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COMPOSITES THEORY AND PRACTICE

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LOW-ENERGY IMPACT ISSUES IN GLARE LAMINATES

The purpose of the study is to present low-energy and low-velocity impact issues of hybrid laminates based on aluminium alloys connected with glass/epoxy composite (GLARE type) composites and conventional glass fibre reinforced polymer (GFRP) used in aerospace. The tested laminates were prepared by means of the autoclave method. Their reaction to low-velocity impact was analyzed using a hemispherical impactor (diameter 38.1 mm). The laminates were characterized in terms of damage size and failure mechanisms after impact with different energy levels (1.5 and 2.5 J). After the impact tests, the failure was evaluated using ultrasonic, microtomography and microscopic methods in order to determine the nature of internal degradation of the structure. It was noted that low-energy impact phenomena are of importance in aerospace materials. They cause barely visible impact damage to composite materials. However, the used FML are innovative materials characterized by higher low-velocity impact resistance because of the superior properties of both metals and fibrous composite materials with a strong adhesion bonding. The damage of GLARE laminates is much less than in polymer composites. Some transverse cracks and micro-delamination between the composite layers and in the adhesive layer are the major failure types in GLARE laminates as a result of low-energy impact.

Keywords: GLARE laminates, low-energy impact, non-destructive testing, failure

PROBLEMATYKA OBCIĄŻEŃ DYNAMICZNYCH O NISKIEJ ENERGII LAMINATÓW TYPU GLARE

Praca przedstawia problematykę uderzeń dynamicznych o niskich energiach i niskich prędkościach hybrydowych laminatów metalowo-włóknistych na bazie stopu aluminium i kompozytu epoksydowo-szklanego (laminat typu GLARE) oraz klasycznych kompozytów epoksydowo-szklanych stosowanych w lotnictwie. Badane laminaty zostały wytworzone metodą autoklawową. Ocenie została poddana odpowiedź laminatów GLARE i GFRP na obciążenia dynamiczne o niskich prędkościach z wykorzystaniem sferycznego wgłębnika o średnicy 38,1 mm. Laminaty oceniano pod względem rozmiaru uszkodzenia i charakteru zniszczenia na skutek obciążeń dynamicznych o różnej energii (1,5 oraz 2,5 J). Wykorzystano nieniszczące metody badań materiałów (m.in. metody ultradźwiękowe, mikrotomografię komputerową, mikroskopię optyczną). Zauważono, że zjawisko obciążeń dynamicznych o niskich prędkościach i niskich energiach ma duże znaczenie w technice lotniczej. Powoduje niewidoczną makroskopowo degradację wewnętrzną struktury materiałów kompozytowych. Podstawowym rodzajem uszkodzenia laminatów GFRP są delaminacje międzywarstwowe. Wykorzystanie laminatów typu GLARE® znacznie ogranicza propagacje uszkodzeń na skutek obciążań dynamicznych w stosunku do materiałów kompozytowych. Dominującym mechanizmem zniszczenia laminatów typu GLARE® po obciążeniach dynamicznych o niskich energiach są pęknięcia poprzeczne osnowy.

Słowa kluczowe: laminaty typu GLARE®, uderzenia dynamiczne o niskich energiach, badania nieniszczące, uszkodzenie

INTRODUCTION

Fibre Metal Laminates (FML) are new kind of hybrid materials, widely used in aerospace technology (e.g. Airbus A380). They are characterized by excellent mechanical properties in relation to density (e.g. tensile strength, fatigue strength) [1]. FMLs consisting of alternately arranged thin aluminium layers and glass fibre reinforced polymer composites, connected together (GLARE®) [1, 2] are most common. This kind of aerospace materials is used especially for aircraft fuselages. Therefore, GLARE laminates are exposed to contact with the external environment during all the cycles of operation (including low-energy and low-velocity impact phenomena).

