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Patryk Różyło

Lublin University of Technology, Faculty of Mechanical Engineering, Department of Machine Design and Mechatronics, ul. Nadbystrzycka 36, 20-618 Lublin, Poland
Corresponding author. E-mail: p.rozylo@pollub.pl

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A STUDY OF FAILURE ANALYSIS OF COMPOSITE PROFILE WITH OPEN CROSS-SECTION UNDER AXIAL COMPRESSION

The paper presents an experimental and numerical study investigating the load carrying capacity of thin-walled composite structures with an omega-shaped cross-section subjected to axial compression. The tested profile was made of carbon-epoxy laminate with symmetrical arrangement of the layers [0/90/0/90]s. The experimental tests were performed on a universal testing machine - Zwick Z100, under full load conditions until total failure of the structure. The post-critical equilibrium paths of the construction were determined, defining the relationship between compressive load and deflection and enabling the FE models to be validated. Based on the obtained post-critical equilibrium paths, the critical load of the construction was determined using well-known approximation methods. Simultaneously, numerical analysis was carried out by the finite element method using Abaqus® software. The critical state was determined via linear eigenvalue analysis, and the critical load and corresponding first buckling mode were estimated. The next stage of numerical analysis involved solving the nonlinear stability problem of the structure with initialized geometric imperfection reflecting the first buckling mode of the composite material. The geometrically non-linear problem was solved by the Newton-Raphson method. The load capacity of the composite profile in the post-buckling state was determined by the progressive failure criterion which estimates damage initiation in the composite material using the Hashin criterion. Progressive failure analysis is described with the energy criterion describing the stiffness degradation of finite elements. The obtained numerical simulation results showed very high correspondence with the presented experimental results conducted on real structures, which confirms the precise preparation of the developed numerical models of the composite structures.

Keywords: **progressive failure analysis, CFRP, stiffness material degradation, uniaxial compression**

ANALIZA ZNISZCZENIA KOMPOZYTOWEGO PROFILU O PRZEKROJU OTWARTYM PODDANEGO OSIOWEMU ŚCISKANIU

Praca dotyczy numeryczno-doświadczalnego badania nośności cienkościennych struktur kompozytowych o omegowym kształcie przekroju poprzecznego poddanych osiowemu ściskaniu. Profile wykonano z kompozytu węglowo-epoksydowego o symetrycznym układzie warstw względem płaszczyzny środkowej. W ramach przeprowadzonych badań rozpatrzono układ o krzyżowej konfiguracji ułożenia warstw laminatu [0/90/0/90]s. Badania eksperymentalne przeprowadzono z wykorzystaniem uniwersalnej maszyny wytrzymałościowej Zwick Z100 w pełnym zakresie obciążeń, aż do całkowitego zniszczenia konstrukcji. Badania numeryczne stanu krytycznego z zastosowaniem liniowej analizy zagadnienia własnego miały na celu wyznaczenie postaci wyboczenia oraz wartości obciążenia krytycznego. Kolejny etap symulacji numerycznych obejmował rozwiązanie zagadnienia nieliniowej stateczności konstrukcji z zainicjowaną najniższą postacią wyboczenia. Zagadnienie geometrycznie nieliniowe prowadzono z wykorzystaniem przyrostowo-iteracyjnej procedury Newtona-Raphsona, wykorzystując jako narzędzie do obliczeń numerycznych program ABAQUS®. Obliczenia numeryczne utraty nośności konstrukcji przeprowadzono za pomocą implementacji algorytmu progresywnego kryterium zniszczenia (uwzględniając degradację sztywności elementów skończonych), w oparciu o uprzednio uwzględnione inicjacyjne kryterium zniszczenia Hashina. Otrzymane wyniki symulacji numerycznych wykazywały bardzo wysoką zgodność z prezentowanymi wynikami badań eksperymentalnych, prowadzonych na rzeczywistych strukturach. Wysoka zbieżność wyników świadczy o precyzyjnym przygotowaniu modelu MES.

