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COMPOSITES THEORY AND PRACTICE

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THE ISSUE OF RESIDUAL STRENGTH TESTS OF THIN FIBRE METAL LAMINATES

Modern aircraft structures contain sheathing elements which are supposed to not only carry loads, e.g static ones, but also at the same time possess resistance to corrosion or dynamic impact. As a consequence, new kinds of hybrid materials, e.g fibre metal laminates, were created. They combine the mechanical and physical properties of various materials. Until now, the most common and widespread structures are GLARE® laminates (aluminium/glass-epoxy composites), characterised by high fatigue and static properties, as well as by impact resistance. The concurrent influence of many negative factors during exploitation causes a gradual decrease in the functional properties of these materials. One of the factors affecting e.g. static strength is low-velocity impact. Low-velocity impact often leads to macroscopically invisible damage of the composite structure, with delaminations and ply cracking occurring during impact energy absorption. Fibre metal laminates possess a much better dynamic load-carrying capacity, limiting negative ply cracking in the composite and absorbing some impact energy through elastic-plastic deformation. In order to assess the influence of low-velocity impact on the residual strength of composite materials, Compression After Impact (CAI) tests are carried out. Normalised CAI testing is used for classic 5 mm thick composite structures. However, as the literature suggests, it is not effective in the case of fibre metal laminates, particularly those with a thickness more then 1.1 mm. The work presents an analysis of the possibility of conducting an effective (ensuring valid assessment of strength reduction) CAI test for 1.5 mm thick FML panels after dynamic impact. An alternative workstation construction was proposed, and simulations and experimental verifications were conducted. It was observed that a solution based on the ASTM standard does not apply to thin FML laminated panels. Deformation of the specimen occurs in areas located far from the impact site. As a consequence, the strength values differ neither for plates with impact-induced damage nor ones without it. The proposed alternative holder construction for compression after impact of thin fibre metal laminates plates testing eliminates premature material damage. On the basis of the conducted numerical simulations, it was stated that using the ASTM holder for CAI test leads to the occurrence of the first buckling mode in the damage area, with stress concentration in its vicinity. Such a form of deformation may allow one to correctly assess the influence of impact damage on FML composites.

Keywords: **fibre metal laminates, low-velocity impact, residual strength, Compression After Impact**

