CHARACTERIZATION OF QUASI-STATIC BEHAVIOR OF HONEYCOMB CORE SANDWICH STRUCTURES

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Summary

Honeycomb core sandwich composite structures gained their popularity in aircraft, aerospace, automotive and naval industries mainly due to their superior flexural stiffness and very low mass, which cause that their application in engineering constructions becomes very attractive. Since they contain core and face sheets made of different materials with different properties their behavior under quasi-static loading is highly nonlinear and the force-displacement response contains characteristic zones caused by various mechanical phenomena. The characterization of such behavior under tensile and bending loading as well as characterization of failure mechanisms accompanied with quasi-static loading is the main goal of this paper. Obtained experimental results and their analysis allow for better understanding of occurred phenomena in such structures, which can be helpful during modeling of elements made of such sandwich composites as well as prediction of their behavior under various loading conditions.

Keywords: sandwich structures, tensile test, three-point bending test, failure mechanisms, elastic return

OCENA ZACHOWANIA QUASI-STATYCZNEGO STRUKTUR PRZEKŁADKOWYCH Z RDZENIEM O STRUKTURZE PLASTRA MIODU

Streszczenie

Kompozyty przekładkowe z rdzeniem o strukturze plastra miodu zyskały swoją popularność w przemyśle lotniczym, kosmicznym, samochodowym oraz okrętowym głównie dzięki swojej wyjątkowej sztywności oraz bardzo niskiej masie, co spowodowało że ich wykorzystanie w konstrukcjach inżynierskich stało się bardzo atrakcyjne. Biorąc pod uwagę fakt, że rdzeń i okładziny wykonane są z różnych materiałów o różnych właściwościach zachowanie tych struktur pod wpływem obciążeń quasi-statycznych jest wysoce nieliniowe, a odpowiedź siła-przemieszczenie zawiera charakterystyczne obszary spowodowane różnymi zjawiskami mechanicznymi. Charakteryzacja takiego zachowania podczas obciążeń rozciągających i zginających oraz mechanizmów zniszczenia towarzyszących obciążeniom quasi-statycznym jest głównym celem tej pracy. Otrzymane wyniki eksperymentalne i ich analiza pozwalają na lepsze zrozumienie zachodzących zjawisk w takich strukturach, co może być przydatne przy modelowaniu elementów wykonanych z kompozytów przekładkowych, jak również predykcji ich zachowania przy różnych warunkach obciążenia.

Słowa kluczowe: struktury przekładkowe, próba rozciągania, próba trójpunktowego zginania, mechanizmy zniszczenia, nawrót sprężysty

1. INTRODUCTION

Wide popularity of sandwich composite structures used as a constructional material in many industrial applications was achieved due to their superior properties, namely high flexural stiffness with simultaneous very low mass. Moreover, due to the specific internal structure and materials used for manufacturing of sandwich structures (lightweight alloys and polymer-based materials), they have excellent damping properties, which make their application attractive in automotive applications. Considering the mentioned properties sandwich structures are also very attractive in aircraft, aerospace, naval applications and others mainly due to their lightweight and high stiffness [1].

The main idea of a sandwich structure is joining flexible core and stiff face sheets in such a way that its resulted stiffness is much higher than its particular components. A sandwich structure consists a thick core and thin face sheets joined with a core. Besides the great mechanical properties and lightweight such a combination of materials in a sandwich structure causes several difficulties, e.g. material anisotropy, non-linear behavior under static and dynamic loading etc., which cause that it is difficult to describe and predict their behavior. Additional difficulty which influences on the behavior of sandwich structures is a very different architecture of a core, starting from homogeneous filling (e.g. foam-based cores) to cores with a cell structure. In applications, where the sandwich composites are used as a constructional material the lowering of its mass without loss of stiffness is a high-priority factor. Therefore the cell structure of a core is a favorable solution, which can be attained at relatively little expense. From a variety of cell configurations used in practice, including rectangular [2], pyramidal [3], hexagonal [4], etc., one of the most favorable cell configurations is a honeycomb one, which ensures a great stiffness-to-mass ratio.