Słowa kluczowe: **progresywna analiza zniszczenia, CFRP, degradacja materiału, osiowe ściskanie**

INTRODUCTION

Thin-walled composite materials are among the most popular engineering materials. They are characterized by high mechanical properties - high stiffness and low specific weight, which enables their use in the aerospace, construction and automotive industries [1]. Regarding their specific properties, polymeric composite material, which is commonly called laminates, is widely used as structural members in thin-walled structures. Under compressive load, three basic states describe the behaviour of thin-walled structures: pre-critical, critical and post-critical [2-5]. In the pre-critical state, the axial load only leads to compression of the structure walls without bending. The critical state of the laminate is characterized by the occurrence of additional flexural effects. In the post-critical state, deflection by a simultaneous increase in load is increased. These problems are investigated in many scientific papers [3-10]. Thin-walled composite profiles may lose their load capacity (laminate failure). The most common failure modes include matrix cracking, and fibre rupture or delamination [11-14]. The dominant failure mode leading to loss of the load-carrying capacity of the composite material is fibre damage [15]. The literature on the subject predominantly offers numerical analysis methods, however, they do not describe the failure mechanism in composite materials in a comprehensive and accurate way [13, 16-19]. Regarding continuous damage mechanics (CDM), the mechanisms of damage to the composite material are represented by material stiffness degradation - progressive damage criterion [20-22]. In PFA (progressive failure analysis) damage initiation was based on the Hashin criterion and the damage evolution on the progressive criterion [22] found in the description of energy [23, 24]. Examples of PFA application in the design of composite structures are mainly mentioned in [16, 17, 24]. In general terms, material damage can be interpreted as the occurrence of microcracks or loss of the effective cross-sectional area due to microcracking [25]. PFA requires data input from a specific material model - damage initiation and damage evolution criteria [26, 27]. When the damage initiation criterion is fulfilled, the stiffness of the damaged composite material is decreased [28]. The total failure of a thin-walled profile occurs when the progressive criterion variables reach a value of 1. When the variables range < 0÷1), this only leads to a decrease in the initial stiffness of the material [29-32]. In numerical calculations, the progressive failure analysis is usually performed by non-linear analysis - the Newton-Raphson method [33].

Based on the literature review, especially referring to publication [6], the main contribution of the author to the development of the research topic is to conduct damage initiation studies and progressive failure analysis of the thin-walled composite structure.

RESEARCH SUBJECT AND METHODOLOGY

The test specimen is a thin-walled composite profile with an open cross-section. The geometrical parameters are presented in Figure 1. An actual construction was made of a unidirectional carbon/epoxy laminate with a symmetrical arrangement $[0/90/0/90]_s$ of 8 layers. A physical model of the tested composite profile and its geometric dimensions are shown in Figure 1.