PROBLEMATYKA BADAŃ WYTRZYMAŁOŚCI ZREDUKOWANEJ CIENKICH LAMINATÓW METALOWO-WŁÓKNISTYCH

Współczesne struktury lotnicze zawierają w sobie elementy pokryciowe, które mają za zadanie przenosić obciążenia m.in. statyczne, a przy tym być odporne na korozję czy uderzenia dynamiczne (impact). W związku z tym opracowano nowoczesne materiały hybrydowe, m.in. laminaty metalowo-włókniste, łączące w sobie właściwości różnych materiałów pod względem właściwości fizycznych i mechanicznych. Najpowszechniej znane i stosowane są dotychczas laminaty typu GLARE® (aluminium/kompozyt epoksydowo-szklany), które charakteryzują się wysokimi właściwościami np. zmęczeniowymi, statycznymi i odpornością na uderzenia typu impact. Jednoczesne oddziaływanie wielu negatywnych czynników w czasie eksploatacji sprawia, że parametry użytkowe tych materiałów stopniowo maleją. Jednym z czynników obniżających np. wytrzymałość statyczną jest oddziaływanie dynamiczne o niskiej prędkości. Uderzenia typu impact o niskiej prędkości często powoduje niewidoczne makroskopowo uszkodzenie struktury kompozytowej, która, absorbując energię uderzenia, ulega licznym rozwarstwieniom i pęknięciom osnowy. Laminaty metalowo-włókniste znacznie lepiej przenoszą obciążenia dynamiczne, ograniczając niekorzystne powstawanie pęknięć osnowy kompozytu, m.in. przez absorpcję części energii uderzenia na odkształcenie sprężysto-plastyczne. W celu oceny wpływu uderzeń typu impact na wytrzymałość materiałów, np. kompozytowych, prowadzi się badania m.in. ściskania osiowego płyt po uderzeniu (Compression After Impact). Znormalizowana próba CAI dotyczy klasycznych struktur kompozytowych o grubości około 5 mm. Jak wynika z literatury, nie jest jednak skuteczna w przypadku laminatów metalowo-włóknistych, szczególnie tych o grubościach od 1,1 mm. W pracy przedstawiono analizę możliwości prowadzenia efektywnej (zapewniającej prawidłową ocenę redukcji wytrzymałości) próby ściskania osiowego płyt FML o grubości 1,5 mm po uderzeniach dynamicznych. Zaproponowano własną konstrukcję stanowiska do badań oraz przeprowadzono symulację i weryfikację eksperymentalną. Zauważono, że rozwiązanie opracowane w normie ASTM nie sprawdza się w przypadku cienkich płyt FML. Następuje odkształcenie próbki w strefie oddalonej od miejsca uderzenia. W rezultacie wartości wytrzymałości nie różnią się względem siebie dla płyt bez uderzenia i po uderzeniu. Zaproponowana alternatywna konstrukcja uchwytu do realizacji testów CAI laminatów metalowo-włóknistych po uderzeniach dynamicznych eliminuje przedwczesne uszkodzenie materiału. Na podstawie przeprowadzonych symulacji numerycznych stwierdzono, że zastosowanie tego uchwytu prowadzi do wyboczenia materiału (pierwsza postać wyboczenia) w obszarze uszkodzenia, koncentrując naprężenia w jego okolicy. Taka forma odkształcenia może pozwolić prawidłowo ocenić wpływ uszkodzeń po uderzeniach na wytrzymałość kompozytów typu FML.

Słowa kluczowe: **laminaty metalowo-włókniste, obciążenia dynamiczne, wytrzymałość zredukowana, ściskanie po uderzeniu**

INTRODUCTION

Modern materials applied in aircraft structures should be characterised not only by high mechanical and fatigue properties, but also by high reliability during exploitation. In response to such demand, new innovative hybrid materials (fibre metal laminates, FMLs), combining the properties of classic metal and composite materials, were developed [1, 2]. These materials are characterised i.a. by unusually high fatigue and static strength, as well as by corrosion and impact resistance [2-4].

The applied parameters of aerospace structures undergo a gradual decrease during exploitation as a consequence of many types of negative factors. One of them is low-velocity impact [5]. Such types of loads, particularly ones with low energy, generate barely visible impact damage (BVID) [6]. It is caused by e.g. hail, runway debris, maintenance damage (e.g. dropped tools), collision with service cars or cargo, ice from the propellers, engine debris and tire shrapnel from tread separation and tire rupture. During the aforementioned processes, a system of ply cracks occurs in the composite structure. The cracks form a characteristic cone shape with the apex in the impact site and numerous delaminations apparent at various levels [6]. Such types of damage are particularly difficult to identify even by NDT methods [7].

Research is being conducted in order to assess the level of mechanical properties reduction of composite materials. It examines e.g. compression after impact resistance on normalised plates with a known scope and type of initiated damage [8]. However, the procedure and workstation consistent with the norm refer only to 4÷6 mm thick composite materials [8].

However, 1.1 mm thick FML materials are used as well [2]. The normalised CAI test is insufficient to assess the impact-induced strength reduction of these materials. Conducting normalised CAI testing for thin composite materials leads to exceeding the maximum strain limits and deformations in areas far from the damage zone [9]. Currently, testing focused on proposing alternative methods for assessing the strength of thin composite materials and FMLs after dynamic impact is being conducted. One of the examples of such testing is the Sanchez-Saez S. et al. approach [5], where the authors suggested using a two-piece compression holder with a free zone in the impact axis. The proposed compression holder reduces the sample free zone to a narrow area near the point of impact. The assumption was to enforce buckling in this area, which may lead to showing the influence of damage on thin laminates compression resistance.

