PENETRATION RESISTANCE OF COMPOSITE STRUCTURES WITH IMPACT DAMAGES

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Summary

The increasing applicability of structures made of polymer composites in industrial applications requires the investigation of strength parameters of these materials as well as the damage and fracture mechanisms in various conditions. In spite of excellent mechanical properties of such materials, they are characterized by low resistance to impact loading. During such loading these structures are subjected to serious damages, which are often invisible during the inspection of surface, and may propagate intensively until failure. The key importance of impact damages have the composite structures, which are used in marine applications, especially in modern small yachts and boats, where the polymer composites is the fundamental construction material. In the presented study the authors investigate the influence of hydrostatic pressure on the penetration resistance of composite structures after impact loading. The laboratory tests were carried out for a representative group of composite plates. Obtained results confirm that the low-velocity impact loading, even with small impact energy, may cause serious damages and initiate leakages in the composite hulls.

Keywords: composite structures, impact damage, penetration resistance, water leakage test

ODPORNOŚĆ PENETRACYJNA STRUKTUR KOMPOZYTOWYCH Z USZKODZENIAMI UDAROWYMI

Streszczenie

Wzrastająca stosowalność struktur wykonanych z kompozytów polimerowych w aplikacjach przemysłowych wymaga zbadania właściwości wytrzymałościowych tych materiałów oraz mechanizmów uszkadzania i pękania w różnych warunkach. Pomimo wyjątkowych właściwości mechanicznych charakteryzują się one niską odpornością na oddziaływania udarowe. Podczas takich oddziaływań te struktury są narażone na poważne uszkodzenia, które często są niewidoczne podczas inspekcji powierzchni i mogą intensywnie propagować, doprowadzając do zniszczenia. Wiedza o uszkodzeniach udarowych w strukturach kompozytowych ma szczególne znaczenie dla struktur stosowanych w aplikacjach okrętowych, w szczególności we współczesnych jachtach i łodziach, gdzie kompozyty polimerowe stanowią podstawowy materiał konstrukcyjny. W niniejszym opracowaniu autorzy zbadali wpływ ciśnienia hydrostatycznego na odporność penetracyjną struktur kompozytowych po oddziaływaniu udarowym. Testy laboratoryjne przeprowadzone zostały dla reprezentatywnej grupy płyt kompozytowych. Otrzymane wyniki potwierdziły, że oddziaływania udarowe o małej prędkości, nawet z małą energią uderzenia, mogą spowodować poważne uszkodzenia i doprowadzić do przecieków w kadłubach kompozytowych.

Słowa kluczowe: struktury kompozytowe, uszkodzenie udarowe, odporność penetracyjna

1. INTRODUCTION

The development of material processing technologies in past few decades cause the increasing interest to the lightweight polymer composites in various industries and technical applications. These materials are widely used for aircraft and automotive structures as well as for small ships, yachts and boats [1]. Nowadays, many small yachts and boats have composite hulls [1,2] and other elements of constructions, like masts [3,4]. Composites are used also during manufacturing of elements of military patrol boats and small ships [5,6]. The most widespread technology used in design of small boats is lamination, [5] because the large dimensions of hulls of these boats make the application of infusion-based technologies difficult or even impossible to apply.

Despite of excellent mechanical properties of polymer composites, they are sensitive to the impact loading, which often causes internal damages not observable on the surface. For small yachts and boats one of the serious dangers is the possibility of collision with rocks, shipwrecks or another obstacle. Due the impact character, the collision is especially dangerous for the boats with composite hulls. The damage character and size caused by the underwater collision, depends on impact energy, the shape of the impacted body and the type of structure of a composite material used to the construction of the hull. Therefore it is necessary to investigate the behavior of a composite element after the impact loading, especially its resistance to the pressure loading in the damaged area.

There are many test methods used for composite structures for evaluation their performance after impact loading including ultrasonic methods [7], thermography [8,9] and hydroelastic characterization [10]. However, these testing methods do not give enough of valuable information about the watertightness of a tested structure.

One of the possible methods for verification of the watertight, is the water leakage test [11-13]. In this method the measure of damage is the amount of the water, which has penetrated through the composite in the damaged area at a certain time. The water leakage test provides unequivocal information about the degree of penetration of the composite by water at the damaged place by evaluation of the velocity of penetration for the given structure. The disadvantage of this method is the long test duration, which should be performed even up to 8 hours in the case of small damage [11].

