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COMPOSITES THEORY AND PRACTICE

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INFLUENCE OF LOADING RATE ON ENERGY ABSORPTION PERFORMANCE OF EPOXY COMPOSITES REINFORCED WITH GLASS FABRIC

The article deals with the problem of investigating the correlations between the loading rate and absorbed energy capability dependence of composite energy absorbing structures. Energy absorbing structures dissipate impact kinetic energy by means of crushing their structure. Numerous investigations have been conducted to evaluate the dependence between the loading velocity and Energy Absorbed (*EA*) for composites, however, the results are quite different and sometimes inconsistent. The material properties defined during static tests are possible to be applied at the initial stage of numerical calculations. More advanced and accurate target simulations require data from dynamic load tests. Single energy absorbing elements and three-element energy absorbing structures were subjected to static and dynamic investigations. The single energy absorbing elements were tube-shaped and built of epoxy composites reinforced with glass fabric. Fragments of sandwich energy absorbing composite elements were prepared from three tube elements arranged symmetrically on an equilateral triangle plan and stuck between composite plates. Static and dynamic energy absorbing tests were conducted. The specimens were loaded statically on a tension machine - Instron 8802. The specimens were compressed at a constant load velocity equal to 40 mm/min (0.0007 m/s). The dynamic tests were performed on a spring impact hammer. The impact load velocity was about 6.0 m/s. Based on the obtained results, it was concluded that the load velocity of a glass/epoxy composite specimen crush leads to an *EA* decrease. B The behaviour of both single energy absorbing elements and multi-element fragments of energy absorbing constructions was compared.

Keywords: **mechanical properties, absorbed energy, polymer composites, dynamic investigations, experimental mechanics**

WPŁYW PRĘDKOŚCI OBCIĄŻENIA NA ZDOLNOŚĆ POCHŁANIANIA ENERGII KOMPOZYTÓW EPOKSYDOWYCH WZMACNIANYCH TKANINĄ SZKLANĄ

W pracy zbadano energochłonność kompozytów polimerowych wzmacnianych tkaniną szklaną w warunkach obciążeń dynamicznych i statycznych. Porównano zachowanie pojedynczych elementów energochłonnych i kilkuelementowych fragmentów konstrukcji energochłonnych. W licznych pracach przedstawionych w literaturze poświęconej tej tematyce podano wyniki badań wpływu prędkości na EA, jednak uzyskane w nich wyniki nie są jednoznaczne. W niektórych pracach stwierdzono, że EA nie zależy od prędkości uderzenia, natomiast w innych pracach - że EA rośnie lub maleje wraz ze wzrostem prędkości. Konstrukcje energochłonne ze swej natury narażone są na obciążenia udarowe. Pochłanianie energii uderzenia polega na zamianie ujemnego przyrostu energii kinetycznej impaktu na pracę niszczenia konstrukcji energochłonnej. W obliczenia numerycznych wymagane są dane materiałowe pozwalające na obliczenie zachowania się konstrukcji energochłonnej podczas obciążeń udarowych. W pierwszej fazie obliczeń można wykorzystać właściwości określone na podstawie badań statycznych, jednak w docelowych opracowaniach powinien znaleźć się model odzwierciedlający zachowanie się kompozytu w warunkach obciążeń dynamicznych. Badaniom statycznym i dynamicznym w zakresie prędkości obciążenia od 0,0007 do 6,0 m/s poddano pojedyncze elementy energochłonne i fragmenty przekładkowych konstrukcji energochłonnych. Materiałem próbek był kompozyt polimerowy z żywicy epoksydowej wzmacniany tkaniną szklaną o strukturze $[(0/90)_T]_n$. Pojedyncze elementy energochłonne wykonane zostały w postaci rurek o średnicy wewnętrznej 40 mm. Fragmenty przekładkowych konstrukcji energochłonnych złożono z trzech elementów energochłonnych rozłożonych symetrycznie na planie trójkąta równobocznego i przyklejonych pomiędzy przekładkami wykonanymi z płyt kompozytowych. Eksperymenty wykonano na dwóch stanowiskach badawczych. Energochłonne badania statyczne przeprowadzono na maszynie wytrzymałościowej z napędem hydraulicznym Instron 8802. Próbki były ściskane ze stałą prędkością obciążenia wynoszącą 40 mm/min. (0,0007 m/s). Badania dynamiczne przeprowadzono na sprężynowym młocie udarowym. Prędkość początkowa uderzenia wynosiła 6,0 m/s. Na podstawie otrzymanych wyników badań eksperymentalnych stwierdzono, że wzrost prędkości niszczenia próbek kompozytowych powoduje spadek energii absorbowanej w przedziale prędkości od 0,0007 do 6,0 m/s. Zarówno pojedyncze elementy energochłonne, jak również struktury energochłonne zachowują się podobnie. Energia absorbowana maleje wraz ze wzrostem prędkości obciążenia. Wyniki badań zostaną wykorzystane do budowy modelu numerycznego panelu ochronnego przeciw uderzeniom pociskami rakietowymi i minami.