The goal of the work was to assess the possibilities of effective research methods concerning thin FML laminates resistance to compression after the low-velocity impact. Experimental verification was conducted for thin layer materials.

MATERIALS AND METHODS

In the first stage of CAI testing of FML composites a numerical simulation with the Fine Element Method (FEM) using DEFORM 3D software was carried out. A holder based on the ASTM norm was modeled [8] (Fig. 1). The samples were modeled as plates 150 mm long, 100 mm wide and 1.5 mm thick (in accordance with the aforementioned norm). A CAI test of aluminium alloy (2024-T3 alloy, E - 69 GPa, υ - 0.33) composed of three connected layers, each 0.5mm thick, was simulated. In the simulation two types of samples were used, one without impact-induced damage and one with a cutout 30 mm in diameter (in the central part of the specimen) simulating impact-induced damage (an area with lower load-carrying properties). It was established that the grid density should be based on 25000 equal cubic elements. The axial compression through the holder stamp sliding down with a constant speed of 0.2 mm/s was modeled.

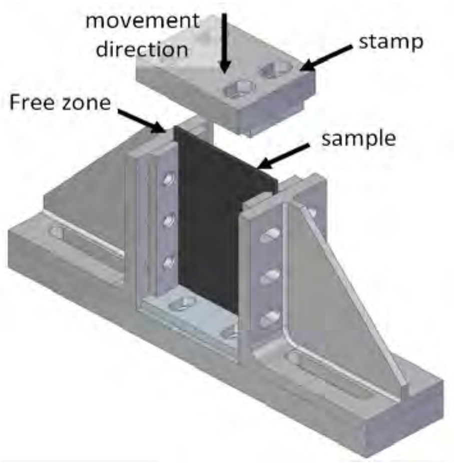

Fig. 1. ASTM holder for CAI test [8]

Rys. 1. Uchwyt ASTM do ściskania metodą CAI [8]

The experiment was conducted on FMLs produced in the Department of Materials Engineering at Lublin University of Technology using the autoclave method in accordance with technology dedicated to aircraft structures [10]. Certified aircraft materials were used - they were made of 2024-T3 aluminium alloy sheets and unidirectional prepregs based on R-type high-strength glass fibres with an epoxy matrix resin (Hexcel, USA). The lay-up scheme of the specimen was 2/1 and consisted of two outer 0.5 mm thick aluminium layers and one composite interlayer with a [0/90] stacking sequence. The research was carried out on laminates without impact-induced damage and laminates after 5 and 10 J energy impact. A drop-weight impact tester (INSTRON 9340) with the possibility to record load-time history and a hemispherical steel impactor tip with a diameter of 12.7 mm (0.5”) were applied [11]. Compression After Impact tests were conducted on a Material Testing System (MTS) machine at a crosshead speed of 2 mm/s.

RESULTS AND DISCUSSION

Figure 2 presents the Compression After Impact test results and the macroscopic image of the FML composite after the conducted experiment.

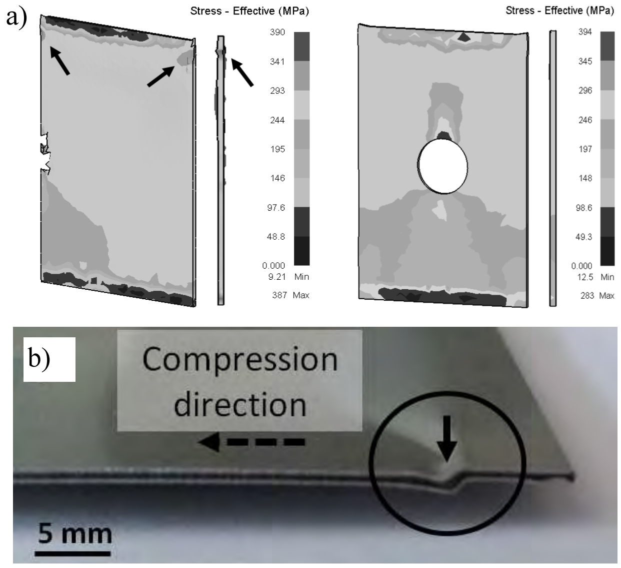

Fig. 2. Results of CAI simulation (a) and experiment (b) (ASTM holder)