The method of water penetration testing of the composites could be developed by the adaptation of the method of watertightness testing of textile materials, which is widely used in textile industry [13-16]. The watertightness test has been described in the European Standard [17]. In this method, the specimen is acted to a constantly increasing hydrostatic pressure. The increase of a pressure is caused by increasing height of the water column pressing on the specimen. The measure of penetration in this method is the height of the liquid column, at which three drops of water in three different places appear on the bottom surface of a tested specimen. The standard provides testing of samples with an area of 100 cm^2 with the increasing pressure of 10 or 60 cm H_2O/min. This method is free from disadvantages of the previous methods, the time of the test in this case, is much shorter.

In the presented study, the method of watertightness testing applied in the textile industry has been adapted for testing of composite structures after impacts. For the purposes of testing of composite structures, the method has been modified. The modifications were related to the surface area of the specimen on which the tests were performed and the speed of increase the liquid column. The measure of penetration resistance of composite structures was the height of the column of liquid at which the leakage has appeared. The tests were performed on the laminated composite plates with artificially induced impact damages of various character, resulted from various geometric properties of impactors and various energies of impact. Results show that the leakages could appear even in the case of small impact energy damages with relatively low pressure amount applied for the surface of a structure. Obtained results were compared with results of numerical and experimental studies concerned with impact damaging of composite hulls of small boats and yachts. Moreover, the nature of low-velocity impact damages occurred during the operation of marine units and possibility of their propagation has been discussed.

2. PREPARATION AND PERFORMING THE TESTS

2.1 SPECIMENS

The tests were performed on the square plates with a side dimension of 300 mm and a thickness of 2.5 mm made of 12-layered polymer glass/epoxy laminate of a type EP GC 201, manufactured and supplied by Izo-Erg S.A. Prior the tests the plates were artificially damaged on the own-designed test rig for the drop weight impact tests (for instance see [18,19]). Using this test rig it was possible to obtain various types of damages (including cracks, delaminations or both) due to application of various types of impactors and various energies of impact. The analysis of influence of impactor type on the resulted damages was presented in [19].

At the initial stage the damaged plates were selected considering the criterion that the damage should be recognizable on top and bottom surfaces of a plate.

Following this, after visual inspection, 19 pre-damaged plates were selected for further analysis. The impactors, were used for the damaging of these plates were presented in Fig.1. Here and further the letters denote the type of impactor. The views of the considered damages can be found in [19]. Some of them were presented in Fig.2.

Fig. 1. Impactors used for inducing damages of the plates

2.2. PENETRATION RESISTANCE TEST

The penetration resistance test presented in this paper was inspired by the studies described in [11-13]. However, due to the specificity of tested structures and character of the impact damages, it was necessary to modify the initial approach presented in the above-cited studies. The applied modification was partially based on the water resistance testing procedure, which is widely applied in the textile industry and regulated by the European Standard [17].

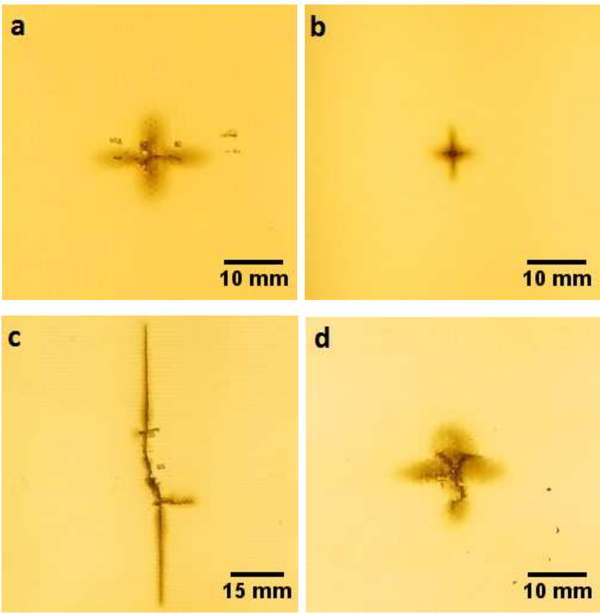

Fig. 2. Exemplary views of the impact damages

The test rig was constructed as follows. Pre-damaged plates were connected with a steel flange, which was connected with a polychlorvinyle pipe of a length of 1 m and diameter of 160 mm. The diameter of a pipe was selected according to the maximal span of cracks in the tested plates. The connections were realized by gluing the mentioned elements using two-component epoxy-based commercial hydraulic mastic. The connected construction was placed on the metallic frame, which allows for observation of a bottom surface of a tested plate. The specimen was oriented in a such way that the pressure of a water column was applied to the impacted surface of a tested structure, which is in agreement with a physical nature of the investigated events. The scheme and a photograph of a test rig was presented in Figs. 3 and 4, respectively.

