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COMPOSITES THEORY AND PRACTICE

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STATIC EXPERIMENTAL TESTING OF U-TYPE COMPOSITE SEGMENTS ENERGY ABSORPTION

The paper presents the static experimental testing of U-type (channel section) composite segments energy absorption. The segments have the overall dimensions $b \times h = 100 \times 80$ mm, rounded corners and damage initiators at their edges. The segments have been made in nine variants with respect to stacking sequence and laminate thickness. The matrix constitutes Polimal 104 N-1 P/p-503 polyester resin, i.e. elasticized and incombustible Polimal 104 resin produced by Organika-Sarzyna Co., Poland. Three types of stitched E-glass fabrics produced by Owens Corning Co., USA were used as reinforcement, i.e. D-610 (Weft 90° , uniaxial fabric [90], 607 g/m^2), CD-600 (Biaxial, fabric [0/90], 610 g/m^2), and CDDB-1200 (Quadriaxial, fabric [0/45/90/-45], 1213 g/m^2). Static experimental tests were performed on a SATEC 1200 testing machine, with pressure force and punch displacement under registration (kinematic excitation at 2mm/min velocity). The failure processes were recorded using a PHANTOM v12 video camera. The tests were performed on segments of 400 mm or 200 mm length due to laminate thickness, using a problem-oriented test stand in which 5 composite panels were placed in parallel. The static testing of U-type segments energy absorption focussed on the quasi-optimal stacking sequence and thickness selection. In order to perform such investigations, the following optimization criteria were adopted: 1) failure level with respect to the following mechanisms: progressive crash, delamination failure, buckling failure, catastrophic failure; 2) maximum relative energy absorption. The tests performed for subsequent segment types have been illustrated with compression force vs. punch displacement curves. The figures showing segment failure mechanisms at selected positions of the punch are presented as well. The maximum values of compression force initiating the failure processes, absorbed energy and absorbed relative energy values are set up, with an estimation of the parallel failure mechanisms level. The energy values are calculated for punch displacements belonging to the interval 0÷50 mm. For further dynamic research, U/LE3 segments with a 8xD-610 stacking sequence and $[90]_8$ ply angles have been chosen as the authors' preferred solution. These segments are characterized by the highest relative energy absorption, dominant progressive crash and *F-s* failure curve adjusted to a typical blast pressure impulse.

Keywords: **U-type composite segments, static energy absorption, experimental tests, quasi-optimal solution**

BADANIA EKSPERYMENTALNE STATYCZNE ENERGOCHŁONNOŚCI SEGMENTÓW KOMPOZYTOWYCH TYPU U

Przeprowadzono badania eksperymentalne statyczne energochłonności segmentów kompozytowych typu U (przekrój ceowy) o wymiarach gabarytowych przekroju poprzecznego mm, z wyokrągleniami w narożach oraz inicjatorami niszczenia na krawędziach. Segmenty wykonano w dziewięciu wariantach ze względu na sekwencję ułożenia warstw i grubość laminatu. Osnowa jest żywicą poliestrową Polimal 104 N-1 P/p-503 (uelastyczniona i uniepalnieniona żywica Polimal 104; producent Organika-Sarzyna). Zastosowano trzy warianty wzmocnień w postaci tkanin szklanych zszywanych (szkło E) produkowanych przez firmę Owens Corning (USA): D-610 (Weft 90°, tkanina jednokierunkowa [90], 607 g/m^2), CD-600 (Biaxial, tkanina dwukierunkowa [0/90], 610 g/m^2), CDDB-1200 (Quadriaxial, tkanina czterokierunkowa [0/45/90/-45], 1213 g/m^2). Przeprowadzono badania statyczne energochłonności na maszynie wytrzymałościowej SATEC 1200, rejestrując siłę nacisku oraz przemieszczenie stempla obciążającego (wymuszenie kinematyczne). Prędkość przesuwu stempla maszyny wytrzymałościowej wynosiła 2 mm/min. Procesy niszczenia rejestrowano z użyciem kamery FANTOM v12. Próby przeprowadzono na segmentach o długości 400 lub 200 mm w zależności od grubości laminatu. Badania przeprowadzono na stanowisku opracowanym przez zespół autorski. W bloku stanowiskowym układa się równolegle 5 paneli. Badania statyczne energochłonności segmentów kompozytowych typu U ukierunkowano na wybór quasi-optymalnej sekwencji warstw i grubości laminatu. Przyjęto następujące kryteria optymalizacyjne: 1) poziom niszczenia według następujących mechanizmów: niszczenie progresywne, niszczenie delaminacyjne, niszczenie przez wyboczenie, niszczenie katastroficzne, 2) maksymalna energochłonność właściwa. Przedstawiono przebiegi eksperymentalne siły ściskającej w funkcji przemieszczenia stempla maszyny wytrzymałościowej dla poszczególnych typów segmentów oraz zdjęcia z próby ściskania wybranych segmentów, ilustrujące mechanizmy niszczenia. Zestawiono wartości maksymalnej siły ściskającej inicjującej niszczenie, wartość energii absorbowanej oraz energii absorbowanej właściwej. Energię obliczono dla przemieszczeń stempla w przedziale 0÷50 mm. Określono poziomy działania poszczególnych mechanizmów niszczenia. Rozwiązaniem preferowanym do dalszych badań dynamicznych są segmenty typu U/LE3 o sekwencji warstw 8 x D-610 i kątach ułożenia $[90]_8$. Segmenty te charakteryzuje najwyższa energochłonność właściwa, dominujące niszczenie progresywne oraz krzywa niszczenia *F-s* dopasowana do impulsu ciśnienia wywołanego wybuchem.