In order to design the engineering constructions using these materials and further use them in different engineering applications the knowledge of their mechanical behavior is required. Several studies were performed in order to identify specific states of sandwich composites under various loading conditions. In particular, He and Hu [4] presented theoretical analysis with experimental verification of all-steel honeycomb core sandwich subjected to three-point bending, while the authors of [5] investigated a behavior of Al-Nomex™ honeycomb sandwich composites under four-point bending numerically and experimentally with analysis of fracture. Numerical identification of effective material properties of honeycomb core sandwich composites with additional foam filling were performed by the authors of [6]. Di Bella et al. [7] studied the influence of manufacturing procedure on properties of foam-based core sandwich composites with extended analysis of stiffness and fracture mechanisms under three-point bending test. Due to the specific structure of these materials their static behavior may differ significantly from the homogeneous materials [8,9] and even static behavior is highly nonlinear [10]. Similarly, the nonlinearities were observed during compression tests [11] and three-point bending tests [12] of Nomex™-based honeycomb core sandwich composites.

Since the sandwich core made of Nomex™ (Kevlar® paper saturated by phenolic resin) is the world's lightest material used in sandwich structures it has found a lot of applications primarily in aircraft, aerospace, automotive and naval industries. For design and constructional purposes the behavior of this Nomex™-based honeycomb core composites under various loading conditions is required to be known. The authors of [12] identified three characteristic zones on load-displacement response for such composites under three-point bending tests, where the force drop is observed. Similar force drops were observed for other sandwich composites during three-point bending [7] and under compression loading [8,9].

The objective of this study is to characterize specific behavior and failure mechanisms of sandwich composites with a honeycomb Nomex™ core subjected to tensile and bending loads. The results of the performed experimental studies as well as microscopic inspection of fractured specimens after the tests were analyzed and discussed.

2. MATERIALS AND METHODS

2.1 TESTED MATERIAL

The specimens for the tests were manufactured and supplied by PPHU Surfpol (Rawa Mazowiecka, Poland). They consisted of a core with a thickness of 3 mm manufactured from aramid paper saturated by phenolic resin with the resulted density of 29 kg/m^3. An applied HX cell configuration has hexagonal geometry with a diameter of single cell of 2.5 mm. The face sheets for the sandwich composite were manufactured in the form of glass fiber-reinforced polymer (GFRP) laminate prepared in vacuum-assisted resin transfer molding technology. The laminate was reinforced by plain weave glass fabric with a grammature of 280 g/m^2 and the matrix of laminate was prepared as a solution of epoxy resin LG 385 with hardener HG 385 manufactured by GRM Systems s.r.o. (Olomouc, Czech Republic). The resulted thickness of sandwich specimens is 4.1 mm. The specimens were cut for the tests to rectangular strips with dimensions of 25×300 mm.

2.2 EXPERIMENTAL PROCEDURES

The quasi-static tests of the specimens were performed on MTS® Criterion™ Series 40 Model 43 universal electromechanical test system with appropriate clamping supports for tensile and three-point bending loading. The tests were carried out under displacement control with a cross-head speed of 2 mm/min both for tensile and bending loading. Both tests were repeated five times. The effective lengths of tested specimens for tensile and bending load were 180 and 80 mm, respectively.

After performing the quasi-static tests the microscopic inspection of fractured specimens was carried out. The fractured areas of specimens were registered using Carl Zeiss SteREO Discovery.V8 stereoscopic microscope under various magnifications.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 TENSILE TESTS

The performed tensile tests of the specimens allow to observe characteristic regions on the stress-strain curve. The test setup is presented in Fig.1. The stress-strain curve of failure behavior under tensile loading is shown in Fig.2.

In the first region (from the beginning to *a* point) the stress-strain curve has linear character due to elastic deformation of face sheets until reaching the stress value of 4.6 MPa and strain of 0.33%. In the second region (between *a* and *b* points) the non-linear character is observed due to plastic deformation occurred in face sheets until reaching the stress value of 7.83 MPa and strain of 0.846%.

Fig. 1. Experimental setup for tensile tests

In the point *b* the yield point is reached. Then, in the region between *b* and *c* points the stress-strain curve has piecewise-linear character caused by plastic deformation of GFRP face sheets with accompanying fiber breakage. In the point *c* (stress of 21.45 MPa, strain of 5.245%) the failure of one of the face sheets occurs. Due to the rapid load fall a similar failure occurred in the second face sheet (region *d*) with stress and strain values of 17.06 MPa and 5.27%, respectively.