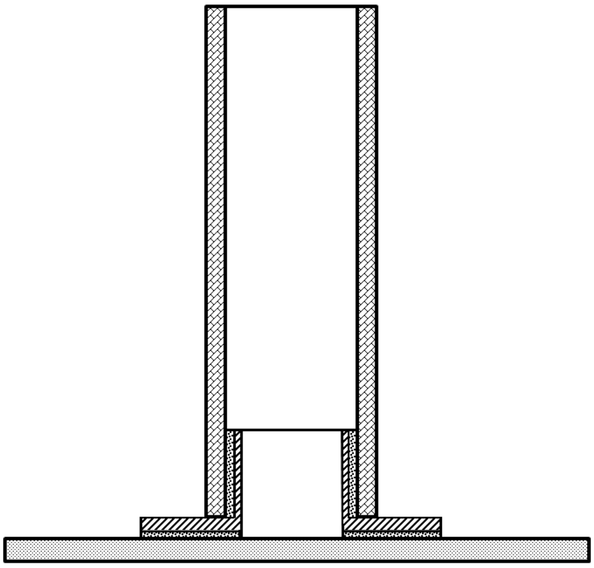

Fig. 3. A scheme of a penetration resistance test rig

Fig. 4. View of the penetration resistance test rig

The penetration resistance of composite structures was tested in the following way. The pipe was filled by water with a capacity of 100 ml. The time interval between the consecutive fillings was 1 min. After every filling the bottom surface of a plate was examined for the formation of a drop (see Fig.5).

Fig. 5. Drop formation in the cracked region on the bottom surface of a plate

Each test was performed until the first drop falls from the bottom surface of a tested plate to the base of a frame. Then the test was stopped and the actual degree of filling was recorded, which is the critical resistance value for a given case of impactor and impact energy.

3. RESULTS AND ANALYSIS

3.1. RESULTS OF PENETRATION RESISTANCE TESTS

Obtained values of critical penetration resistance were transformed into the values of a hydrostatic pressure p following the formula:

$$p = \rho g h\,, \tag{1}$$

where is a density of a liquid, g is a gravitational constant and h is a height of the actual fluid column corresponded with the critical penetration resistance. In this study it was assumed that = 1000 kg/m^3 and g = 9.81 m/s^2. Obtained results were presented in Table 1, where the symbols of tested plates denote the type of impactor (see Fig.1) and the impact energy value (numeral), for instance see [19].

Presented results show that the critical values of penetration resistance are quite small even in the cases when the impact damages are insignificant. In most cases the rapid decrease of a values hydrostatic pressure necessary for penetration of an impacted structure can be observed. The great influence on the critical penetration resistance has also the shape of the end of impactor, i.e. for the round-ended impactors these values were much higher than for conic-ended and arched-ended as well as for impactors with immersed stones.

Table 1. Critical penetration resistance

Symbol of a plate	Capacity, l	Hydrostatic pressure, kPa
E20	12.3	6.001
E30	20.0	9.758
E40	1.3	0.634
H20	7.2	3.513
H30	1.3	0.634
H40	1.2	0.585
I20	7.2	3.513
I30	2.7	1.317
I40	1.8	0.878
K35	7.7	3.757
K40	3.9	1.903
L35	0.7	0.341
L40	0.3	0.146
M15	1.0	0.488
M20	1.6	0.781
M25	3.3	1.610
M30	0.7	0.341
M35	0.6	0.293
M40	0.4	0.195

The simulation of damages caused by the impactors with stones in various orientations and evaluation of the penetration resistance after the impacts has a great importance for the analysis from practical point of view. Due to the irregular shape of impacted bodies it is very difficult to predict the mechanisms of damaging and resulted damages in the structure. With the stone oriented by the vertex in the direction of impact, even small impact energies may cause serious damages in the structure, which could be noticed from the Table 1. In order to analyze the practical meaning of presented study it is necessary to compare the obtained values of hydrostatic pressure corresponded to the critical penetration resistance values (the pressure necessary for occurring the leakage) with typical pressure distributions on the hulls of small boats and yachts.

3.2. ANALYSIS OF LEAKAGES POSSIBILITY IN BOAT AND YACHT COMPOSITE HULLS

Considering the numerical results presented by the authors of [20] for two hulls of boats, it was noticed that the dynamic pressure in the simulated cases does not exceeded 5 kPa. Therefore the damages caused by the impact with hydrostatic pressure lower than the mentioned value could initiate the leakages in the composite hull. Such pressure has been obtained for most tests. It should be mentioned that the typical thickness of such hulls in the case of small boats and yachts often do not exceed the value of 3 mm [21-23]. This is also valid for the sandwich structures used in the manufacturing of yachts, where the face sheets were manufactured as multilayered composites [24-26].