Słowa kluczowe: **segmenty kompozytowe typu U, energochłonność statyczna, badania eksperymentalne, rozwiązanie quasi-optymalne**

INTRODUCTION

Nowadays, the passive defence of military vehicles and critical infrastructure objects against blast shock wave is mainly in the form of energy-absorbing layered shields, including lightweight aluminium foam and polymer-matrix laminates layers. Military vehicles have serious restrictions regarding energy-absorbing shield thickness which must not exceed 70÷100 mm. For critical infrastructure objects, energy-absorbing screens can be thicker, which allows geometric-material shaping of the polymer-matrix laminates used in these screens.

In Poland, the research and development of energy-absorbing structures have been carried out since 2004 in the Department of Mechanics and Applied Computer Science of the Military University of Technology, Warsaw. Paper [1] presents the results of static tests on the energy absorption of tubes and cones made of three types of glass-epoxy laminates. Failure mechanisms, an influence of tube wall thickness and cone half-angle were investigated with the relative energy absorption (REA) taken into consideration. The static energy absorption of glass–epoxy and carbon-epoxy composites was compared in [2-4]. Reference [5] presents wide investigations on the influence of various energy absorption capability factors of composite elements, including the energy-absorbing element wall thickness, stacking sequence, fibre fraction, ply angles and half-cone angle. Moreover, various energy-absorbing elements were compared, such as cones, tubes, spheres, flat plates, corrugated (wavy) plates, angle bars, channel bars, square tubes, ellipses and tubes filled with foamed materials. The subsequent development of energy absorption investigations of composite cone and tube shaped structures is presented in [6-8]. References [1-8] present the experimental investigations only.

U-TYPE COMPOSITE SEGMENTS DESCRIPTION

The composite segments under investigation are energy-absorbing U-type (channel section) structures of overall dimensions $b \times h = 100 \times 80$ mm, with rounded corners and damage initiators at the edges (Fig. 1). The segments have been manufactured in nine variants with respect to stacking sequence and laminate thickness (Table 1). The matrix constitutes Polimal 104 N-1 P/p-503 polyester resin, i.e. elasticized and incombustible Polimal 104 resin produced by Organika-Sarzyna Co., Poland. Three types of stitched E-glass fabrics produced by Owens Corning Co., USA were used as reinforcement, namely:

1. D-610 (Weft 90°, uniaxial fabric [90], 607 g/m^2, basis weight of fibres set 12/595)
2. CD-600 (biaxial fabric [0/90], 610 g/m^2, basis weight of fibres set 283/317/10)
3. CDDB-1200 (quadriaxial fabric [0/45/90/-45], 1213 g/m^2, basis weight of fibres set 300/300/300 /300/13).

The [0] orientation corresponds to the axial (longitudinal) direction of the segment. Table 1 introduces the following notation: g - average thickness of channel flanges of laminate segments, f_m - fibre mass fraction.