Rys. 2. Wyniki symulacji (a) i eksperymentu (b) wytrzymałości na ściskanie (uchwyt ASTM)

The results of numerical simulation proved the generation of more or less evenly located stress areas with similar values. However, an area of strong stress concentration, located in the free zone, was noticed in the specimen without the cutout. In the case of the sample with the cutout, stress is mainly concentrated in the area of the cutout, which allowed us to assume that impact damage would result in a strength decrease in the compression test. The experimental verification of the simulation showed that impact damage does not influence the laminates resistance to compression and that the area of strong stress concentration in the free zone causes exceeding of the critical stress and damage of the specimen. After the CAI test of the specimen, compression shear failure in the free area between the supported and the clamped zones near the top loading plate was observed [5, 12]. Failure in the sample was due to compression shear in one of the free zones, between the loading and the anti-buckling plates. Specimen fracture occurred owing to this mechanism and not because of local buckling of the delaminated areas [9]. Such a type of sample cracking in the free zone results from i.a. a small cross-section and too low specimen rigidity [5, 9]. Furthermore, the ASTM holder enables only 4 mm stamp displacement. It is not sufficient for thin laminates due to their resilience properties and plastic deformation. In order to solve the problem, a special holder (holder no. 1) for CAI testing of thin laminates was designed, in which the sample's free zone and stamp displacement limitations were eliminated (it made conducting the test possible regardless of the deformation mode till a load-carrying capacity loss was registered on the force-displacement graph). Figure 3 shows holder no.1 for CAI testing of thin FML composites.

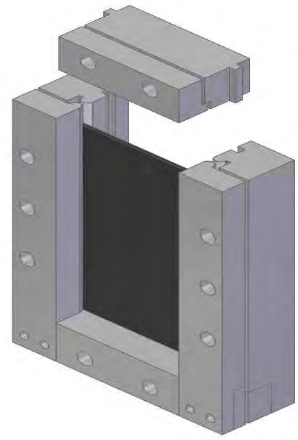

Fig. 3. Holder no. 1 for CAI test

Rys. 3. Zaprojektowany uchwyt nr 1 do ściskania metodą CAI

In the suggested solution, all degrees of freedom in the whole sample perimeter were removed. The idea for this solution was to generate stress in the central part of the specimen and enforce local buckling in the impact damage area. Furthermore, the stamp moved axially in the guide bars, which eliminated measurement errors caused by the geometric incompatibility of the samples (initial deformation after impact) [5]. In order to verify the concept, a compression simulation of thin Al/GFRP laminated plates with and without impact-induced damage, as well as with a centrally located cutout was conducted. The simulation and experiment results are presented in Figure 4.

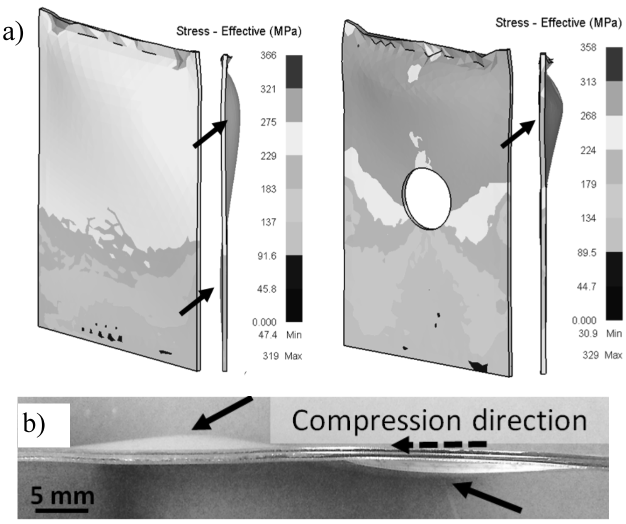

Fig. 4. Results of CAI simulation (a) and experiment (b) (holder no. 1)