It is known that contemporary aerospace materials such as polymer matrix composites are characterized by reduced resistance to impact phenomena because of the brittle matrix and rigid fibres [3]. It is necessary to protect high strength composites with elasto-plastic metal layers against dynamic loads. Low-velocity impact resistance is one of the important issues in composite structures, particularly in aerospace. According to Vogelesang et al. [4] and Sohn et al. [5], impact damage is extremely dangerous for the maintenance and reliability of fibre metal laminates and general composite materials.

In the case of low energy dynamic impacts, composites can fail in a wide variety of modes and contain barely visible impact damage (BVID) which, nevertheless, severely reduces the structural integrity of the component. Lower-energy impact causes damage to the subsurface, without plastic deformation or penetration in the composite materials, but leaves an extensive area of failure inside the composites. Various damages such as matrix cracks, delamination and fibre breakage are observed [3-5]. Frequently it is very difficult to detect the damages with the naked eye; therefore significant reduction in the strength and stiffness of the materials is possible.

The present study presents research in the scope of impact behaviour at low velocity and energies especially for Fibre Metal Laminates such as the GLARE type (aluminium/glass fibre reinforced polymer) and some aspect of this phenomena of conventional glass fibre reinforced polymer. Analysis of the scale and character of laminate structure failure mechanisms was carried out.

MATERIALS AND EXPERIMENTAL PROCEDURE

Al/GFRP laminates (GLARE® type) - fibre metal laminates consisting of glass fibre reinforced polymer composites (GFRP) and thin aluminium layers (2024-T3 aluminium alloy sheets) 0.3 and 0.5 mm thick were the main object of examination. Besides that, monolithic GFRP were examined in comparison to Al/GFRP. The both types of laminates consisted of unidirectional prepregs (Hexcel, USA) based on high-strength glass fibres (R-type) with an epoxy matrix resin (thickness of 0.25 mm). The nominal fibre content was about 60 vol.%. Before laminating, the surfaces of the aluminium alloy sheets were anodized in a chromic acid electrolyte, and an adhesive primer to improve bonding with fibre reinforced polymers was applied thereafter. All the examined materials were produced at the Department of Materials Engineering - Lublin University of Technology by means of the autoclave method (Scholz Maschinenbau, Germany) under a vacuum of 80 kPa, holding the material for 2 h at 135°C and 0.4 MPa pressure. The Al/GFRP laminates were prepared as 2/1 in the (0/90) stacking sequence.

Samples with dimensions of 150 x 100 mm were subjected to low velocity (< 2.5 m/s) impact at room temperature by means of a drop-weight impact tester (INSTRON 9340). A hemispherical impactor tip with a diameter of 38.1 mm (1.5") and mass of 1.4 kg was used. All low velocity impact tests were conducted based on the ASTM D7136 standard [6]. The impact was realized with two different energies - 1.5 and 2.5 J. After the impact samples were tested by means of ultrasonic methods with C-scan visualization (OmniScan MX1, Olympusm Japan), computer microtomography and microscopic (Nikon MA200, Japan) methods were applied for failure evaluation.

RESULTS AND DISCUSSION

Figure 1 illustrates typical load - time (*l-t*) curves after low velocity impact of the laminates.

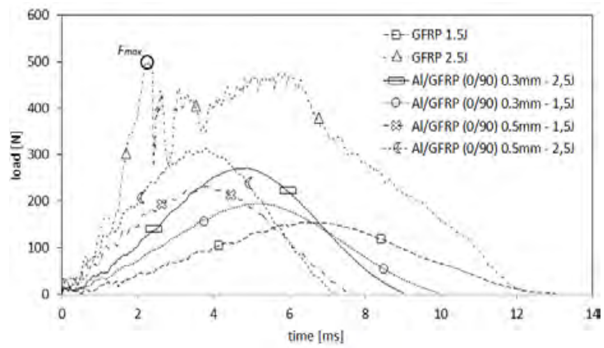

Fig. 1. Experimental load-time curves after impact of Al/GFRP and GFRP laminates

Rys. 1. Eksperymentalna krzywa siła-czas po uderzeniu laminatów Al/GFRP oraz GFRP