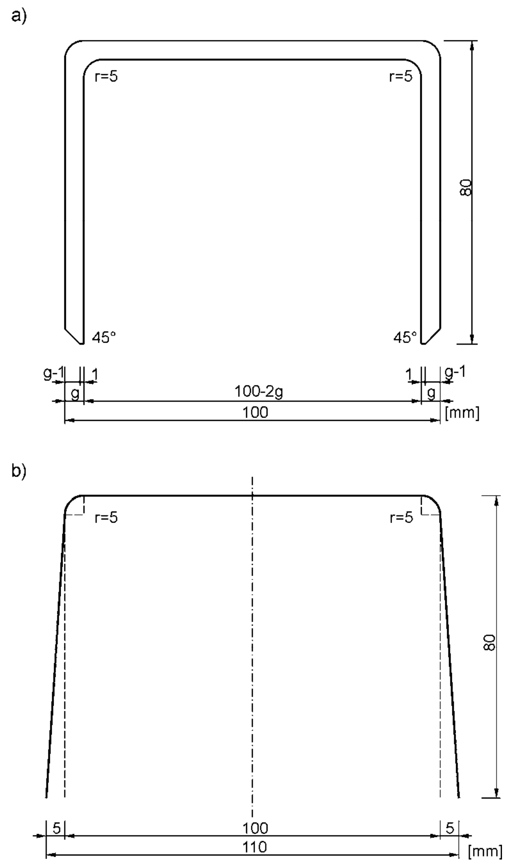


Fig. 1. U-type composite segment

Rys. 1. Segment kompozytowy typu U

TABLE 1. **U-type composite segments variants**

TABELA 1. **Warianty segmentów kompozytowych typu U**

Code	Stacking sequence	Ply angles	g [mm]	f_m [%]
LE1	4 x D-610	$[90]_4$	2.40	56.4
LE2	6 x D-610	$[90]_6$	3.51	61.2
LE3	8 x D-610	$[90]_8$	4.54	64.3
LE4	4 x CD-600	$[0/90]_4$	3,34	47.9
LE5	6 x CD-600	$[0/90]_6$	4.51	48.4
LE6	8 x CD-600	$[0/90]_8$	6.55	48.3
LE7	2 x CDDB-1200	$[0/45/90/-45]_2$	2.09	62.8
LE8	3 x CDDB-1200	$[0/45/90/-45]_3$	3.32	61.1
LE9	4 x CDDB-1200	$[0/45/90/-45]_4$	4.53	63.3

EXPERIMENTAL STATIC TESTING OF U-TYPE COMPOSITE SEGMENTS ENERGY ABSORPTION

Static experimental tests were performed on an SATEC 1200 testing machine with parallel pressure force and punch displacement registration (kinematic excitation at a traverse velocity of 2 mm/min). The failure processes were recorded using a PHANTOM v12 video camera. The tests were performed on LE1, LE2, LE4, LE5, LE7, LE8 segments of 400 mm length and on LE3, LE6, LE9 segments of 200 mm length. For the latter segments, the values of pressure force and absorbed energy were multiplied by 2 in order to compare the results for all the variants.

As mentioned before, the tests were performed on the specially developed test stand depicted in Figure 2, where 5 composite panels can be placed in parallel. Resistance angle bars were connected to the bottom plate with M8 bolts.