The impact energy amounts, considered during the above-presented study, can be classified to the low-velocity impacts, which, in the case of composite hulls and other elements exposed to the seawater, may cause potential dangers of the structural integrity and safety [27]. Such impact loading can be caused during the collision of a boat or yacht with small objects, e.g. floating debris or ice, and during production, e.g. “tool drops”, or during docking [28,29]. The other potential events, which can influence on the impact resistance of the composite marine structures are the breaking waves interacted with a hull [30] or the strong current, which may contain the debris. All of the mentioned events may cause the low-velocity impact damages, which could initiate the structural degradation and cause growth of undetected cracks and delaminations under service examination.

Considering the experimental results of the long-term tests on various composite structures obtained by Barcikowski [11] the penetration process of a composite structure after impact damaging has an incremental character. Therefore, even in the case when after the initiation of an impact damage the penetration is not observable, the damage may propagate under the influence of the hydrostatic pressure (the long-term exposition) and cause the leakages. This is also related with the case of multiple impact loads of a structure described in [11]. As it was reported, such loading may significantly increase the ability of penetration of a structure.

4. CONCLUSIONS

The presented study deals with a determination of penetration resistance of composite structures after impact loading and dedicated for marine tests of structural integrity and safety. The tests were performed on glass-epoxy composite laminated plates typical for marine structures, which were artificially damaged using various impactors with various energy of impact. The tests were performed using the approach of determination of a critical pressure, which causes the leakage in the damaged area, which was adapted basing on similar tests applied in the textile industry. The results and analyzes of typical practical problems coincided with the impact damaging of hulls of boats and yachts show that even small energy of impact may cause the damage, which initiates water penetration through the structure under the hydrostatic pressure. Moreover, the presented results of analysis show that in the case, when the structure is not interpenetrated directly after impact loading and is exposed to the long-term hydrostatic pressure, the impact damages may propagate, which, in consequence, may cause the initiation of a leakage.

The presented study has an initial character and will be developed in future works in several directions. Due to the great complexity of damaging mechanisms and interpenetration of a liquid under the hydrostatic pressure it is necessary to simulate such damages numerically in order to investigate the ability of penetration for various impact energy amounts and various impacted bodies and then verify the numerical tests experimentally on the larger number of impacted specimens.

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References

1. Klimke J., Rothmann D.: Carbon composite materials in modern yacht building. “Reinforced Plastics” 2010, Vol. 54, p. 24 - 27.
2. Stenius I, Rosén A., Kuttenkeuler J.: On structural design of energy efficient small high-speed craft. “Marine Structures” 2011, Vol. 24, p. 43 - 59.
3. Skórski W.: Maszty kompozytowe – wdrażanie nowej technologii. „Przegląd Mechaniczny” 2001, vol. 60, s. 9-12.
4. Chiliński B., Markuszewski D.: Określanie cech konstrukcyjnych masztów kompozytowych stosowanych w jachtach żaglowych. „Przegląd Mechaniczny” 2013, vol. 72, p. 37 - 39.
5. Mouritza A.P., Gellertb E., Burchillb P., Challisb K.: Review of advanced composite structures for naval ships and submarines. “Composite Structures” 2001, Vol. 53, p. 21 - 42.