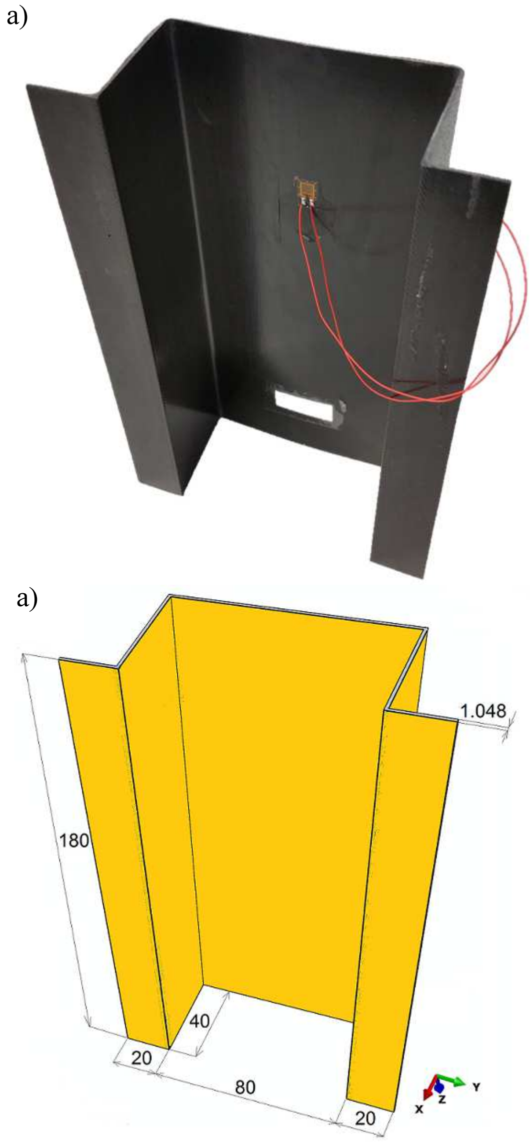

Fig. 1. Composite profile with open cross-section: a) physical model, b) geometric model

Rys. 1. Profil kompozytowy o przekroju otwartym: a) model fizyczny, b) model geometryczny

The mechanical properties of the composite material were determined in experimental tests conducted in compliance with the relevant ISO standard (Table 1).

TABLE 1. **Material properties [33]**
TABELA 1. **Właściwości materiałowe [33]**

E_1 [MPa]	E_2 [MPa]	v_{12} [-]	G_{12} [MPa]	X_t [MPa]	X_c [MPa]	Y_t [MPa]	Y_c [MPa]	S_{12} [MPa]	G_{ft} [N/mm]	G_{fc} [N/mm]	G_{mt} [N/mm]	G_{mc} [N/mm]
130710	6360	0.32	4180	1867.2	1531	25.97	214	100.15	133	10	0.5	1.6

EXPERIMENTAL STUDY

Experimental tests of thin-walled composite profiles under compression were performed using a universal testing machine - Zwick Z100. Axial compression tests were carried out at room temperature, with the upper cross-bar velocity maintained at a constant value equal 2 mm/min. The ends of the cross-section of the composite profiles were simply-supported on a base panel to prevent any inaccuracies of the profile edge. In addition, the ends of the profiles were aligned with teflon inserts fitted on the inner side of profile (Fig. 2a).

