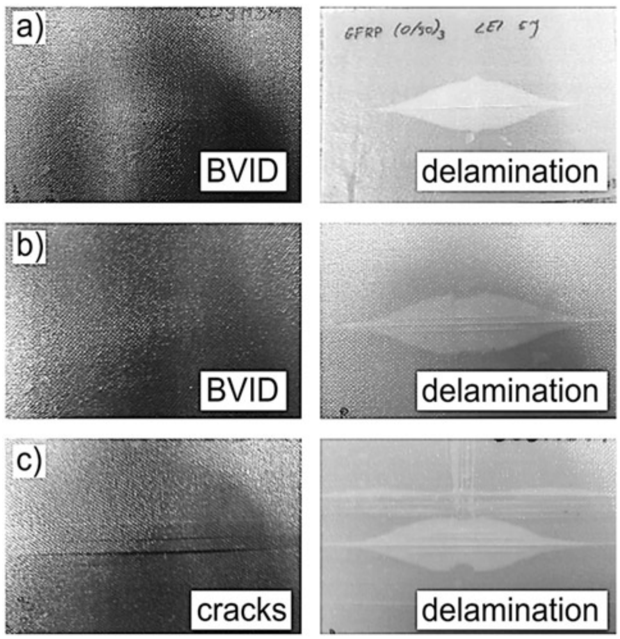

Fig. 2. Macroscopic image of composites plates (CFRP left side and GFRP right side) after one (a), three (b) and five (c) impacts

The damage zone in case of an epoxy carbon composite is characterized by an invisible internal damage. The macroscopic observation of damage propagating in the material is not possible after the first and third impact (Fig. 2a,b). It indicates that occurred damage is an internal damage and may initiate and propagate in the form of delaminations and matrix cracks. This type of damage area after low energy impacts was described in many published testing results [17, 19, 26]. Richardson et al. [19], in his overview study referred to many studies describing this type of damage as Non-Visible Impact Damage (NVID) or Barely Visible Impact Damage (BVID), which nevertheless severely reduces the structural integrity of the component. Barely Visible Impact Damages (BVID) propagate in composite structures mainly in case of low energy impacts [17, 26]. On the basis of executed tests it has been denoted that the damage propagates in external layers at the fifth impact. The breaking of external layer (bottom layer on impact end) is observable along the fibres direction in this layer (Fig. 2c). Longitudinal matrix crack propagated practically through the entire length of sample. Such type of damage is caused by bending strain at impact point but any fibres crack has been not observed in CFRP composite.

In case of the transparent epoxy carbon composite, the macroscopic observation makes it possible to identify the damage after the next impacts (Fig. 2). Extensive delaminations have been detected within the structure after the first impact. The growth of delaminations is conforming with the direction of composite layers in its bottom layers. Bidirectional composite layers system (0/90) caused prevailing delaminations propagation. Delaminations in the laminates subjected to dynamic impact observed on the interface layer with various fibre orientation. Delamination shape is quite oval with the major axis aligned with fibre orientation in the lower layer. According to Richardson et al. [19] delaminations occur in the areas with higher resin content between layers with various orientations. The shape of the delamination results from shear stress distribution around the area surrounding the impactor, low interlayer shear resistance alongside or close to the fibre orientation direction as well as from matrix cracking caused by bending stress [11].

The system 0/90 is characterized by the highest anisotropy of stiffness with prevailing shear stresses in composite.The third and fifth impacts in GFRP composite result in the growth of delaminations and in the occurrence of the matrix cracks also in the external layers of composite. The third impact causes the ignition of the matrix cracks also in 0 direction. The fifth impact causes further propagation ofthese cracks (Fig. 2c). In order to determine the trends in the scope of the damage growth as a result of multiple impacts, the surface area has been determined for composites after the first, third and fifth impact. The damage area growth versus impact number is presented in Figure 3.