The *l-t* curves may be divided into the part of force increasing to the maximum level and the part of decreasing force. The ascension of the force is rather smooth in each case of impacted materials (exception is GFRP under 2.5 J impact energy), however, some fluctuations may be observed, especially, at the beginning, where some vibrations of the system are detected [7]. In the case of the low-energy impact, it is not possible to observe clear incipient force, as was noted in other research about low-velocity impact [4, 7]. It is caused by a low level of impact energy, which is mainly converted into elastic and plastic deformation. On the basis of the *l-t* curves, it can be concluded that low-energy impact in GLARE® laminates has no clear structure degradation meaning as is in the case of low-energy impact phenomena. Nevertheless, in the *l-t* curves, some fluctuations near maximum force (F_{max}) are observed. It is possible that these fluctuations and especially maximum force are the response to the micro-degradation of the composite structure [8]. The values of maximum force and the time of its achievement are similar. However, it was noted that Al/GFRP laminates have better low-energy impact resistance than GFRP laminates because of the elastic-plastic nature of aluminium. In the case of GFRP laminates, it can be observed that 2.5 J impact energy causes high structural degradation (many high fluctuations). Moreover, Al/GFRP laminates absorb impact energy much faster than GFRP laminates, and this process is much more stable. All the differences on the *l-t* curves between the laminates indicate that in the laminates structure the size and character of failure are different as a result of low-energy impact.

Examples of the results of non-destructive testing of Al/GFRP and GFRP laminates after impact are presented in Figure 2.

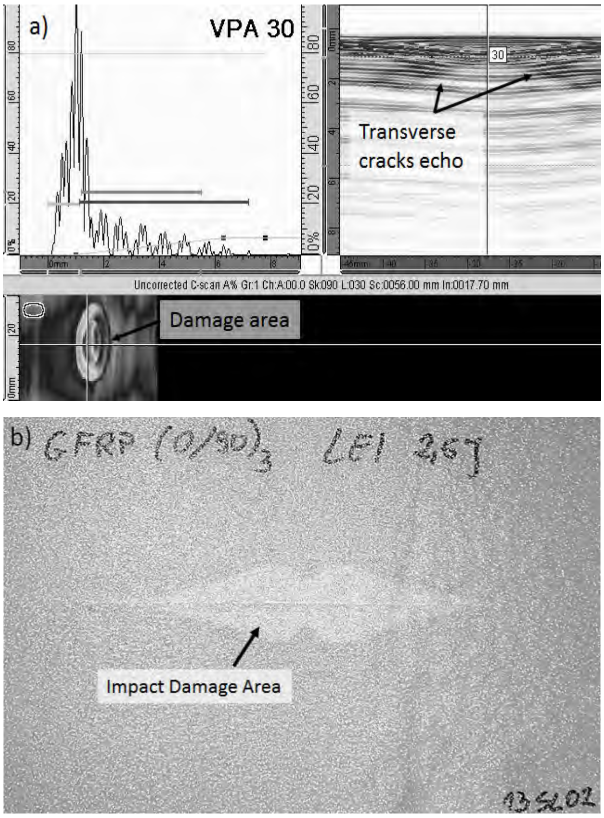

Fig. 2. Damage area of Al/GFRP (ultrasonic view) and GFRP (macroscopic image) after 2.5 J energy impact

Rys. 2. Obszar uszkodzenia laminatów Al/GFRP (widok ultradźwiękowy) oraz GFRP (obraz makroskpowy) po uderzeniu z energią 2,5 J

In the case of GFRP laminates which are slightly transparent, a real damage area can be noted. Delaminations are complex and occur between the different layers of the composite. It has been observed that the elongated shape of the delamination in the case of GFRP composites is convergent with the orientation of the fibres in the layer. Similar results have been recorded by Hosseinzadeh et al. [9] Pearson et al. [10] and Davies et al. [11].