Słowa kluczowe: **właściwości mechaniczne, energia absorbowana, kompozyty polimerowe, badania dynamiczne, mechanika doświadczalna**

INTRODUCTION

Energy absorbing structures are potentially subjected to impact load. The kinetic energy of an impact is changed into the work of structure failure. The finite element method (FEM) requires material data enabling the calculation of behaviour of an energy absorbing structure during impact loads. Polymer composites are widely used in the production of energy absorbing elements due to their low density and high energy absorption to mass ratio. The properties of these materials are strain rate dependent. The material properties defined during static tests are possible to be applied at the initial stage of numerical calculations, while more advanced and accurate target simulations require data from dynamic load tests.

The literature includes numerous papers presenting investigations of the influence of the loading rate on the energy absorption capability of composites. However, the obtained results do not reveal unequivocal conclusions. In some cases the loading rate does not influence the *EA*, in other cases a rising loading rate increases or decreases the *EA*. Due to the elastoplastic properties of polymer composites, their mechanical properties (tensile strength, compression strength, elastic modulus) are strongly influenced by the loading rate.

Table 1 presents selected case studies of the influence of the loading rate on the energy absorption capability of epoxy composites reinforced with glass fabric (G/E).

TABLE 1. **Literature review of energy absorption behaviour of epoxy composites reinforced with glass fibres in different loading rate conditions**

TABELA 1. **Zestawienie przeglądu literaturowego wpływu prędkości obciążenia na energię absorbowaną kompozytów epoksydowych wzmacnianych włóknami szklanymi**

Composite	Shape and reinforcement type	Reinforcement structure	Loading rate	EA growth [kJ] in [%]	Literature
G/E	Tubes, roving	$[0/\pm\theta^o]_4$	Static-dynamic	0.0	[1]
G/E	Ring- and square-cross section tubes	different	Static-dynamic	0.0	[2-4]
G/E	Tubes	$[0_2/\pm45_9]$	static and 5÷6 m/s	-25	[5]
Al+G/E	Aluminium tubes wrapped with composite	$[15^o]_n$, $[\pm45^o]_n$, $[90^o]_n$ (n = 3 and 6 plies)	static and 5.5 m/s	+10.3÷ 14.5	[6]
G/E	Composite structures	[0/90°]	static and 8.5 m/s	increases	[7]
G/E	Composite tubes	different	0.00033÷4 m/s	+20	[8]

Al - aluminium
G/E - glass/epoxy composite

It was verified that the absorbed energy drops along with the growth of the loading rate [5]. An increase of absorbed energy was documented in [7, 8]. In most of the reported cases, the loading rate does not influence the energy absorption capability of composites [1-4]. It should be underlined that the authors of the above analysed papers dealt with different structures of a given composite, namely: the number of plies, fibre direction, fibre types (roving, fabric) and epoxy resin type. Additionally, insufficient data describing the applied composites hinder comparative analysis of the results.

It can be concluded that there is no general rule regarding composite behaviour in dynamic load conditions compared to static loads. Each type of composite structure requires a separate series of energy absorbing investigations with additional consideration of specific target applications, particularly: the expected loading rate range, work temperature, etc.

The main object of the research is to determine the relation between the loading rate and energy absorption for a given composite (glass/epoxy). A single energy absorbing element versus a three-element energy absorbing structure is being investigated. The results are intended to develop a numerical model of a protective panel against projectiles and mines.

RESEARCH DESCRIPTION

The article presents the results of experimental tests of the influence of impact velocity on the energy absorption capability of epoxy composites reinforced with glass fabric $[(0/90°)_T]_n$ (fabric fibres oriented at 0° and 90° in respect to the specimen axis). Epidian E53 resin and glass fabric STR-012-350-110 (made by Krosglass company) with a density of 350 g/m^2 were used in the investigated composites.