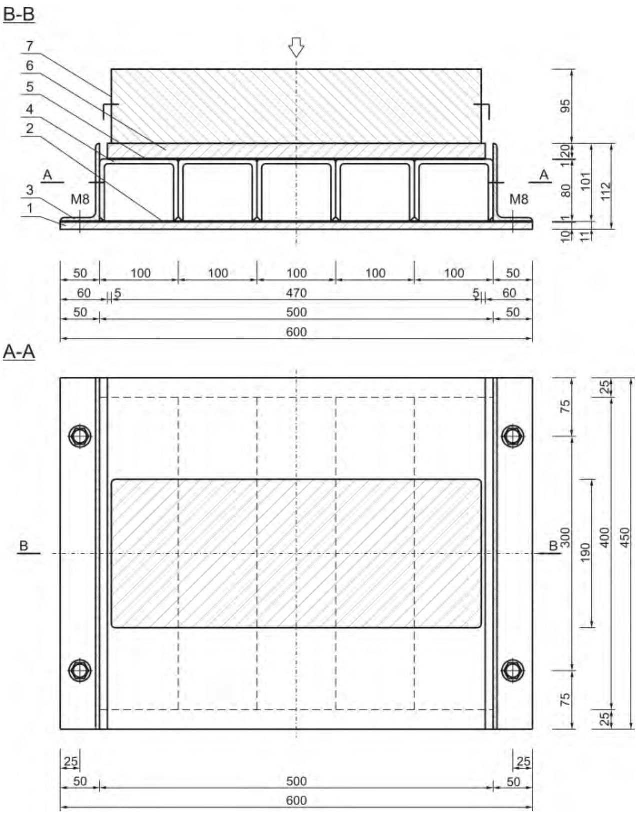


Fig. 2. Test stand for U-type segments energy absorption static experiments: 1 - bottom plate St3, 600 x 450 x 10 mm; 2 - aluminium plate 600 x 450 x 1 mm; 3 - angle bar L 100x50x5 mm, l = 450 mm (x2); 4 - U-type segments, l = 400 mm,(x5); 5 - aluminium plate 480 x 450 x 1 mm; 6 - pressure plate St3, 480 x 450 x 20 mm, 7 - SATEC machine punch, 470 x 190 x 95 mm

Rys. 2. Stanowisko do badań statycznych energochłonności segmentów typu U: 1 - płyta dolna St3, 600 x 450 x 10 mm; 2 - blacha aluminiowa 600 x 450 x 1 mm; 3 - kątownik L 100x50x5 mm, *l* = 450 mm, szt. 2; 4 - segmenty typu U, *l* = 400 mm, szt. 5; 5 - blacha aluminiowa 480 x 450 x 1 mm; 6 - płyta dociskowa St3, 480 x 450 x 20 mm, 7 - stempel trawersy maszyny SATEC, 470 x 190 x 95 mm

The static tests of energy absorption of U-type segments focussed on the quasi-optimal stacking sequence and laminate thickness selection. In order to perform such investigations, the following optimization criteria are adopted:

- failure level with respect to the following mechanisms: progressive crash, delamination failure, buckling failure, catastrophic failure,
- maximum relative energy absorption.

Figure 3 depicts the compression force versus punch displacement curves for segments reinforced with D-610 fabric. Figures 4, 5 illustrate the LE1 and LE3 segments failure mechanisms during compression tests at selected punch displacement values *s*.

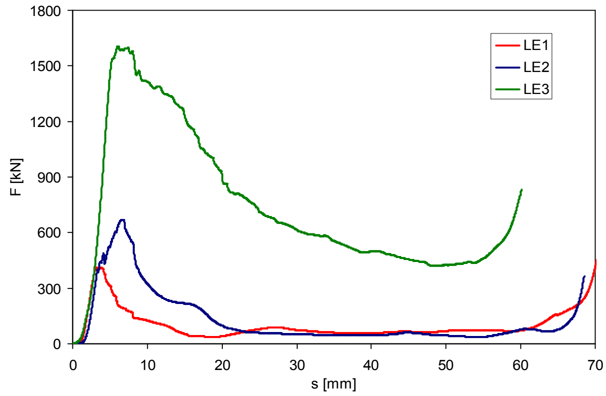
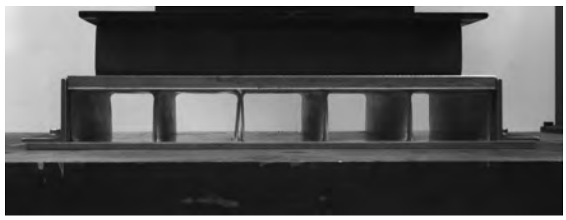


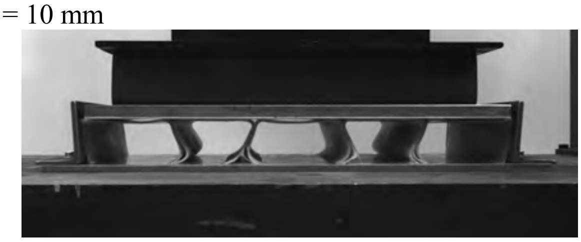
Fig. 3. Compression force vs. punch displacement curves for U-type segments reinforced with D-610 uniaxial fabric (LE1, LE2, LE3 variants)

Rys. 3. Przebiegi siły ściskającej w funkcji przemieszczenia stempla (*F-s*) dla 5 segmentów kompozytowych typu U wzmocnionych tkaniną jednokierunkową D-610 (warianty LE1, LE2, LE3)

$s = 0$



$s = 10$ mm



$s = 30$ mm

$s = 50$ mm

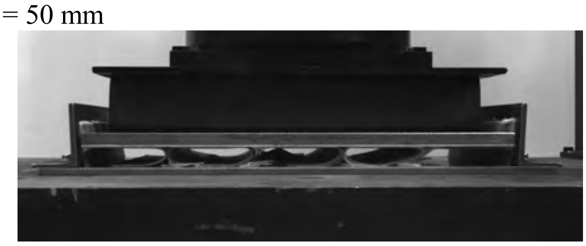


Fig. 4. Photographs illustrating failure mechanisms during energy-absorption test performed on U/LE1 segments