On the basis of the obtained ultrasonic views (especially B- and C-scan imaging) of Al/GFRP, it can be concluded that delaminations are a prevailing damage mode in the laminates being tested. Reduction of the elastic wave amplitude illustrated by means of grey scale indicates that delaminations occur in laminates at diversified depths. However, the damage area in the case of Al/CFRP laminates is nearly circular with plastic deformation in the aluminium layers. The occurrence of additional delaminations is also possible in Al/CFRP laminates at the metal-composite interface; this fact was also reported by Nakatani et al. [12] and Liaw et al. [13] in their research. Plastic deformation is the barrier which makes the detection and separation of real failure impossible. Display type B indicates transverse cracks, besides delaminations noted on a C-scan. These cracks are located around the impact point. Similar locations of transverse cracks have been observed by Caprino et al. [3] and Abrate et al. [14].

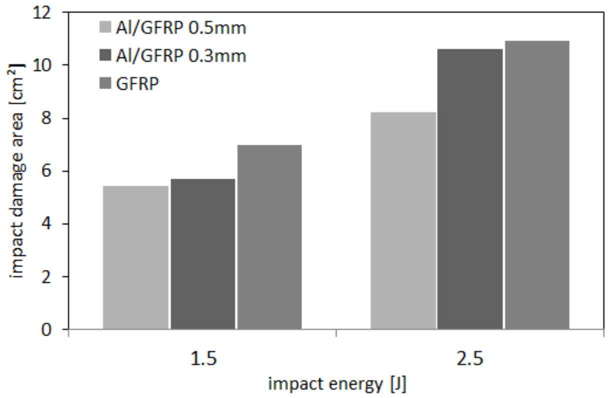

Fig. 3. Value of damage area after low-energy impact of Al/GFRP and GFRP laminates

Rys. 3. Wartość pola powierzchni uszkodzenia po uderzeniu z niską energią laminatów Al/GFRP oraz GFRP

The damage area in the case of FML is determined by the plastic deformation of the metal. It does not mean that structure failure occurs in this whole region. As shown in Figure 3, the impact damage area propagates with impact energy [14]. Besides that, the material is of particular importance for the damage size value. Fibre metal laminates have a lower damage area in the case of a thicker metal layer. The highest damage area occurs in conventional laminates (GFRP). The reason for this phenomena is the energy absorption by an elastic-plastic metal such as aluminium. Similar conclusions have been drawn by Vlot et al. [1]. The microscopic view shown in Figure 4, is an example of the failure type in fibre metal laminates after low energy impact.

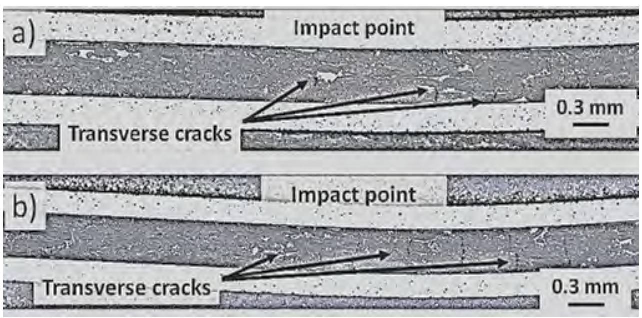

Fig. 4. Cross-sections of Al/GFRP 0.3 mm laminates after low-velocity impact: 1.5 J (a) and 2.5 J (b)

Rys. 4. Przekrój poprzeczny laminatów Al/GFRP 0.3 mm po uderzeniu z małą prędkością: 1,5 J (a) oraz 2,5 J (b)

The cross-sections of Al/GFRP laminates after two different impact energy levels revealed that the failure mechanism of both laminates is the same but its scale is different. It was noted that low-energy impact is the reason for cracks in the laminate structure, which propagate around the impact point [15].