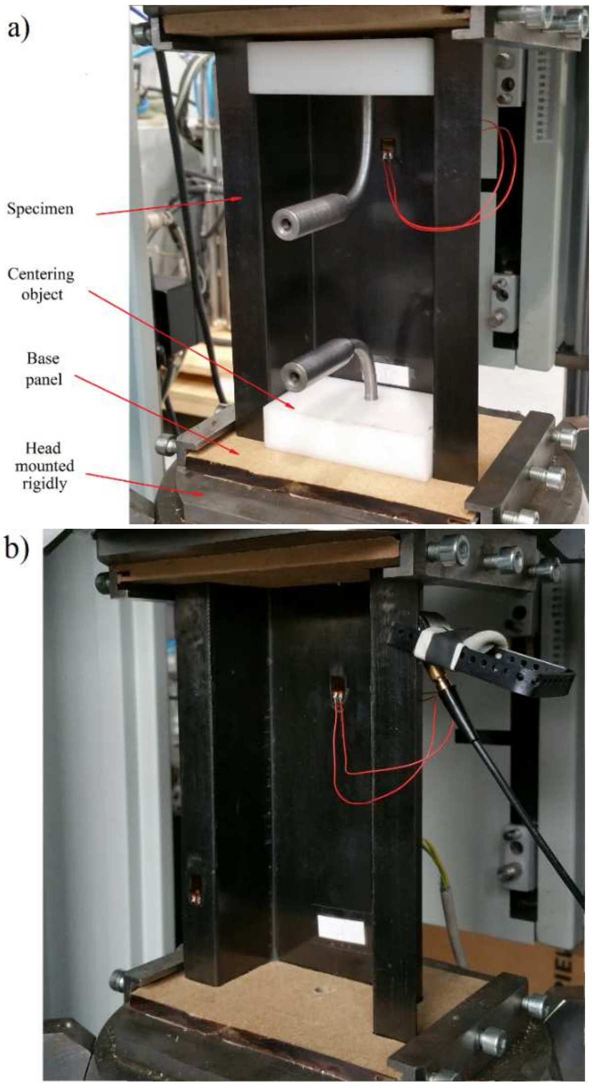

Fig. 2. Experimental stand

Rys. 2. Stanowisko badawcze

The composite profiles were subjected to uniaxial compression until failure of the material. The composite structure behaviour was assessed based on the post-critical equilibrium paths describing the load-strain relationship. Testing of the load-carrying capacity was conducted by two independent methods. The first one was strain measurements (using two strain gauges) for the entire tested range of load. The strain gauges were placed on both sides of the profile web at the same height, in the place of the largest deflections (which was determined on preliminary numerical analysis - linear buckling analysis). The second method was acoustic emission (AE). The following were mainly measured: the number of events and counts, as well as the energy and amplitude of acoustic emissions, in real time. The acoustic emission measurements were made with an AMSY-5 instrument equipped with a piezoelectric sensor, which was placed directly on the profile flange (to measure elastic waves).

Figure 2b shows the test specimen with the installed sensor for acoustic emission measurement and the strain gauges.

NUMERICAL ANALYSIS

The numerical analysis was performed by the finite element method using ABAQUS® software. The analysis involved solving a nonlinear problem of stability for a structure with an initiated geometric imperfection reflecting the lowest buckling mode (from buckling analysis) with an initial amplitude equal to 5% of the profile wall thickness. The nonlinear problem was solved by means of the iteration-incremental Newton-Raphson method [34]. Evaluation of the composite failure was performed using the progressive damage criterion [35]. The Hashin criterion considers four independent modes of damage: fibre and matrix tension, and fiber and matrix compression. When the damage initiation criterion is met, degradation of the composite structure begins with a decrease in the stiffness of the material properties. Damage evolution is described here with an energy criterion [28, 29] - Figure 3.

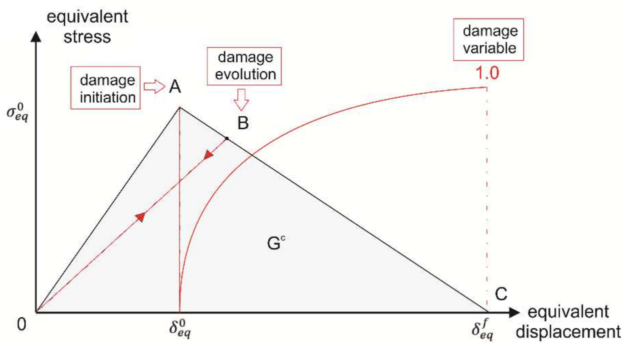

Fig. 3. Damage initiation and evolution law

Rys. 3. Charakterystyka inicjacji i ewolucji zniszczenia

The discretization of the composite profile was carried out using shell S8R finite elements. S8R are 8-node quadratic finite elements with reduced integration and 6 degrees of freedom at each of the 8 nodes per one finite element. Additionally, the numerical model contained rigid finite elements with a linear shape function - R3D4, which were used for the discretization of elements describing rigid plates. The created discrete model consisted of 11620 finite elements and 20187 nodes. Moreover, a single ply of the laminate was described with an orthotropic material. The boundary conditions of the numerical model reflected the real support of the ends of the actual construction. The contact interactions (in tangential and normal directions) were defined between the profile ends and the rigid plate (non-deformable) supports in tangential and normal directions - friction coefficient equal 0.1. In the analysis, the loading of the structure was modelled as displacement of the upper plate toward the Z axis. The discrete model and boundary conditions are presented in Figure 4.