Rys. 4. Zdjęcia ilustrujące mechanizmy niszczenia podczas próby badania energochłonności segmentów typu U/LE1

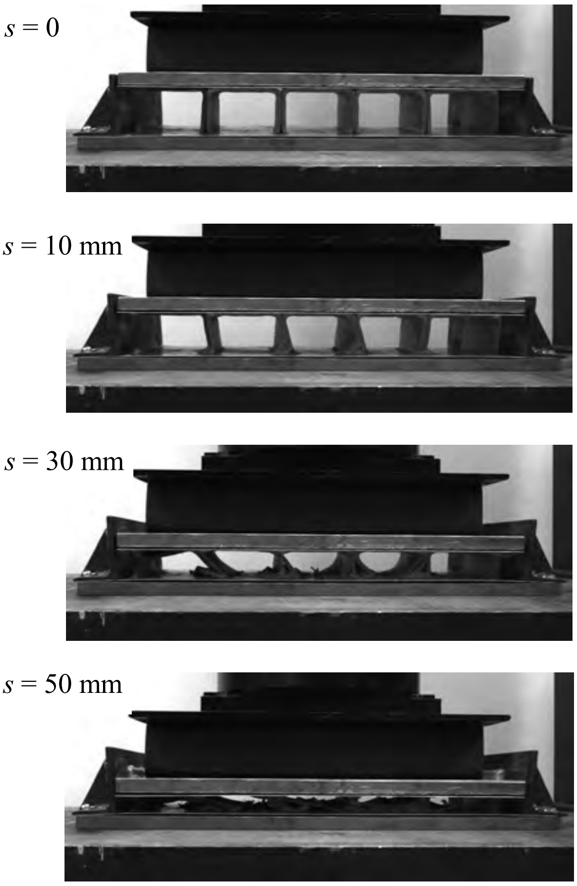


Fig. 5. Photographs illustrating failure mechanisms during energy-absorption test performed on U/LE3 segments

Rys. 5. Zdjęcia ilustrujące mechanizmy niszczenia podczas próby badania energochłonności segmentów typu U/LE3

Figure 6 depicts the compression force versus punch displacement curves for segments reinforced with CD-600 biaxial fabric. Figures 7, 8 illustrate the LE4 and LE6 segments failure mechanisms during compression tests at selected punch displacement values *s*.

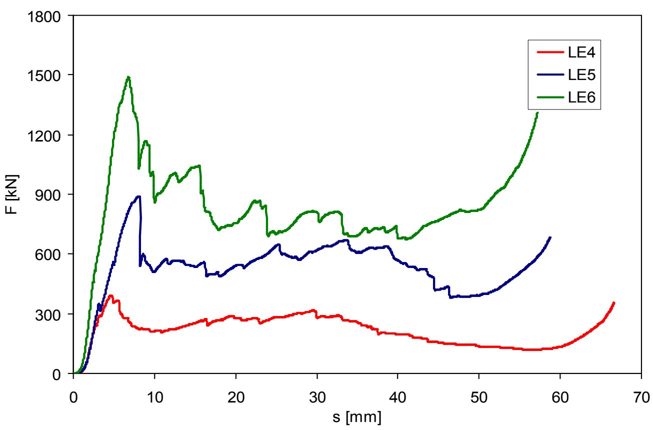


Fig. 6. Compression force vs. punch displacement curves for U-type segments reinforced with CD-600 biaxial fabric (LE4, LE5, LE6 variants)

Rys. 6. Przebiegi siły ściskającej w funkcji przemieszczenia stempla (*F-s*) dla 5 segmentów kompozytowych typu U wzmocnionych tkaniną dwukierunkową CD-600 (warianty LE4, LE5, LE6)

