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COMPOSITES THEORY AND PRACTICE

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ANALYSIS OF LOAD-DISPLACEMENT CURVES AND ENERGY ABSORPTION RELATIONS OF SELECTED FIBRE METAL LAMINATES SUBJECTED TO LOW-VELOCITY IMPACT

The goal of this paper is to analyse damage in Fibre Metal Laminates, containing glass and carbon fibre reinforced composites, subjected to low-velocity impact. The analysis is based on the assessment of force-displacement characteristics in the aspect of energy absorption connected with initiation and damage propagation in the examined laminate. On the basis of experimental research and result analysis, it may be stated that: (1) Fibre Metal Laminates with glass and carbon fibres are characterized by higher impact resistance in comparison to classic composite structures. This assumption is proved by higher maximum load levels, as well as by higher aggregate absorbed impact energy. Moreover, the aluminium layers can have a protective function as they absorb a significant amount of dynamic impact energy and lower the scope of damage in the laminate. (2) Fibre Metal Laminates with carbon fibres show greater susceptibility to damage resulting from dynamic impact than laminates with glass fibres. The main factors influencing the impact resistance of the examined materials are the properties of particular components, especially the composite reinforcing fibres. Carbon fibres show a relatively small deformation range until failure and are brittle in comprison to glass ones, which raises their susceptibility to damage resulting from dynamic impact. (3) Force-displacement (*F-d*) analysis, aggregate absorbed impact energy (E_a) as well as initiation energy (E_i) and damage propagation (E_p) may represent some of the more vital criteria of composite materials assessment in terms of their resistance to low-velocity impact.

Keywords: Fibre Metal Laminates, impact, impact energy, damage

ANALIZA WYKRESÓW SIŁA-PRZEMIESZCZENIE ORAZ RELACJI ABSORBOWANEJ ENERGII PRZEZ WYBRANE LAMINATY METALOWO-WŁÓKNISTE PODDANE UDERZENIU Z NISKĄ PRĘDKOŚCIĄ

Prezentowana praca ma na celu analizę zniszczenia laminatów metalowo-włóknistych zawierających kompozyt wzmacniany włóknem szklanym i węglowym poddanych uderzeniom dynamicznym poprzez ocenę charakterystyk siła--przemieszczenie w aspekcie absorbowanej energii związanej z inicjacją i propagacją zniszczenia lamiantu. Na podstawie badań eksperymentalnych oraz analizy wyników można stwierdzić że: (1) Laminaty metalowo-włókniste z włóknami szklanymi i węglowymi odznaczają się wyższą odpornością na uderzenia dynamiczne w porównaniu do klasycznych struktur kompozytowych. Świadczą o tym wyższe poziomy maksymalnego obciążenia oraz sumarycznej zaabsorbowanej energii uderzenia. Ponadto warstwy aluminium mogą pełnić rolę ochronną absorbując w znacznym stopniu energię uderzenia dynamicznego i zmniejszając ogólny poziom zniszczenia laminatu. (2) Większą podatność na zniszczenie poprzez uderzenia dynamiczne wykazują laminaty metalowo-włókniste z włóknami węglowymi w porównaniu do laminatów z włóknami szklanymi. Decydującym czynnikiem o odporności na uderzenie badanych materiałów jest charakterystyka poszczególnych komponentów, w szczególności włókien wzmacniających kompozyt. Włókna węglowe wykazują stosunkowo małe odkształcenie do zniszczenia i są kruche w porównaniu do szklanych, co zwiększa ich podatności na zniszczenie poprzez uderzenia dynamiczne (3) Analiza krzywych siła-przemieszczenia (*F-d*), sumaryczna zaabsorbowana energia uderzenia (E_a) oraz energia inicjacji (E_i) i propagacji (E_p) zniszczenia mogą stanowić jedno z istotnych kryteriów oceny odporności materiałów kompozytowych na uderzenia dynamiczne o niskich prędkościach.

Słowa kluczowe: laminaty metalowo-włókniste, uderzenia dynamiczne, energia uderzenia, zniszczenie

INTRODUCTION

Fibre Metal Laminates (FMLs) are a new kind of hybrid materials which are used in such elements of aircrafts as fuselage or plating [1, 2]. As a consequence of combining such properties of metals as plasticity and resilience with a polymer fibre composite, to which anisotropic features can be given, FMLs are characterised by superior fatigue resistance, damage tolerance, high strength properties as well as impact and corrosion resistance [1, 3, 4]. During exploitation, aerospace structures and the materials which the composites are made of are susceptible to dynamic impact [5].