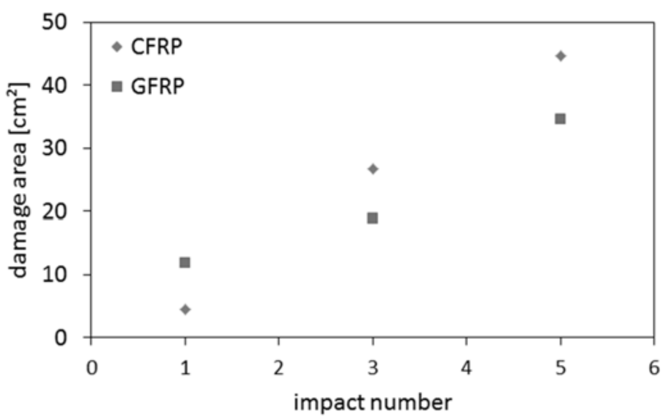

Fig. 3. Damage area growth vs. number of impacts

The analysed damage surface area is one of the most frequently used evaluation criteria for the influence of low velocity impacts on the condition of composite materials structure [4, 14, 22]. The damage surface area determined by means of NDT methods encompasses all detectable types of damage which may occur in the composite structures. Mainly delaminations and cracks belong to this group. The calculations of damage surface areas after the impacts presented in the literature determine the surface area for the largest delamination. In case of systems consisting of fibres with many interface layers with different fibres orientation, the damages occurring in individual layers are not added together [14, 15]. In case of materials under test, the delamination propagates mainly at the boundary between 0 and 90 layers. On the basis of completed measurements it may be concluded that the damage surface area increases after the next impact. In case of CFRP composite a stable growth of damage is noticeable after the next impacts. The damage surface area increases with increasing number of impacts (Fig. 3). In case of CFRP composite, the growth is more dynamic after later impacts. The larger values of surface areas of the damage in carbon composite in case of repeated impacts indicate its lower resistance to this type of loads than in case of glass composites. This trend is caused among others by higher stiffness of CFRP composite (E~131 GPa in 0° direction, E~8 GPa in 90° direction) [25] than GFRP composite (E~56 GPa 0° direction, E~16 GPa in 90° direction) [7]. The greater part of energy can be absorbed by initiation and propagation in carbon composites. But in glass composites, the part of absorbed energy is associated with larger deformation achievable in course of impact. In accordance with data accessible in literature [10], at sufficiently high number of impacts, the growth of damage surface area is characterized by more and more decreasing growth dynamics. Increasing number of impacts leads to fibres degradation and trend to perforations.

4. Conclusions

The following conclusions can be drawn on the basis of executed tests consisting in repeated impacts by means of concentrated force for polymer fibre composite materials:

1. Composite materials with polymer matrix reinforced with continuous glass and carbon fibres demonstrate limited resistance to repeated impacts. The laminates resistance to impacts depends mainly on the properties and type of components, particularly in case of reinforcing fibres and orientation of layers in composite.
2. Tested laminates with carbon fibres are characterized by lower resistance to repeated impacts than laminates with glass fibres. This is proved by the curves of laminate response to impacts, wider damage area and tendency to laminate structure perforation as a result of repeated impacts.
3. Repeated impacts lead to damage growth mainly through the propagation of damage initiated at the time of initial impacts. Delaminations and matrix cracks belong to the basic mechanisms of damage in composite materials.
4. With the increasing number of impacts, the composite damage propagates in fibres orientation direction, particularly in lower layers of composite. Further impacts may lead to increased concentration of stresses and initiation energy responsible for damage growth in various areas of material. The next impacts increase the damage leading to gradual growth of damages initiated previously.

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Jarosław BIENIAŚ
Barbara SUROWSKA
Patryk JAKUBCZAK
Department of Materials Engineering
Mechanical Faculty
Lublin University of Technology
ul. Nadbystrzycka 36, 20-618 Lublin, Poland
E-mail: j.bienias@pollub.pl