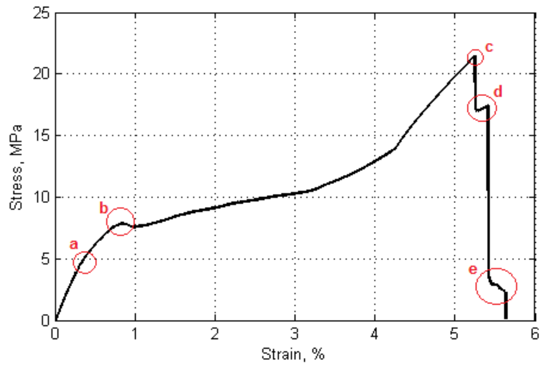

Fig. 2. Stress-strain curve of failure behavior of honeycomb core sandwich composite strip under tensile loading

The next rapid load fall causes the failure of a core (region *e*) at the stress and strain values of 2.9 MPa and 5.46%, respectively. In order to investigate the tensile loading consequences the microscopic inspection of specimens was performed. Typical failure modes under tensile loading are presented in Figs.3 and 4.

It can be concluded from Fig.2 that the strength properties of face sheets have a dominant influence on tensile failure of a sandwich structure.

In Fig.3 one can observe irregular fracture of reinforcing fibers in the tension direction and their pull out, which is connected with breaking points in the region between *b* and *c* points on the stress-strain curve. The irregularly-shaped failure of a core observed in the Fig.4 is connected with a load drop in the region *e* in the stress-strain curve. A typical shear-type failure observed in Fig.4 is caused by subsequent failure of face sheets, i.e. after failure of a first face sheet the appeared shear components of stress cause a shear failure of a core.

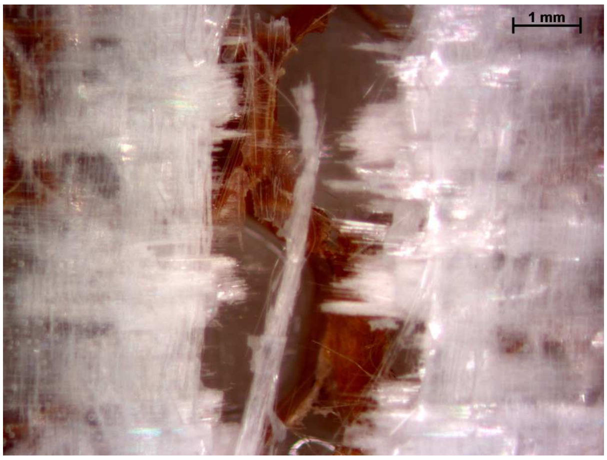

Fig. 3. Failure mode under tensile loading – top view (magnification 10x)

Fig. 4. Failure mode under tensile loading – side view (magnification 10x)

3.2 THREE-POINT BENDING TESTS

A typical stress-strain curve of three-point bending tests is presented in Fig.5. The specimens were initially pre-stressed in order to hold them in a fixture (see Fig.6).

Five regions of failure behavior can be observed for a tested sandwich structure. The first region (from the beginning to the point *a*) reveals linear elastic character due to the elastic deflection of the whole structure until reaching the stress value of 41.6 MPa and strain of 0.95%, the core in this case is subjected to shear loading. In the second region (between the points *a* and *b*) the plastic deformation of face sheets can be observed due to the non-linear character of deflection. The shearing of a core is continued. After achieving the peak load at point *b*, which is the buckling strength limit (stress value of 52.61 MPa and strain of 1.59%), the failure of an upper face sheet is started with accompanied its plastic deformation and shear failure of a core. This resulted in sudden drop of the load to the point *c* on the stress-strain curve (stress value of 22.72 MPa and strain of 1.84%).