A single energy absorbing element and a three-element energy absorbing structure were subjected to static and dynamic investigations in the research. Single energy absorbing elements were built in the shape of tubes of 40 mm diameter, 38 mm high and various wall thicknesses. Fragments of sandwich energy absorbing composite elements were prepared from three tube-shaped energy absorbing elements arrayed symmetrically on an equilateral triangle plan and stuck between composite plates of a structure identical to one of the tubes. An initiator, in the form of 45° chamfering, defining the place of failure initiation and preventing unpredictable catastrophic crush, was placed on one of the edges of each tube. Figure 1 presents the scheme of a single tube which can be compared to the fragment of sandwich energy absorbing composite structure shown in Fig. 2a. The detailed scheme of a tree-element structure is presented in Figs. 2b and c. The specimens were tested in two types of testing beds with a load velocity in the range of 0.0007 to 6.0 m/s.

Static energy absorbing tests were performed on a tension machine - Instron 8802. The specimens were compressed at a constant load velocity equal to 40 mm/min. (0.0007 m/s). The machine recorded the displacement of the compressing head and crush force. On the basis of these data, the graphs of crush force in the function of specimen shortening were outlined.

Dynamic energy absorbing tests were performed on a spring impact hammer of the authors' own production (in the range up to 17 kJ). The impact velocity amounted to 4.5÷6 m/s and resulted from the arrangements of the impact hammer (spring compression degree) corresponding to the predicted impact energy required to crush the composite structure. The graphs of crush force in the function of specimen shortening were obtained.

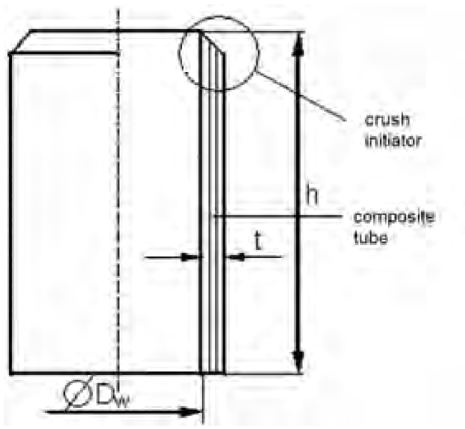

Fig. 1. Scheme of single energy absorbing element in shape of tube

Rys. 1. Schemat pojedynczego kompozytowego elementu energochłonnego w kształcie rurki

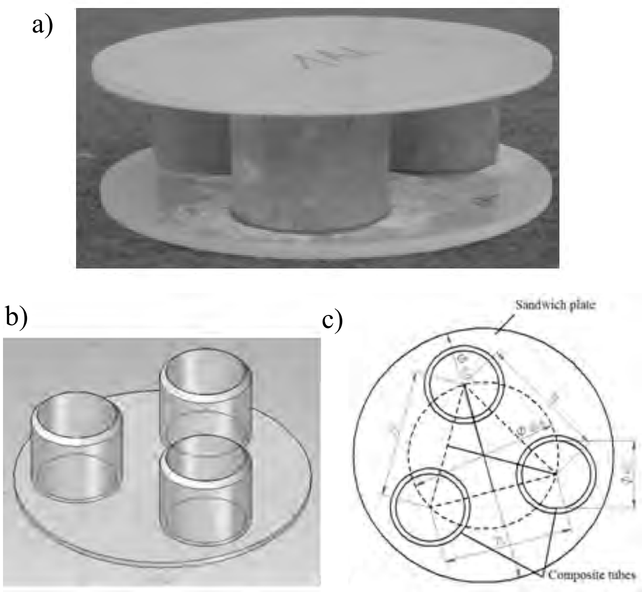

Fig. 2. Fragment of energy absorbing structure made of three composite tubes (a), isometric view (b) and scheme of tube elements arrangement onequilateral triangle plan (c)

Rys. 2. Fragment konstrukcji energochłonnej wykonany z trzech rurek kompozytowych (a), obraz izometryczny (b) i schemat trzech rurek ułożonych na planie trójkąta równobocznego (c)

RESEARCH RESULTS

Absorption energy (*EA*) was calculated with the use of numerical integration of the field under the force-displacement graph. The integration step was constant and resulted from the sampling frequency. The *EA* was calculated from the following formula:

$$EA = \int_0^l P dl = \sum_{i=1}^{n} \frac{(P_i + P_{i+1})}{2}(l_{i+1} - l_i) \tag{1}$$

where: P - crushing force, l - specimen shortening, index i - measurement sampling number.