Depending on velocity, impact can be divided into low-velocity (< 10 m/s) and high-velocity (> 10 m/s) [6]. Dynamic impact causes degradation of the composite structure in forms ranging from ply *cracking*, reinforcing *fibre* breakage and interlayer delamination to complete damage resulting from perforation [6]. Composite structure damage occurring as a consequence of dynamic impact significantly influences the integrity of the structure and lowers the durability of the elements. That is why it is vital to continue research concerning laminate resistance and explore the mechanisms of their degradation in the aspect of their design, use and component selection [1, 6].

The impact resistance of the laminates can be characterized by comparing force-displacement curves (*F-d*), energy level and damage of the material. Analysis of the impact force-indentation relationship with known energy at the point of impact allows one to determine the maximum strain point for the material, as well as the amount of energy expended on deformation and further damage extension [7].

The goal of this paper is to analyse the damage of Fibre Metal Laminates containing glass and carbon fibre reinforcements subjected to low-velocity impact. The analysis is based on the assessment of force-displacement characteristics in the aspect of energy absorption connected with initiation and damage propagation in the examined laminates.

MATERIALS AND METHODS

The subject of examination was aluminium/glass-epoxy fibre metal laminates (Al/GFRP) and *aluminium/carbon-epoxy* fiber metal laminates (Al/CFRP). 2024-T3 EN (AW-2024, AlCu4Mg1) aluminium alloy sheets with thicknesses of 0.3 and 0.5 mm were used. The composite layers consisted of unidirectional prepregs (Hexcel, USA) based on AS7J high-strength carbon and R-type high-strength glass fibers with an epoxy matrix resin (thickness of 0.134 mm and 0.255 mm, respectively). The nominal fibre content was about 60 vol.%. For the sake of the research, some laminates in the configuration 2/1 (two external aluminium layers and composite laminate stacking sequence (0/90) and layer thickness of 0.25 mm), were manufactured. All the laminates were produced in the Department of Materials Engineering at Lublin University of Technology by means of the autoclave method [8].

Samples with dimensions of 150 x 100 mm were subjected to low-velocity impact at room temperature by using a drop-weight impact tester (INSTRON 9340) with the possibility to record load-displacement history. A hemispherical tip with a diameter of 12.7 mm (0.5") made of steel was used as the impactor. All the low-velocity impact tests were conducted based on the ASTM D7136 standard [9]. The impactor velocity immediately before contact with the samples was 3.7 m/s. The impact energy was 25 J.

RESULTS AND DISCUSSION

Figure 1 shows the impact force-indentation relationship (*F-d*) during the dynamic impact for various examined Fibre Metal Laminates.

The force-displacement curves can be divided into two categories. Each *F-d* curve has an ascending section of loading, reaching the maximum load value and a descending section of unloading (Fig. 1c).

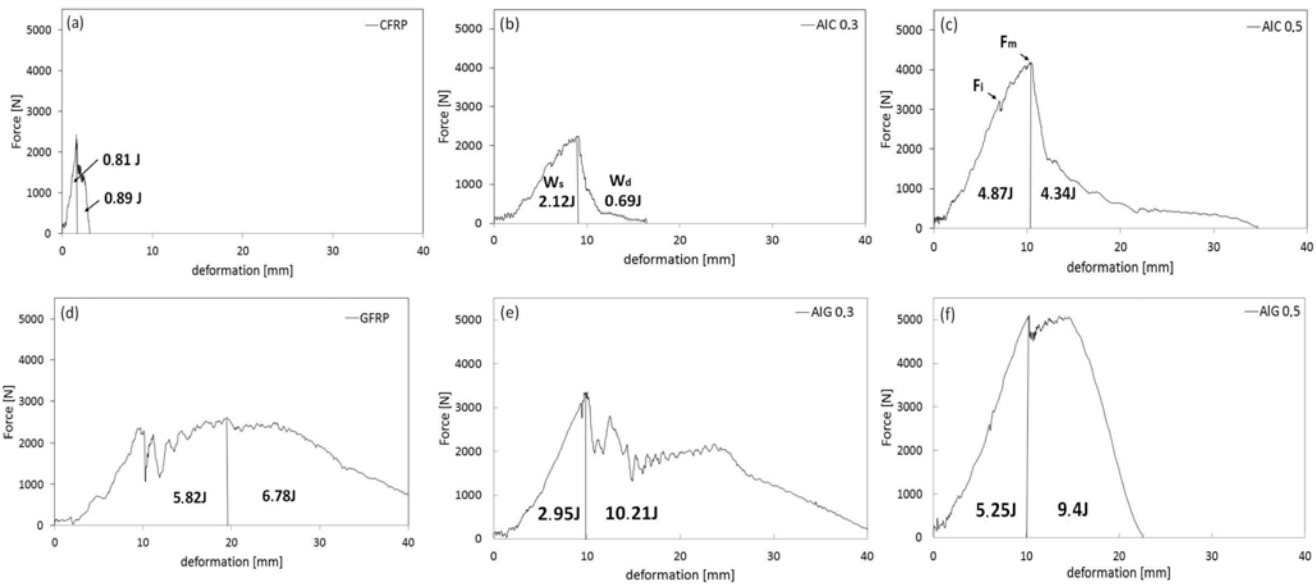

Fig. 1. Force-displacement (*F-d*) diagrams after impact of laminates: CFRP (a), Al/CFRP 0.3 (b), Al/CFRP 0.5 (c), GFRP (d), Al/GFRP 0.3 (e), Al/GFRP 0.5 (f)