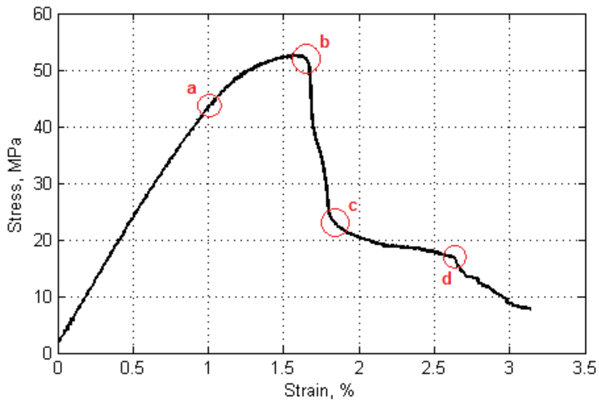

Fig. 5. Stress-strain curve of failure behavior of honeycomb core sandwich composite strip under three-point bending

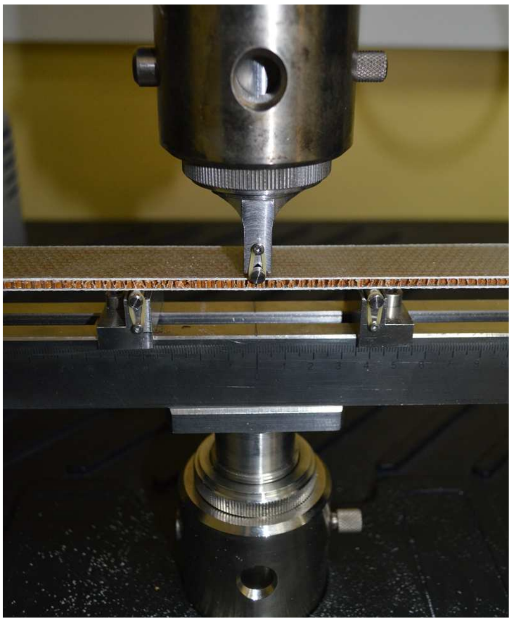

Fig. 6. Experimental setup for three-point bending tests

It should be noticed that the deformation is not symmetrical with respect to applied loading (see Fig.7). This is caused mainly by the core configuration and stress redistribution during indentation phase as well as much higher stiffness of face sheets with respect to the stiffness of a core. The non-symmetric location of a deformed region is resulted by shearing of a core during successive loading. Similar behavior was observed for other polymer-based sandwich composites subjected to bending loading [8,12]. It is interesting that the same behavior is observed for metallic sandwich structures [13-15]. The indentation region occurred at the right side of applied load is connected with core thinning, which decreases the load capacity. A face wrinkling in this region occurred.

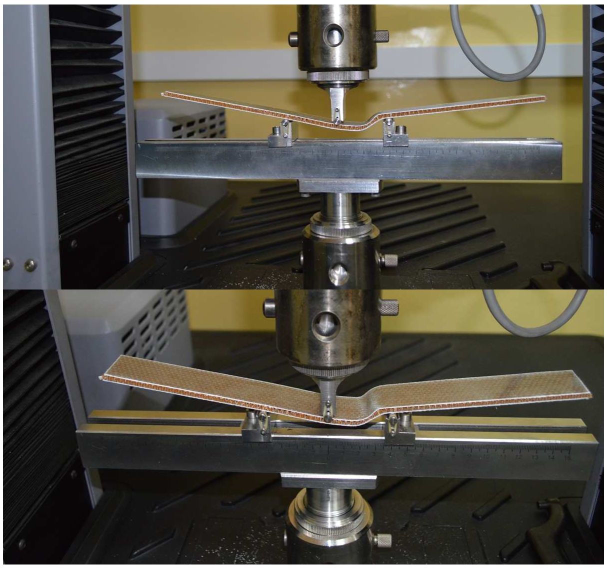

Fig. 7. Non-symmetrical shear failure during three-point bending test of a tested sandwich composite

The indentation process is continued until the reaching of the point d on the stress-strain curve (stress value of 19.7 MPa and strain of 2.64%), at which the core reaches its densification stage. It is connected with direct bending of face sheets and densified core in between, which results in plastic deformation of the bottom face sheet of a sandwich. The shear failure of the core of tested sandwich using three-point bending setup in the thinning region is presented in magnification in Fig.8. A typical shear failure of a core is observed with buckling of the cell walls.