Rys. 4. Wyniki symulacji (a) i eksperymentu (b) wytrzymałości na ściskanie (uchwyt nr 1)

The conducted simulation showed the existence of strain distribution in the central and upper part of the specimen. This phenomenon is particularly visible in the case of the samples with the cutout. The greatest stress was observed in the area above the cutout, which resulted in strong buckling of the area. The presence of the cutout reduced the buckling load due to stress concentration [13]. Further loading led to the onset of the second buckling mode with a neutral axis in the damage area The numerical simulation results were confirmed by experimental verification (Fig. 4b). The plate was made to buckle into two half-waves, one rightward and the other in the opposite direction. The isotropy of the material change had no influence on the negative buckling mode [14]. Figure 5 presents compression after the impact test results for thin Al/GFRP laminated panels without impact and after 5 and 10 J impact, carried out using holder no.1.

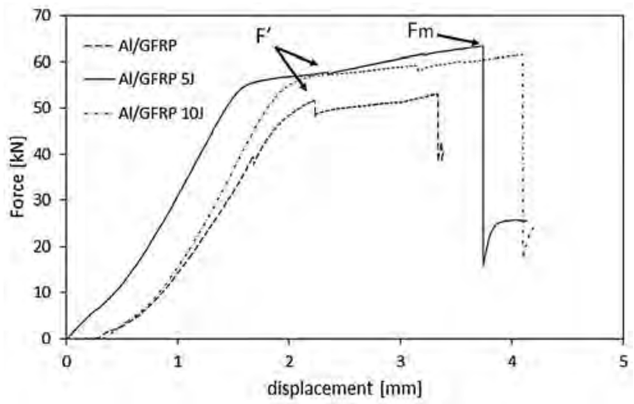

Fig. 5. Force-displacement curve during compression of Al/GFRP laminate without impact and after 5 and 10 J impact

Rys. 5. Wykres siła-przemieszczenie przy ściskaniu laminatu Al/GFRP bez uderzenia oraz po uderzeniu z energią 5 i 10 J

The received force-displacement curves for each of the samples are characterised by a stable course in the initial compression stage. The force increases in time in a stable manner till the moment when the yield point of the laminate is exceeded and a second deformation mode is created. The load at which the initial part of the curve deviates from linearity is called the critical buckling load [15]. Further compression causes the force to increase much slower and leads to substantial deformation. This represents the second buckling mode in the specimen, after which the plate is considered failed. Since the thickness of the plate is very small, the plate shows a large deflection for a small increment in the load. Similar conclusions were made by M Mohan K. et al. [15]. When the critical stress is exceeded, a drastic force decrease and loss of load-carrying properties (F_m) happen [15, 16]. Damage occurs to the composite on which the laminate strength is mainly based and which is characterised by a lower deformation scope than aluminium. In the plastic deformation zone, a characteristic peak of slight force decrease (F') was observed. It should be assumed, that this area imitates the moment of loss of connection between the composite and metal layer, which has a greater tendency to buckle [16].

The experiment carried out on three different sample types showed a tendency opposite to the expected one. Impact damage caused laminate strengthening. The differences between the damage resulting from the 5 J and 10 J energy impact are insubstantial, whereas for the specimen without damage, the F' and F_m values are much lower. The observed tendency may be related to the buckling mode.

In order to eliminate the second mode, holder no. 1 was modified for the needs of the simulation by introducing the sample's free zone into the impact axis. The idea was to enforce generation of the first buckling mode with a deformation near the damage area**.** The modified holder (holder no. 2) is presented in Figure 6.