The EA_{30} quantity presents a proportional energy value which would be absorbed by a specimen on a 30 mm crushing distance (specimen shortening):

$$EA_{30} = \frac{EA}{\Delta l} 30 \tag{2}$$

The 30 mm shortening distance is a fixed value which was assumed based on the results from dynamic tests where different values of specimen shortening were achieved. The results of EA_{30} obtained in dynamic tests were compared to the results obtained during static tests.

Initial impact velocity v_{imp} was obtained by the numerical integration of displacement versus time data taken from a laser displacement measurement device.

The energy absorption capability tests results for single energy absorbing elements are presented in Table 2. These results are average values from three tests carried out for each type of sample. The subsequent columns in the Table present: initial impact velocity v_{imp}, specimen thickness t, maximal shortening of the specimen Δl, maximal force P_{max}, average force P_{aver}, absorbed energy EA (1), energy absorbed proportionally on a 30 mm distance EA_{30} (1). In the last column, the ΔEA percentage increase between the energy absorbed by the current specimen and the reference specimen investigated in the static tests was placed.

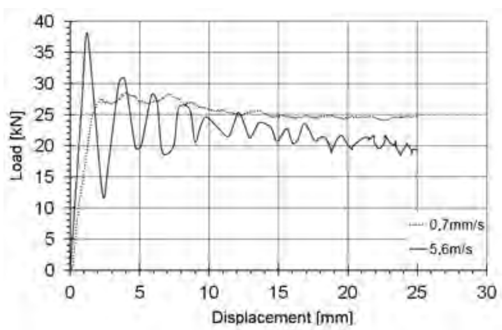

Fig. 3. Comparison of load versus displacement dependence for single tubes investigated in static and dynamic tests

Rys. 3. Rzut izometryczny (a) i schemat rozmieszczenia rurek kompozytowych na planie trójkąta (b)

The graph of the load versus displacement dependence for 2.5 mm thick tubes investigated in the static and dynamic tests is presented in Figure 3. It was recorded that the average force during failure progress for the dynamic tests was lower than in the case of the static ones. The detailed results are presented in Table 2. In the case of a specimen of 1.5 mm thickness, an average load of 11.0 kN was recorded during the static tests, while 10.2 kN was recorded for a dynamically crushed specimen. The thicker specimens crushed with an average static force of 24.8 kN. The dynamic force was equal to 22 kN. An EA_{30} decrease ranging from 6.8% for thin tubes to 11.2% for thicker tubes was noted.

TABLE 2. **Results for single-tube energy absorbing elements**
TABELA 2. **Wyniki badań pojedynczych elementów energochłonnych**

v_{imp}	t	Δl	P_{max}	P_{aver}	EA	EA_{30}	ΔEA_{30}
[m/s]	[mm]	[mm]	[kN]	[kN]	[kJ]	[kJ]	[%]
0.0007	1.5	30.0	12.7	11.0	0.33	0.33	-
4.5	1.5	28.3	17.1	10.2	0.29	0.31	-6.8
0.0007	2.5	30.0	28.5	24.8	0.74	0.74	-
6.0	2.5	28.3	37.9	22.0	0.62	0.66	-11.2

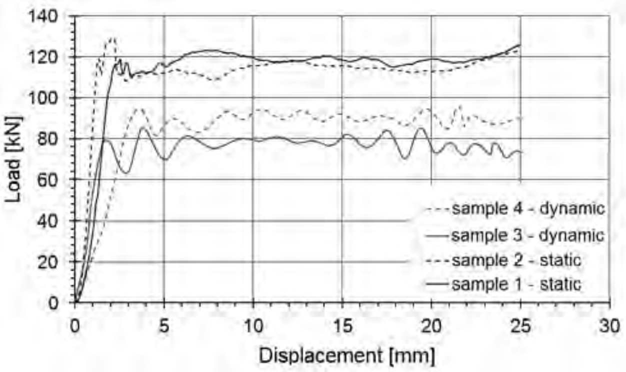

Fig. 4. Comparison of load versus displacement dependence for three-element energy absorbing composite specimens loaded statically and dynamically

Rys. 4. Porównanie krzywych siła-przemieszczenie dla pojedynczych elementów energochłonnych badanych statycznie i dynamicznie

The comparison of load versus displacement dependence for the three element energy absorbing structures crush with static and dynamic load is presented in Figure 4. It shows that the static force is clearly higher than the dynamic load, which results in a lower absorbed energy obtained from the dynamic tests. The detailed results are compared in Table 3. The average values for the static and dynamic investigations were calculated. The symbols are defined identically as in the case of Table 2. The ΔEA percentage difference between the energy absorbed by the current specimen and the specimen loaded statically is presented in the last column.