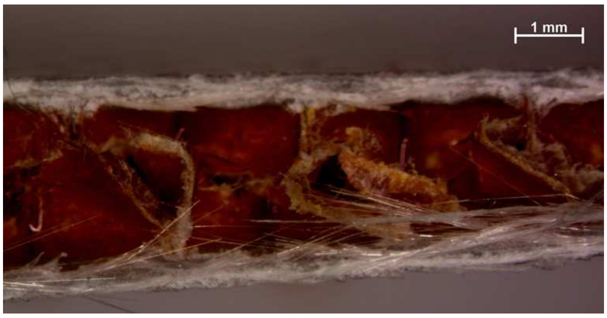

Fig. 8. Shear failure of a core after three-point bending test (magnification 10x)

Though the local plastic deformation of the face sheets as well as shear failure of a core occurred during loading of a sandwich specimen the failure of a specimen was not fractured. After the load release its elastic return was observed (see Fig.9).

Small plastic deformations are still observable as well as debonding on the upper face sheet-core interface, however the elastic nature of GFRP face sheets causes a return to the initial state of a specimen. Such behavior was also observed by the authors of [9] in numerical tests of sandwich structures and by the authors of [16-18] during experimental studies. This phenomenon is characteristic for the sandwich composite structures which face sheets are made of flexible polymeric materials. Even in the case of flexible core the metallic skins dominate the deflection and the return to initial geometry is not occurred [5,19].

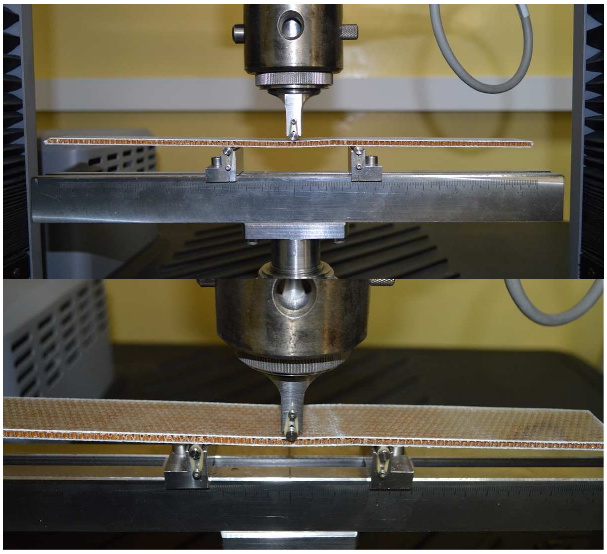

Fig. 9. Sandwich specimen after load release

The collapse load F can be predicted using the formula proposed in [20]:

$$F = 2\sigma_{yf}\frac{bt^2}{L} + 2bc\tau_{yc}\left(1+\frac{H}{L}\right) + \sigma_{yc}\frac{bL}{4}, \quad (1)$$

where σ_{yf}, σ_{yc} and τ_{yc} is a yield stress of face sheets, a yield stress of a core and a shear yield stress of a core, respectively; L is a support span; H is an overhang specimen length; b is a specimen width; t is a face sheet thickness and c is a core thickness.

4. CONCLUSIONS

Mechanical behavior of sandwich composite structures with a Nomex™ honeycomb and GFRP face sheets has been studied experimentally including tensile and three-point bending tests. The obtained stress-strain curves of failure behavior of the tested structure under various loading conditions were analyzed and discussed. It was found that during tensile loading of a structure the fracture mechanism is dominated by the fracture of face sheets, which reveals linear behavior in the elastic zone and becomes nonlinear due to plastic deformations until reaching the yield point. The typical failure modes were presented. The obtained results of three-point bending tests allow characterizing the failure of a structure and connecting the specific zones of failure with mechanical phenomena occurred during the loading. In particular, elastic and plastic zones were identified as well as shear failure of a core. It was observed that after load release the elastic return of a sandwich specimen occurred. Such behavior is typical for sandwich structures with flexible face sheets.

The obtained results allow for better understanding of failure mechanisms of sandwich composite structures and can be useful for development of new analytical and numerical models which can consider the observed phenomena.