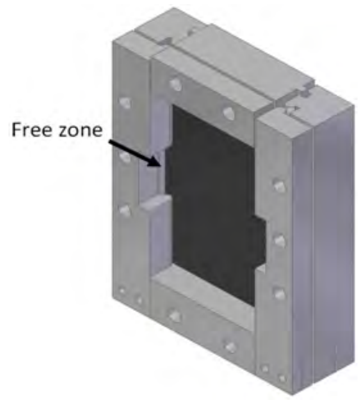

Fig. 6. Holder no. 2 for CAI test

Rys. 6. Uchwyt nr 2 do ściskania metodą CAI

The compression after impact simulation results resulting from employing holder no. 2 are presented in Figure 7.

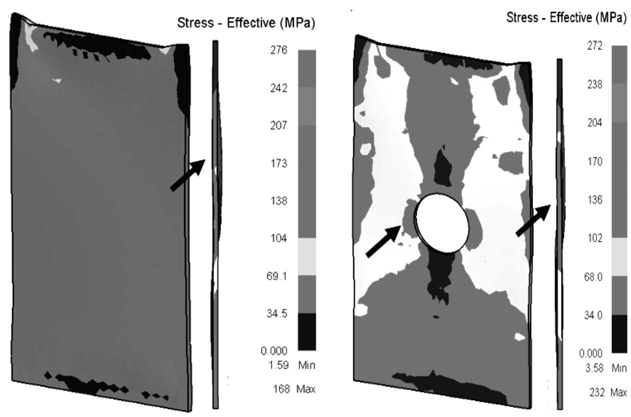

Fig. 7. Results of CAI simulation (holder no. 2)

Rys. 7. Wyniki symulacji CAI (uchwyt nr 2)

The simulation results showed an even stress distribution in the whole volume of the specimen without impact-induced damage. Simultaneously, an increase in deformation can be noticed in the cross-section. The aforementioned deformation is closest to the first buckling mode. The first buckling mode in the holder with the free zone on the sample side edges was characterised by i.a. M Mohan K. et al. [15]. Moreover, the simulation results for the specimen with the cutout showed varied stress values in the specimen volume. Stress concentration occurs in the cutout area. Similar observations concerning stress concentration placement were described by Nagendra et al. [17]. In the case of this holder, the stress concentration effect is more important than the material damage size, provided that the dimension of the damage is not so large with respect to the plate dimension [13]. It means that the damage dimension depending on impact energy affects the force reduction value, and not the loading conditions. The bending stiffness of the impacted laminates is lower than that of the non-impacted laminates, therefore they buckle locally and failure occurs under a lower load than in the case of the unimpacted laminates [5]. The results of the conducted simulation allow one to assume that the proposed holder no. 2 will enable valid assessment of strength reduction caused by dynamic loads in thin FML laminates.

CONCLUSIONS

On the basis of the conducted numerical simulations and experiments, it may be stated that:

It is impossible to assess thin FML composite resistance to compression using a workstation and procedure in accordance with the ASTM norm for classic composite structures. In the case of fibre metal laminates, exceeding the critical stress and damage of the specimen in areas located far from the impact damage occur during sample compression. This phenomenon does not depend on the presence of the damage, which makes it impossible to assess strength reduction caused by compression of thin fibre metal laminated panels after impact.

The second buckling mode of thin FML composites during CAI testing does not show a decrease in their resistance to compression. As a consequence, a lack of influence of impact damage on strength, and even its increase during structure degradation, may be noticed.

The proposed alternative holder construction for conducting compression after impact tests for thin fibre metal laminated plates eliminates premature damage of the material. On the basis of the carried out numerical simulation, it was stated that employing the holder leads to the first buckling mode in the damage area, by concentrating stress in its vicinity. Such a form of deformation may allow us to approriately assess the influence of impact damage on FML composite strength and durability.

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