Rys. 1. Wykresy siła-przemieszczenie (*F-d*) po uderzeniu dynamicznym laminatów: CFRP (a), Al/CFRP 0,3 (b), Al/CFRP 0,5 (c), GFRP (d), Al/GFRP 0,3 (e), Al/GFRP 0,5 (f)

The ascending section of the *F-d* curve is called bending stiffness due to the resistance of the composite to impact loading, at the point when the maximum load value reaches the highest maximum load (F_m). After reaching the maximum load value, a descent in force occurs as a result of the impactor bouncing off the examined material surface or damage of the material. A sudden force decrease causes perforation of the composite structure by the impactor (Fig. 1c). It was observed that for the examined materials, the maximum load values are lower for Fibre Metal Laminates with carbon fibres than for those containing glass fibres. One of the parameters used in the process of composite structure damage assessment resulting from dynamic impact is impact energy E_u and absorbed energy E_a. Energy E_a is defined as the amount of energy absorbed by the composite structure during dynamic impact. The absorbed energy can be determined from the force-displacement curves (*F-d*) registered during dynamic impact [1, 5, 10].

The point of reaching maximum force (F_m) determines the areas of damage initiation energy E_i till the maximum force point is reached, as well as the area of damage propagation energy E_p after reaching the maximum force point (Fig. 1c). The aggregate energy E_a absorbed by the material during dynamic impact is the sum of the initiation E_i and propagation E_p energy [5].

The aggregate energy absorbed by the tested materials during dynamic impact is shown in Figure 2.

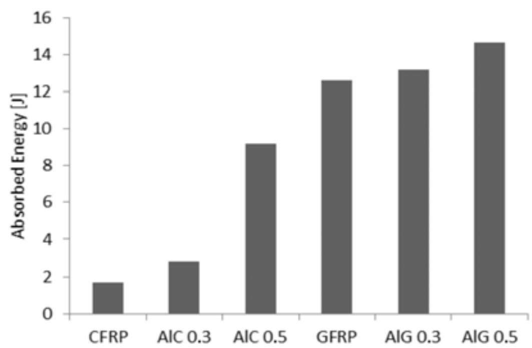

Fig. 2. Aggregate energy absorbed by tested materials during dynamic impact

Rys. 2. Sumaryczna zaabsorbowana energia dla badanych materiałów podczas uderzenia dynamicznego

The determined values of the aggregate absorbed energy for Fibre Metal Laminates with glass fibre reinforcement are in all cases higher than for the laminates containing carbon fibres. The classic composite materials reinforced with carbon fibres are characterised by the lowest E_a values.

After analysing particular components of the aggregate absorbed energy, i.e. damage initiation energy (E_i) and damage propagation energy (E_p), it may be claimed that for specific laminate groups, both classic and Fibre Metal Laminates reinforced with carbon fibre, those energies reach lower values in comparison to laminates containing glass fibres (Fig. 1, Fig 3). In the case of the tested Fibre Metal Laminates, increasing the thickness of the metal layer causes a surge in the initiation and propagation energy values.

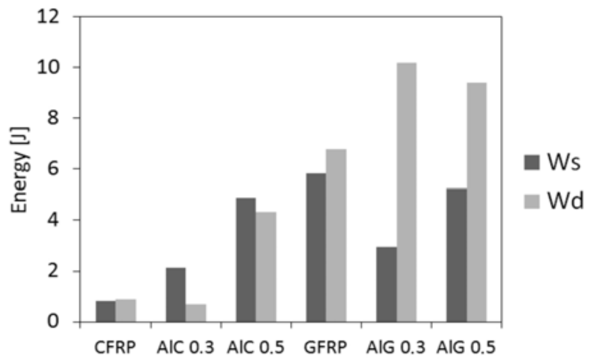

Fig. 3. Initiation E_i and propagation E_p energy values of examined composite materials

Rys. 3. Wartości energii inicjacji E_i oraz propagacji E_p badanych materiałów kompozytowych

In the case of classic composites and Fibre Metal Laminates reinforced with carbon fibres, the propagation energy values are lower than the initiation energy values. The reverse can be observed in glass reinforced FMLs. Here the propagation energy values are higher than the initiation energy ones.