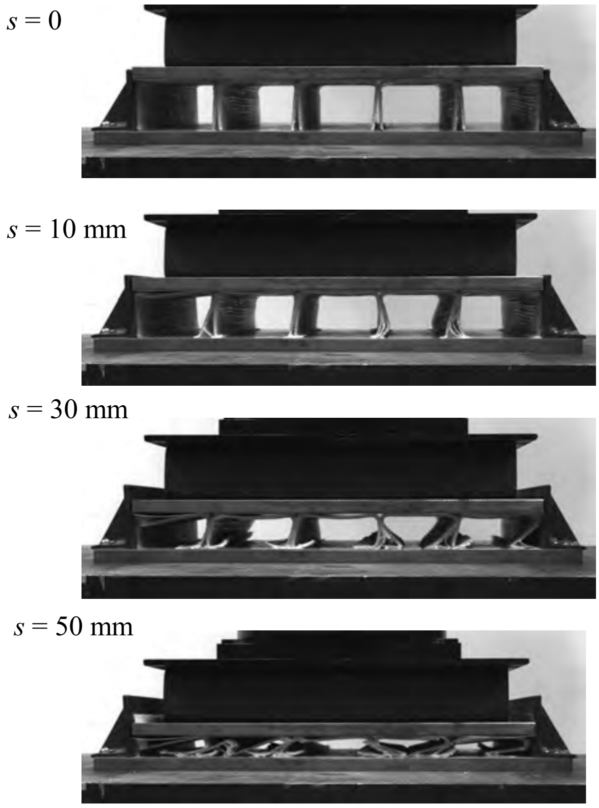


Fig. 7. Photographs illustrating failure mechanisms during energy-absorption test performed on U/LE4 segments

Rys. 7. Zdjęcia ilustrujące mechanizmy niszczenia podczas próby badania energochłonności segmentów typu U/LE4

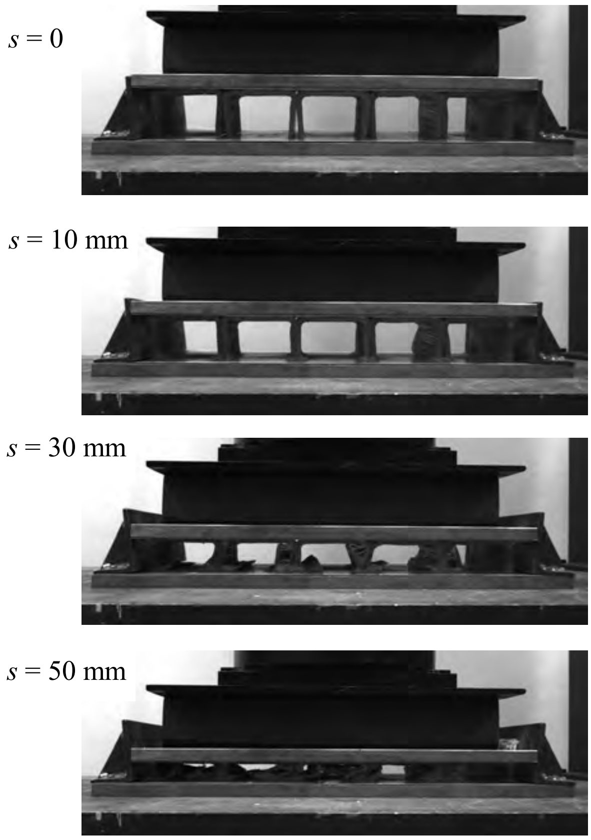


Fig. 8. Photographs illustrating failure mechanisms during energy-absorption test performed on U/LE6 segments

Rys. 8. Zdjęcia ilustrujące mechanizmy niszczenia podczas próby badania energochłonności segmentów typu U/LE6

Finally, Figure 9 depicts the compression force versus punch displacement curves for segments reinforced with CDDB-1200 quadriaxial fabric. Figures 10, 11 illustrate the LE7 and LE9 segments failure mechanisms during compression tests at selected punch displacement values *s*.

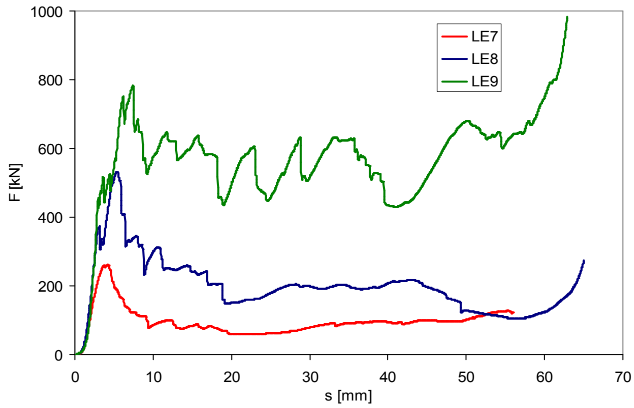


Fig. 9. Compression force vs. punch displacement curves for U-type segments reinforced with CDDB-1200 quadriaxial fabric (LE7, LE8, LE9 variants)