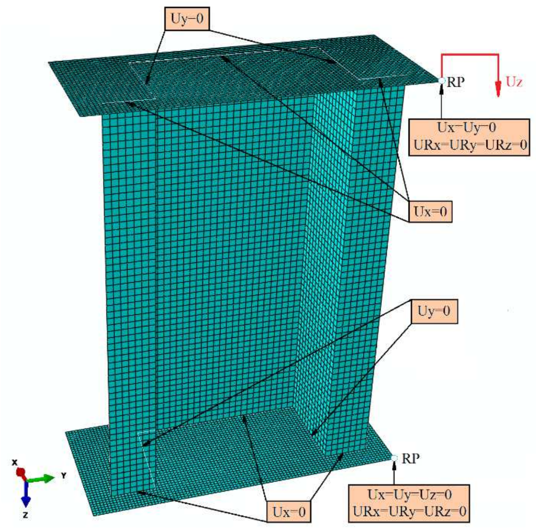

Fig. 4. Boundary conditions of numerical model

Rys. 4. Warunki brzegowe modelu numerycznego

RESULTS - FAILURE ANALYSIS

The investigation of the critical state of the actual structures demonstrated the loss of stability in the tested composite profiles under compression - the occurrence of two half-waves in the longitudinal direction. The numerical and experimental results of the buckling state were equal - Figure 5.

The experimental study enabled identification of the damage initiation mechanisms. According to the Hashin criterion, the damage of composite material begins when the damage initiation parameters (HSNFCCRT - fibre compression, HSNFTCRT - fibre tension, HSNMCCRT - matrix compression, and HSNMTCRT - matrix tension) reach the value of 1. In the analysed case, the identified damage initiation mode was matrix damage due to tension, at the compressive load of $P_{f\text{-}ini\_FEM}$ = 14032 N - Figure 6.

After reaching damage initiation due to continuous axial loading of the structure, damage evolution occurred. On the basis of the conducted numerical studies, the failure load value P_{f_FEM} = 23218 N was determined, which caused loss of the load-carrying capacity of the profile. The stiffness of the material significantly decreases with increasing the load of the structure. Failure of the composite material occurred when the following PFA variables reached a value of 1: DAMAGEFC - compressive fibre damage, DAMAGEFT - tensile fibre damage, DAMAGEMC - compressive matrix damage, DAMAGEMT - tensile matrix damage, and DAMAGESHR - shear damage. Figures 7 and 8 show a comparison of the experimental and numerical results with respect to the loss of load-carrying capacity of the structure. The example results (fulfilment of shear damage) show qualitative agreement between the physical and numerical models.

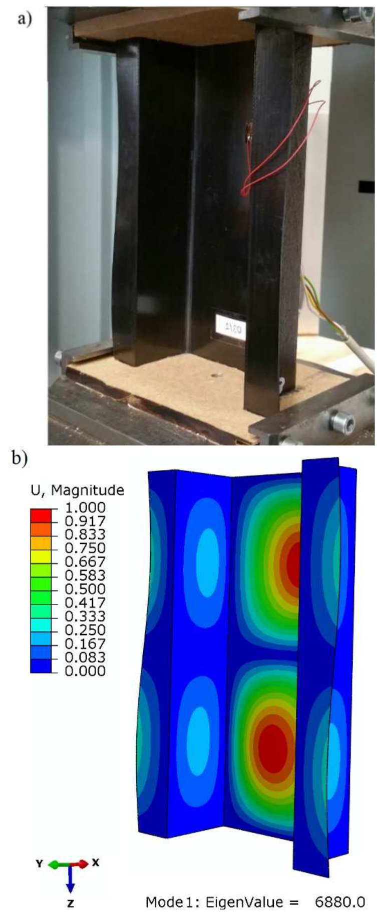

Fig. 5. Stability loss of composite profile under compression: a) EXP, b) FEM

Rys. 5. Utrata stateczności ściskanej konstrukcji kompozytowej: a) eksperyment, b) MES