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References

1. Zenkert D.: An introduction to sandwich constructions. EMAS, Solihull, UK, 1995.
2. Manshadi B.D., Vassilopoulos A.P., de Castro J., Keller T.: Instability of thin-walled GFRP webs in cell-core sandwiches under combined bending and shear loads. "Thin-Walled Structures" 2012, Vol. 53, p. 200-210.
3. Xiong J., Ma L., Stocchi A., Yang J., Wu L., Pan S.: Bending response of carbon fiber composite sandwich beams with three dimensional honeycomb cores. "Composite Structures" 2014, Vol. 108, p. 234-242.
4. He M., Hu W.: A study on composite honeycomb sandwich panel structure. "Materials and Design" 2008, Vol. 29, p. 709-713.
5. Abbadi A., Koutsawa Y., Carmasol A., Belouettar S., Azari Z.: Experimental and numerical characterization of honeycomb sandwich composite panels. "Simulation Modelling Practice and Theory" 2009, Vol. 17, p. 1533-1547.
6. Sandowski T., Bęc J.: Effective properties for sandwich plates with aluminium foil honeycomb core and polymer foam filling – Static and dynamic response. "Computational Materials Science" 2011, Vol. 50, p. 1269-1275.
7. Di Bella G., Borsellino C., Calabrese L.: Effects of manufacturing procedure on unsymmetrical sandwich structures under static load conditions. "Materials and Design" 2012, Vol. 35, p. 457-466.
8. Jin F., Chen H., Zhao L., Fan H., Cai C., Kuang N.: Failure mechanisms of sandwich composites with orthotropic integrated woven corrugated cores: experiments. "Composite Structures" 2013, Vol. 98, p. 53-58.

9. Zhou X., Wang H., You Z.: Mechanical properties of Miura-based folded cores under quasi-static loads. "Thin-Walled Structures" 2014, Vol. 82, p. 296-310.
10. Du Y., Yan N., Kortschot M.T.: Light-weight honeycomb core sandwich panels containing biofiber-reinforced thermoset polymer composite skins: fabrication and evaluation. "Composites: Part B" 2012, Vol. 43, p. 2875-2882.
11. Roy R., Park S.J., Kweon J.H., Choi J.H.: Characterization of Nomex honeycomb core constituent material mechanical properties. "Composite Structures" 2014, Vol. 117, p. 255-266.
12. Boukharouba W., Bezazi A., Scarpa F.: Identification and prediction of cyclic fatigue behaviour in sandwich panels. "Measurement" 2014, Vol. 53, p. 161-170.
13. Crupi V., Montanini R.: Aluminium foam sandwiches collapse modes under static and dynamic three-point bending. "Journal of Impact Engineering" 2007, Vol. 34, p. 509-521.
14. Belouettar S., Abbadi A., Azari Z., Belouettar R., Freres P.: Experimental investigation of static and fatigue behaviour of composites honeycomb materials using four point bending tests. "Composite Structures" 2009, Vol. 87, p. 265-273.
15. Crupi V., Epasto G., Guglielmino E.: Collapse modes in aluminium honeycomb sandwich panels under bending and impact loading. "International Journal of Impact Engineering" 2012, Vol. 43, p. 6-15.
16. Zinno A., Prota A., Di Maio E., Bakis C.E.: Experimental characterization of phenolic-impregnated honeycomb sandwich structures for transportation vehicles. "Composite Structures" 2011, Vol. 93, p. 2910-2924.
17. Shi S., Sun Z., Hu X., Chen H.: Flexural strength and energy absorption of carbon-fiber-aluminium-honeycomb composite sandwich reinforced by aluminium grid. "Thin-Walled Structures" 2014, Vol. 84, p. 416-422.
18. Abbadi A., Tixier C., Gilgert J., Azari Z.: Experimental study on the fatigue behaviour of honeycomb sandwich panels with artificial defects. "Composite Structures" 2015, Vol. 120, p. 394-405.
19. Giglio M., Gilioli A., Manes A.: Numerical investigation of three-point bending test on sandwich panels with aluminum skins and Nomex™ honeycomb core. "Computational Materials Science" 2012, Vol. 56, p. 69-78.
20. Crupi V., Montanini R.: Aluminium foam sandwiches collapse modes under static and dynamic three-point bending. "International Journal of Impact Engineering" 2007, Vol. 34, p. 509-521.