Rys. 9. Przebiegi siły ściskającej w funkcji przemieszczenia stempla (*F*-*s*) dla 5 segmentów kompozytowych typu U wzmocnionych tkaniną czterokierunkową CDDB-1200 (warianty LE7, LE8, LE9)

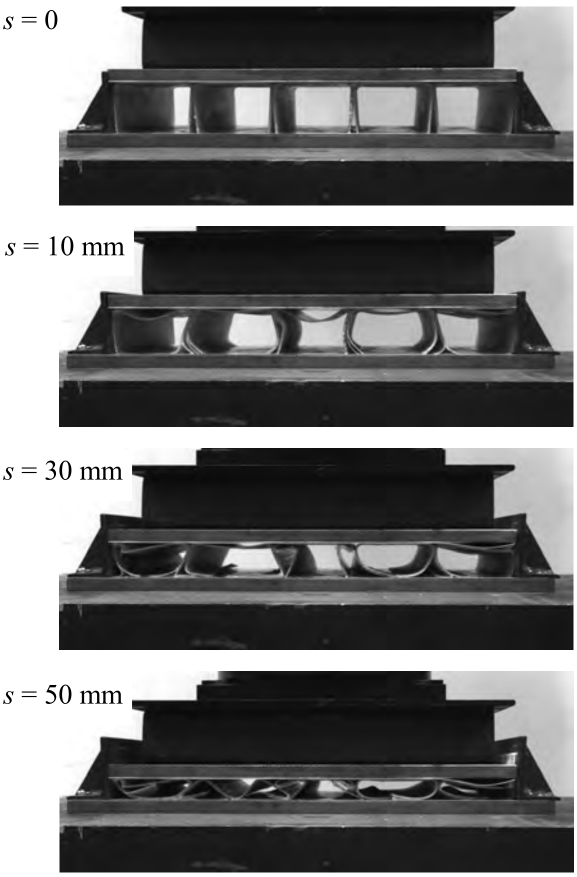


Fig. 10. Photographs illustrating failure mechanisms during energy-absorption test performed on U/LE7 segments

Rys. 10. Zdjęcia ilustrujące mechanizmy niszczenia podczas próby badania energochłonności segmentów typu U/LE7

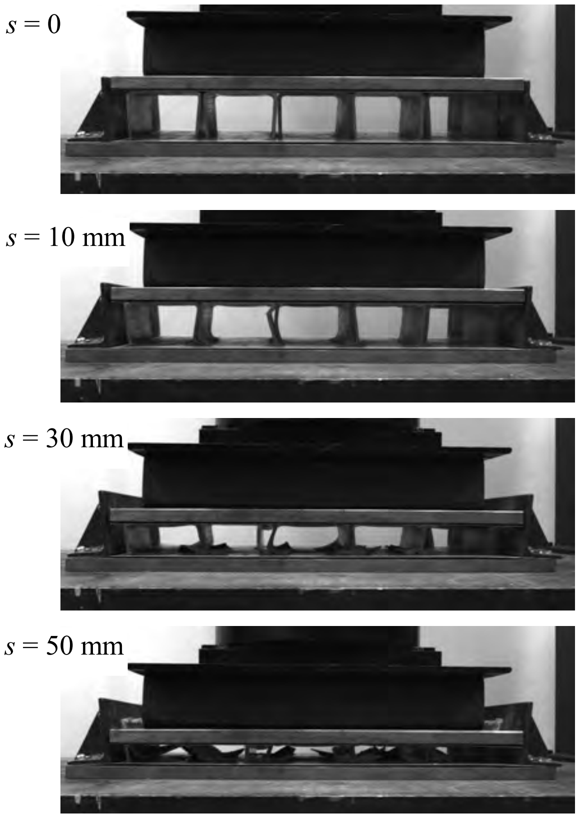


Fig. 11. Photographs illustrating failure mechanisms during energy-absorption test performed on U/LE9 segments

Rys. 11. Zdjęcia ilustrujące mechanizmy niszczenia podczas próby badania energochłonności segmentów typu U/LE9

Table 2 collects the maximum values of compression force F_{max} initiating the failure processes, absorbed energy E_a and absorbed relative energy e_a for the sets of five composite segments of 400 mm length. The energy values correspond to the punch displacement interval 0÷50 mm. The action levels of the failure mechanisms in reference to the considered glass-polyester segments are collected in Table 3 using the following notations:

- PC - progressive crash (at compression and bending)
- DF - delamination failure
- SF - stability failure
- CF - catastrophic failure

TABLE 2. **Basic numerical results for U-type composite panels static energy absorption experimental tests**

TABELA 2. **Główne wyniki numeryczne prób statycznych energochłonności paneli kompozytowych typu U**

Laminate code	F_{max} [kN]	E_a(s = 50 mm) [kJ]	e_a(s = 50 mm) [kJ/kg]
LE1	413	4.6	2.1
LE2	671	7.4	2.4
LE3	1607	39.3	9.6
LE4	392	11.6	4.5
LE5	890	26.7	7.0
LE6	1473	42.0	8.1
LE7	262	4.7	2.4
LE8	533	10.9	3.6
LE9	983	26.7	6.9

TABLE 3. **Failure mechanisms action levels for U-type composite panels**
TABELA 3. **Poziomy działania mechanizmów niszczenia paneli kompozytowych typu U**

Code	Failure mechanisms			
	PC	DF	SF	CF
LE1	low	medium	high	medium
LE2	low	low	high	medium
LE3	high	low	low	low
LE4	low	low	high	high
LE5	high	low	low	low
LE6	medium	high	low	high
LE7	lack	lack	high	low
LE8	lack	medium	high	low
LE9	high	lack	low	medium

Analysis of experimental energy-absorption tests

The energy-absorption test stand developed in the study functioned correctly. The SATEC machine punch has a translational vertical degree-of-freedom only. The 20 mm thick upper pressure plate is practically a rigid body compared to the composite panels. The geometric-material properties and configuration of the punch, the upper pressure plate, the panels, and the boundary angle bars ensure quasi-uniform and quasi-symmetric degradation of a set of five panels. This statement is confirmed by the experimental results shown in Figures 4, 5, 7, 8, 10, 11. The upper and lower sheet aluminium protected friction resistance minimization during the crash tests.

The U-type composite panels developed in the study constitute a systematic system in reference to stacking sequence and laminate thickness. Three types of stitched E-glass fabrics produced by Owens Corning Co. have been used and the research experience from previous studies [1-8], particularly in reference to relative laminate thickness has been adopted as well. The LE1, LE2, LE3 panels are reinforced with uniaxial fabric (weft fibres). The LE4, LE5, LE6 are cross-ply laminates. The LE7, LE8, LE9 panels are reinforced with quadriaxial fabric, thus they have increased resistance to shear.

Panels LE1 occurred to be too slender, thus they were destroyed according to the SF failure mechanism. The thickest panels in this subgroup, LE3, were destroyed according to the preferable PC mechanism and are characterized by the highest relative energy absorption. Moreover, the *F-s* characteristic for the LE3 panel reflects the typical blast shock wave pressure diagram.

The cross-ply LE4 panels have dominant SF and CF failure mechanisms resulting in a low level of energy absorption. The LE5 panel behaviour is similar to that of the LE3 but the relative energy-absorption of the LE5 is lower. Increasing thickness in the form of LE6 panels negatively influences destruction; DF and CF failure mechanisms are dominant.

The LE7 and LE8 composite panels reinforced with quadriaxial fabric are also too slender. Higher energy-absorption with a dominant PC mechanism appeared in the LE9 panel but the relative energy-absorption is lower by 28% compared to LE3 panels.

Taking into account the results of the energy absorption analysis, it is concluded that segments U/LE3 constitute the quasi-optimal solution of energy-absorbing glass-polyester U-type panels. The relative energy-absorption for these panels equals 9.6 kJ/kg for a crash length of 50 mm.

CONCLUSIONS

The study presents the results of energy absorption static experimental tests of U-type (channel section) composite segments for 9 variants of stacking sequence and laminate thickness. For the thicker segments LE3, LE6, LE9 - the SATEC compression force range of 1200 kN was exceeded. These segments had to be twice shorter than the other segments and the results were multiplied by 2 in order to compare all the variants.

Due to the contact technology used in the manufacturing of the segments, the channel beam webs were slightly thicker and some geometrical imperfections occurred on the channel flanges. Therefore, Table 2 contains the average thickness of the channel flanges.

For further dynamic investigation, LE3-type segments are recommended. These energy-absorbing segments have an 8xD-610 stacking sequence and $[90]_8$ ply angles. The segments are characterized by the highest relative energy absorption, dominant progressive crash and failure curve *F-s* adjusted to a typical blast pressure impulse.

Aknowledgements

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