However, some differences can be observed. First of all, the deformation depth is much greater after the 2.5 J impact energy, which is the cause of the increase in the value of the bending stress and leads to higher propagation of transverse cracks (transverse cracks are longer). The direction of propagation is the same as in the case of lower impact energy [15]. Besides that, it was noted that a higher thickness of aluminium layers (0.5 mm) does not influence the failure mechanism but the number of cracks only. More details of structure damage are presented in Figure 5.

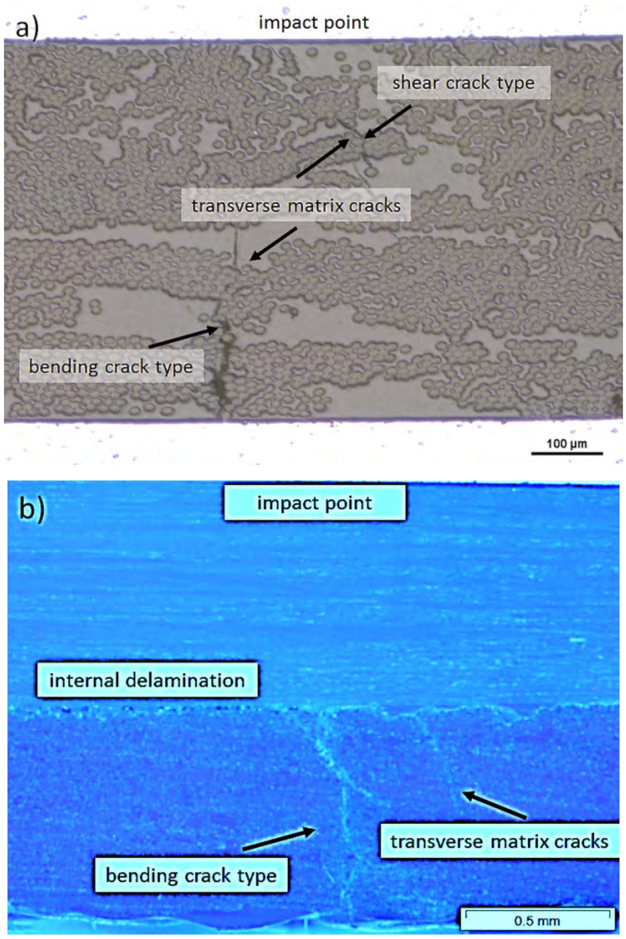

Fig. 5. Examples of laminates failure mechanisms after low-energy impact: Al/GFRP 0.3-2.5 J (a) and GFRP 2.5 J (b)

Rys. 5. Przykład mechanizmów degradacji laminatów po uderzeniu z niską energią: Al/GFRP 0,3-2,5 J (a) oraz GFRP 2,5 J (b)

No delaminations were observed in the case of the tested GLARE® type laminates (between metal and composites and internal delaminations). Internal delaminations are the dominant type of failure in conventional GFRP laminates, but the propagation of some matrix cracks is also possible. Similar conclusions have been described by Richardson et al. [15]. Transverse cracks of the matrix were observed in both types of tested materials. It was noted that in the bottom layers, major cracks are the cause of bending stress and of shear stress in the upper layers (characteristic angle of propagation). This different type of matrix cracks has been observed in several other studies [1, 15].

CONCLUSIONS

1. On the basis of the obtained results, the following conclusions can be drawn: Low-energy impact is a serious and complex phenomenon in conventional polymer composite and fibre metal laminates such as GLARE® used in aerospace.
2. The impact energy and thickness of the metal layer has a significant influence on the size of the degradation area. It is connected with the possibility of energy absorption by the laminate.
3. The nature of damage in the tested materials is complex. Delaminations and transverse cracks are the dominant mechanism of degradation in polymer composite materials as a result of low energy dynamic impacts. Numerous matrix cracks are the major type of failure in fibre metal laminates. The observed transverse cracks are the result of different states of stress. Two types of cracks can be distinguished: bending cracks (perpendicular to sample surface) and shear cracks (oriented in shape of cone with top at impact point).

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