Generally, laminates reinforced with glass fibres absorb more impact energy and are characterised by higher maximum load values in comparison to laminates containing carbon fibres. Highly modular fibres reinforcing composites, i.e. carbon fibres, show relatively small damage deformation, which makes them comparatively brittle and influences their susceptibility to damage due to dynamic impact.

The literature suggests that ply toughness has very little influence on energy absorption during dynamic impact. However, the most vital factor is the fibre stress-strain characteristics. Replacing brittle fibres with e.g. glass ones in composite structures results in reaching much higher energy levels [11].

Brittle and highly durable materials will be characterised by higher initiation energy and lower propagation energy. Carbon fibre reinforced composites can be assigned to this group. On the other hand, more plastic but less durable materials will have a lower initiation energy and higher propagation energy. This may also concern laminates containing glass fibres [11].

On the basis of the acquired results, it may be stated that laminates containing a higher metal volume absorb more energy during dynamic strain. This phenomenon may be caused by greater elastic deformation during the first stage of contact with the impactor or greater plastic deformation of the aluminium layers during impact. The literature distinguishes the elastic deformation aspect as a mechanism responsible for energy absorption during the first stage of impact [12]. It is also the dominant mechanism of energy absorption in the case of the lack of perforation resulting from impact

[12, 13]. However, it concerns mainly polymer fibre composites. As distinct from classic composite structures, FMLs are a combination of inflexible and brittle materials with plastic-elastic ones.

Figure 4 presents the impact damage area of laminates with different destruction kinetics.

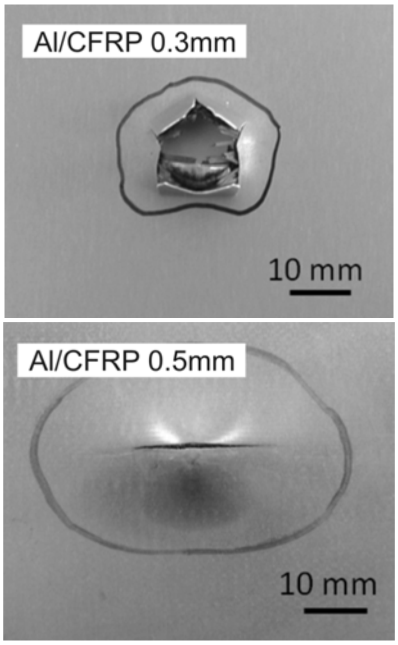

Fig. 4. Impact damage area of laminates with different destruction kinetics (impact back side)

Rys. 4. Strefa zniszczenia laminatów o różnej kinetyce zniszczenia (widok od spodu uderzenia)

In the case of the glass reinforced Fibre Metal Laminates, it may be observed that the energy absorbed during dynamic impact is higher and it is expended on deformation, damage initiation and damage expansion. The impact damage area of Al/GFRP is characterized by permanent deformation in the area of impactor interaction. Wave front deformation (black line) and a relatively small aluminium layer crack is visible. Moreover, propagating damage may display a more surface nature (e.g. delaminations). However, in the case of carbon reinforced FMLs, the absorbed energy is expended on composite structure damage leading to complete perforation of the composite material.

CONCLUSIONS

It is possible to draw the following conclusions on the basis of the load-displacement curves and energy absorption relations carried out for selected Fibre Metal Laminates after low-velocity impact:

- Fibre Metal Laminates with glass and carbon reinforcements are characterized by higher impact resistance in comparison to classic composite structures. It is proved by higher maximum load levels, as well as by higher aggregate absorbed impact energy. Moreover, the aluminium layers can have a protective function as they absorb a significant amount of the dynamic impact energy and lower the scope of damage in the laminate.
- Fibre Metal Laminates with carbon fibres show greater susceptibility to damage resulting from dynamic impact than laminates with glass fibres. The observed maximum load and the aggregate absorbed impact energy are lower. Furthermore, the initiation energy value is higher than the propagation energy value and the dynamic impact energy is expended mainly on laminate damage. The properties of particular components, especially the composite reinforcing fibres, is the deciding factor as far as the resistance of the examined materials to impact is concerned. Carbon fibres show a relatively small deformation range until failure and are brittle in comparison to the glass ones, which raises their susceptibility to damage resulting from dynamic impact.
- Force-displacement curves analysis (F-d), the aggregate absorbed impact energy (E_a) and the initiation energy (E_i), as well as the damage propagation energy (E_p) may represent some of the more vital criteria of composite materials assessment in terms of their resistance to low-velocity impact.

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