The energy absorbing elements investigated with the 0.0007 m/s loading rate obtained an average force equal to 111.8 kN. The absorbed energy EA_{30} is equal to 3.35 kJ. The same structures loaded dynamically with an initial velocity of about 10.7 m/s were crushed with an average load of 74.1 kN. The EA_{30} amounts to 2.2 kJ and is 34.3% lower than the corresponding static EA_{30}.

TABLE 3. **Results for three-element energy absorbing elements**
TABELA 3. **Wyniki badań trójelementowych fragmentów konstrukcji energochłonnych**

v_{imp}	t	Δl	P_{max}	P_{aver}	EA	EA_{30}	ΔEA_{30}
[m/s]	[mm]	[mm]	[kN]	[kN]	[kJ]	[kJ]	[%]
0.0007	3.0	25.0	126.0	112.4	2.8	3.4	-
0.0007	3.0	25.0	129.4	111.2	2.8	3.3	-
Aver.	**3.0**	**25.0**	**127.7**	**111.8**	**2.8**	**3.35**	**-**
9.8	3.0	26.4	98.6	66.6	1.8	2.0	-40.3
11.7	3.0	24.4	114.5	70.3	1.7	2.1	-37.3
10.3	3.0	28.5	85.6	74.3	2.1	2.2	-34.3
11.1	3.0	31.2	95.4	85.1	2.6	2.5	-25.4
Aver.	**3.0**	**27.6**	**98.5**	**74.1**	**2.1**	**2.2**	**-34.3**

Figure 5 shows pictures of the crushed single-tube specimens investigated in both static tests (picture a) and dynamic tests (Fig. 5b), while Figure 6 presents pictures of the three-element specimens after the investigations in the same conditions. All the specimens were crushed progressively through layer bending and crushing inside and outside the tubes.

a) b)

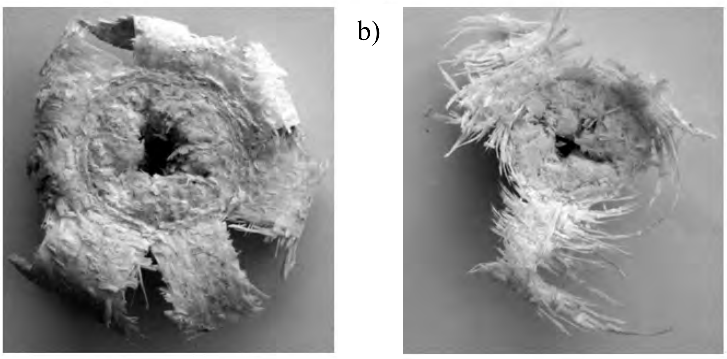

Fig. 5. View of crushed single tubes investigated in: a) static tests, b) dynamic tests

Rys. 5. Porównanie krzywych siła-przemieszczenie dla trójelementowych konstrukcji energochłonnych badanych statycznie i dynamicznie a)

b)

Fig. 6. View of crushed three-element structures investigated in: a) static tests, b) dynamic tests

Rys. 6. Widok zniszczonych pojedynczych rurek badanych: a) statycznie, b) dynamicznie

SUMMARY

Energy absorbing tests were performed in static and dynamic loading conditions. The energy absorbed both by a single energy absorbing element and a structure consisting of several elements was determined.

Based on the results obtained from the experimental investigations, it was verified that:

- The increase of load velocity in the range of 0.0007 to 6.0 m/s for epoxy composites reinforced with glass fabric results in a drop of energy absorption capability.
- Both single- and multi-element energy absorbing constructions behave similarly. In the case of multi-element specimens, the *EA* drop is greater because of the higher load velocity than in the case of single tubes, which can be explained by the two times higher load velocity.

The material data for the FEM model of an energy absorbing protective panel against projectiles and mines were prepared.

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