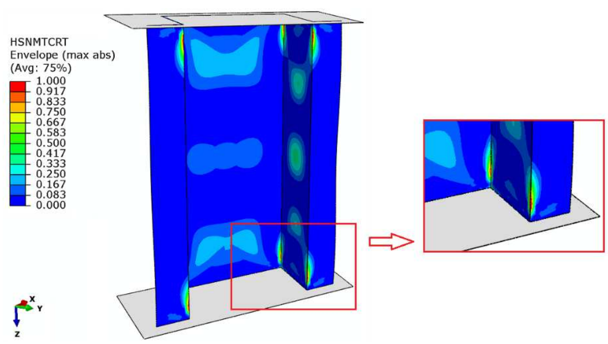

Fig. 6. Damage initiation in composite profile - HSNMTCRT tensile matrix damage

Rys. 6. Inicjacja zniszczenia profilu kompozytowego - HSNMTCRT zniszczenie rozciąganej osnowy

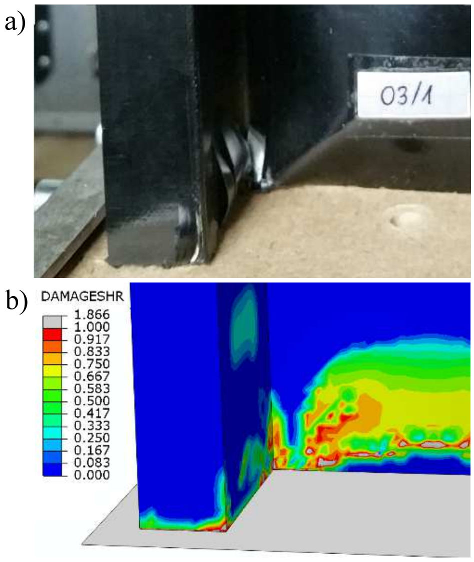

Fig. 7. Loss of load capacity in composite profile: a) EXP, b) FEM (shear damage)

Rys. 7. Utrata nośności konstrukcji kompozytowej: a) eksperyment, b) MES (ścinanie)

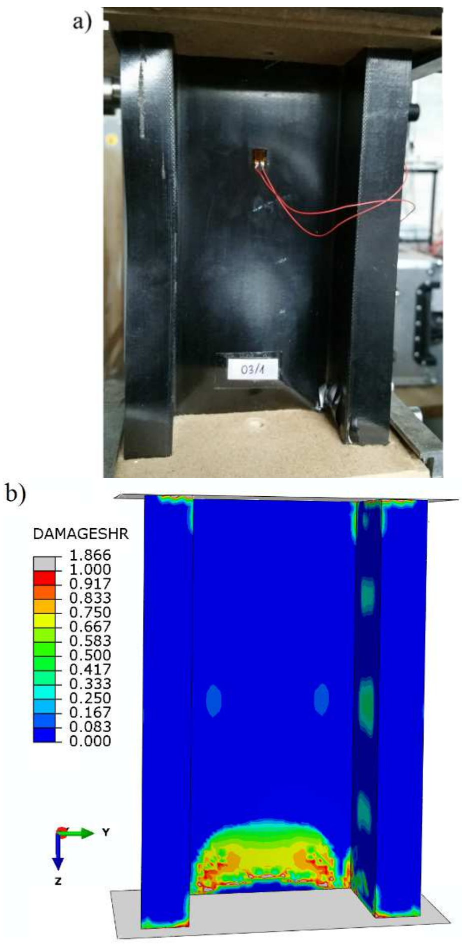

Fig. 8. Loss of load capacity in composite profile - whole model: a) EXP, b) FEM (shear damage)

Rys. 8. Utrata nośności konstrukcji - cały model: a) eksperyment, b) MES (ścinanie)

On the basis of the conducted studies of the failure of the compressed composite profiles, post-critical equilibrium paths were determined. The obtained characteristics from the strain measurements, acoustic emission and FEM allow the load value causing the loss of capacity to be estimated (Fig. 9). The critical load of the numerical model was determined based on the relationship between the load and profile shortening. The experimental and FEM results of the limit load were compared (Table 2).