6. Mouritz A.P.: The damage to stitched GRP laminates by underwater explosion shock loading. "Composites Science and Technology" 1995, Vol. 55, p. 365 – 374.
7. Raišutis R., Kažys R., Žukauskas E., Mažeika L.: Ultrasonic air-coupled testing of square-shape CFRP composite rods by means of guided waves. "NDT&E International" 2011, Vol. 44, p. 645 - 654.
8. Montanini R., Freni F.: Non-destructive evaluation of thick glass fiber-reinforced composites by means of optically excited lock-in thermography. "Composites: Part A" 2012, Vol. 43, p. 2075 - 2082.
9. Suratkar A., Sajjadi A.Y., Mitra K.: Non-destructive evaluation (NDE) of composites for marine structures: detecting flaws using infrared thermography (IRT. In: Non-Destructive Evaluation (NDE) of Polymer Matrix Composites, Karbhari V.M., Ed., Woodhead Publishing, Cambridge 2013, p. 649 - 667.
10. Stenius I., Rosén A., Battley M., Allen T.: Experimental hydroelastic characterization of slamming loaded marine panels. "Ocean Engineering" 2013, Vol. 74, p. 1 - 15.
11. Barcikowski M.: Wpływ materiałów i struktury laminatów poliestrowo-szklanych na ich odporność na udar balistyczny. PhD Thesis, Szczecin 2012.
12. Królikowski W.: Einige Eigenschaften der mischverstarkten Polyester-Konstruktionsplatten, besonders bei Zug- und Kugelschlag-Beanspruchung. I Internationale Tagung uber Glasfaserverstakte Kunststoffe und Epoxydharze 22-27.03.1965 Berlin-Adlershof, E 4/1-E 4/12.
13. Gibbs & Cox, Inc. Naval Architects and Marine Engineers, Marine design manual for fiberglass reinforced plastics. McGraw-Hill, New York, 1960.
14. Pan C., Shen L., Shang S., Xing Y.: Preparation of superhydrophobic and UV blocking cotton fabric via sol-gel method and self-assembly. "Applied Surface Science" 2012, Vol. 259, p. 110 - 117.
15. Yin Y., Wang C.: Water-repellent functional coatings through hybrid SiO_2/HTEOS/CPTS sol on the surfaces of cellulose fibers. "Colloids and Surfaces A" 2013, Vol. 417, p. 120 - 125.
16. Vo L.T.T., Široká B., Manian A.P., Duelli H., MacNaughtan B., Noisternig M.F., Griesser U.J., Bechtold T.: All-cellulose composites from woven fabrics. "Composites Science and Technology" 2013, Vol. 78, p. 30 - 40.
17. Standard PN-EN 20811:1997. Tekstylia – Wyznaczanie wodoszczelności – Metoda ciśnienia hydrostatycznego.
18. Katunin A., Sznura M.: Stanowisko badawcze do kontrolowanych testów udarowych płyt kompozytowych. „Aparatura Badawcza i Dydaktyczna" 2013, Vol. 18, s. 297 - 302.
19. Katunin A., Zuba M.: Influence of the impactor geometry on the damage character in composite structures. "Modelowanie Inżynierskie" 2013, nr 49, t. 18, p. 33 - 39.
20. Owen H., Houzeaux G., Samaniego C., Lesage A.C., Vázquez M.: Recent ship hydrodynamics developments in the parallel two-fluid flow solver Alya. "Computers & Fluids" 2013, Vol. 80, p. 168 - 177.
21. Lee M.C.W., Payne R.M., Kelly D.W., Thomson R.S.: Determination of robustness for a stiffened composite structure using stochastic analysis. "Composite Structures" 2008, Vol. 86, p. 78 - 84.
22. Chirica I., Musat S.D., Chirica R., Beznea E.F.: Torsional behaviour of the ship hull composite model. "Computational Materials Science" 2011, Vol. 50, p. 1381-1386.
23. Landowski M., Budzik M., Imielińska K.: Water sorption and blistering of GFRP laminates with varying structures. "Advances in Materials Science" 2013, Vol. 12, p. 23 - 29.
24. Mouritz A.P., Thomson R.S.: Compression, flexure and shear properties of a sandwich composite containing defects. "Composite Structures" 1999, Vol. 44, p. 263 - 278.
25. Capello F., Mancuso A.: Lay-up optimization for the hull of a racing sailing yacht. "Advances in Engineering Software" 2001, Vol. 32, p. 133 - 139.
26. Kumar S.S., Milwich M., Deopura B.L., Plank H.: Finite element analysis of carbon composite sandwich material with agglomerated cork core. "Procedia Engineering" 2011, Vol. 10, p. 478 - 483.
27. Hossain M.K., Chowdhury M.M.R., Imran K.A., Salam M.B., Tauhid A., Hosur M., Jeelani S.: Effect of low velocity impact responses on durability of conventional and nanophased CFRP composites exposed to seawater. "Polymer Degradation and Stability" 2014, Vol. 99, p. 180 - 189.
28. Sutherland L.S., Guedes Soares C.: Impact behaviour of typical marine composite laminates. "Composites: Part B" 2006, Vol. 37, p. 89 - 100.
29. Sutherland L.S., Guedes Soares C.: The use of quasi-static testing to obtain the low-velocity impact damage resistance in marine GRP laminates. "Composites: Part B" 2012, Vol. 43, p. 1459 - 1467.
30. Panciroli R., Abrate S., Minak G.: Dynamic response of flexible wedges entering the water. "Composite Structures" 2013, Vol. 99, p. 163 - 171.