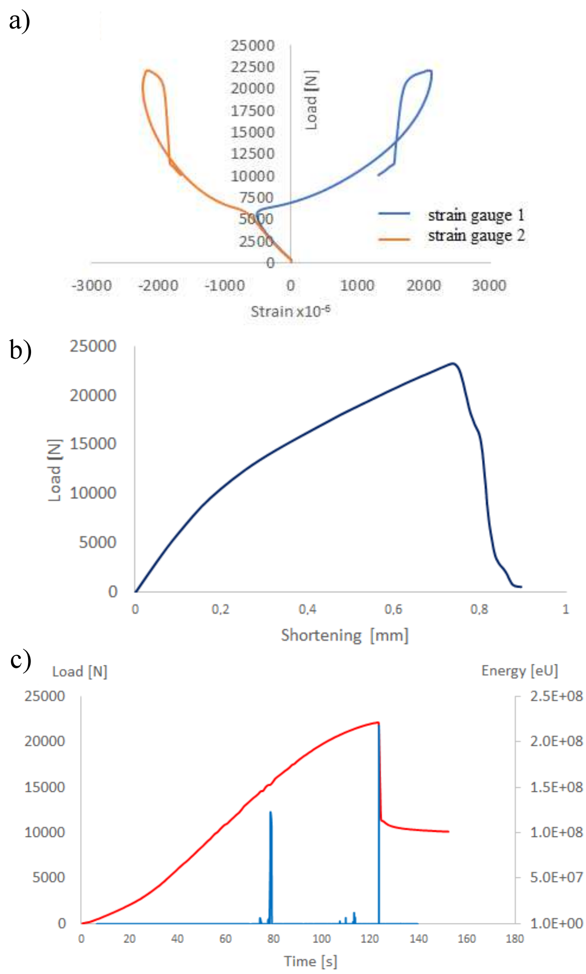

Fig. 9. Failure characteristics: a) strain measurement, b) FEM analysis, c) acoustic emission measurement

Rys. 9. Charakterystyki zniszczenia: a) pomiar odkształceń, b) analiza MES, c) emisja akustyczna

TABLE 2. **Limit loads**
TABELA 2. **Wartości graniczne**

EXP - strain measurement [N]	FEM [N]	Difference [%]
22078	23218	4.91
EXP - acoustic emission [N]		Difference [%]
22088		4.87

On each of the obtained characteristics curves, the upper bend of the experimental and numerical curves is equivalent to achieving the value at which the structure loses its load-carrying capacity (failure load). The obtained results of the limit state of the tested thin-walled structure showed high correspondence, which confirms the correctness of the numerical model preparation. Regarding the results of the acoustic emission measurement, a more detailed description of the structure behaviour can be observed in Figure 9c. In the diagram one can notice two clear peaks of energy. The first energy signal peak reflects the moment of composite material damage initiation occurring when the load is $P_{f\text{-}ini\_exp}$ = 15266 N. This value corresponds to the numerical value of $P_{f\text{-}ini\_FEM}$ = 14032 N at which tensile matrix damage occurs (Fig. 6). The discrepancy between the experimental and numerical results of the damage initiation load amounted to 8%. A similar comparison can be made for the second energy peak, where the corresponding load is P_{f_exp} = 22088 N. Comparing this value with the numerical analysis value P_{f_FEM} = = 23218 N, a high agreement of the limit load, amounting to 4.9% was observed.

CONCLUSIONS

This paper presented the results of the behaviour of a thin-walled composite structure subjected to axial compression. The numerical study of progressive failure analysis was verified experimentally (strain measurement and acoustic emission) on a universal testing machine. As observed from the analysis of a short thin-walled composite profile, the failure is mainly connected and dominated by local buckling.

Progressive failure analysis of the composite material enabled description of the damage modes of the composite material. The use of damage initiation based on the Hashin criterion allow further identification of damage evolution. The use of the progressive failure analysis criterion to describe the damage evolution confirmed the complex nature of the composite material failure. The obtained results confirm that the loss of load capacity of the compressed profile is caused by a complex state of damage. The conducted studies showed high compliance of the results of limit loads and the area of damage between the numerical calculations and experimental tests.

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