ISSN 1392 - 1207. MECHANIKA. 2010. Nr.5(85)

Numerical investigation of impact behaviour of sandwich fiber reinforced plastic composites

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1. Introduction

A fiber reinforced plastic (FRP) composite has a high stiffness and strength, low weight, corrosion resistance, and electromagnetic neutrality [1-3]. Because of this more and more often FRP composites are used in new modern structures as well as in sandwich composites.

The use of sandwich structure consisted of thick honeycomb core and thin laminated composite facesheets is prevailed in safety important objects such as aircrafts, transport means, vessels and pipes due not only to the various advantages in terms of stiffness, stability and weight savings, but the good energy absorption under impact, also, because the risk of some impact damage is unavoidable for these objects.

Sandwich composites are widely used in lightweight construction in aerospace industries [4]. In the service life of a sandwich panel, impacts are expected to arise from a variety of causes. Debris may be propelled at high velocities from the runway during aircraft takeoffs and landings. Other examples include tools dropping on the structure during maintenance or even collisions by birds. That loading cases were investigated by C.C. Foo et al. [5]. Visual inspection may reveal little damage on the sandwich panel, but significant damage may occur between the impacted facesheet and the core. Reduction of structural stiffness and strength can occur, and consequently, propagate under further loading. Their behaviour under impact is an important problem.

Accidents of tank cars carrying hazardous materials that lead to rupture can cause serious public safety dangers. D. Tyrell et al. [6] investigated improving of tank car designs that are better equipped to keep the commodity contained during impacts. Authors presented a framework for developing strategies to maintain the structural integrity of tank cars during accidents. A conceptual design that can protect its lading at twice the impact speed of current equipment in the car-to-car impact scenarios was developed. Alternative means of absorbing impact energy suggested by authors are the use of plastic foams, aluminium honeycomb, and steel sandwich structures.

The carbody of tilting train was developed using a hybrid design concept combined with a sandwich composite structure for bodyshell and a stainless steel structure for the under frame to match the challenging demands with respect to cost efficient lightweight design for railway carriage structures [7]. These components have to sustain considerable external forces without undergoing any local failure or critical deformation to guarantee safety of passengers.

A new concept of thermoplastics sandwich structure for extrusion-welded storage tanks was developed by E. Lagardere et al. [8]. It consists of a fibre-reinforced core (glass/polypropylene) and of neat polypropylene facesheets. Compared to regular neat polypropylene tanks, this sandwich structure provides improved impact resistance at low temperature, reduced creep under pressure and temperature, and minimized overall wall thickness. The use of composites in the tank structure also reduced material consumption by as much as 60 %, compared to the neat thermoplastic solution at identical industrial performances and use conditions.

A structural sandwich composite comprises of two thin facesheets adhered to a thick core [9]. The facesheets resist nearly all of the applied in-plane loads and flatwise bending moments and offer nearly all the bending rigidity to the sandwich. The core spaces the facings and transmits shear between them. The core also provides shear rigidity to the sandwich structure. To achieve high flexural strengths or flexural natural frequencies, the honeycomb core height is usually about 80–95 % of the total composite thickness [10, 11]. By varying the core, the thickness and the material of the face sheet of the sandwich structures, it is possible to achieve various properties and desired performance [12]. The core can be foam, honeycomb, truss, corrugated, or solid. The foam can be made of various polymers such as polystyrene, polymethacrylimide, polyvinylchloride, polyurethane, and polypropelyne. The metallic foam can be used also [13]. In honeycomb core sandwich composites, the honeycomb core material (composite, polymer, metal, paper) is expanded into hexagonal cells.

Characterization of sandwich materials has been carried out in scientific studies. The determination of sandwich material behaviour under crushing loads and the measurements of ductile fracture limits is normally done with the help of compression tests [14]. Cores are the weakest part of sandwich structures and they fail due to shear. The shear strength properties of sandwich core are important in the design of sandwich structures subjected to flexural loading. Three-point bending tests are performed to find the flexural and shear rigidities of sandwich beams [15].

Mechanical behaviour of sandwich structures is strongly dependent on the loading rate [16]. In the case of static loading the structure can have a ductile behaviour, but in the case of impact loading it may behave in a brittle manner and fail catastrophically. As impact assessment needs to be considered, like in the transportation industry, it is very important to predict the impact behaviour and to collect data on impact resistance of materials. Such structures must be designed to withstand static and fatigue loads as well as to be able for maximum energy absorption in the case of an impact.

In comparison to quasistatic, studies of impact loading suggested that dynamic effects were significant due to a combination of more complicated crushing patterns, inertia effects and material strain rate sensitivity [17]. E. Wu and W. S. Jiang [18] founded that the final impact deformation of metallic honeycomb contained more irregular and extra folding mechanisms compared to those of the quasistatic. It was obtained that the dynamic crush strength was significantly higher by between 33 and 74%. Similar studies [19] showed a 40% and 50% increase, respectively, from the quasistatic to dynamic cases.

Energy-absorbing capacities of sandwich structures with honeycomb under impact are closely linked to the core crushing. Core crushing is a complex mechanical phenomenon characterized by the appearance of various folds and failures in the hexagonal structure [17, 20].

Currently, the impact design problem is approached in two separated ways. The first one is experimental and requires several measurements of impact behaviour of the studied material under different loading conditions and sample geometry. The second one is mainly related to the simulation of impact phenomena using finite element methods and requires very powerful hardware and software resources.

The analysis of recent scientific studies showed that, investigation of honeycomb sandwich composites is talking point. Although researches are numerous but in some materials combinations are poor.

The present paper is the continuation of previous studies. The research object is FRP sandwich composite made from woven glass fiber and polyvinylester resin composite facesheets and polypropylene honeycomb core. The aim of this study is to investigate dynamical properties of this composite structure and obtain the effective value of FRP thickness in honeycomb core according dynamic stiffness, which depends on maximal deflection and maximal reaction force.

2. Modelling

The experimental investigation of deformation behaviour under quasistatic and dynamic loading of sandwich structure made from fiber reinforced plastic, i. e., woven glass fiber and polyvinylester resin composite, facesheets and polypropylene honeycomb core was carried out. According to these results, the numerical models of impact loading were validated with the 10% accuracy. This investigation was presented in earlier study [21]. In the present study, these validated numerical models of sandwich composite specimens are used for the investigation.

The finite element analysis (FEA) were performed using code LS-DYNA v.971. The FE model consists of about 20,000 nodes. Mainly quadrilateral, first order, flat Belytschko-Tsay shell elements, with Mindlin-Reissner plate theory formulation. Edge length of the shell elements was in range of 2 -4 mm. The separate numerical models of honeycomb and facesheets was validated experimentally and coupled using *CONTACT_TIED_ NODES_TO_SURFACE keyword.

For drop-weight impact testing simulation by FEA, the impacted model geometry presented in Fig. 1, a was used. The specimens' support arrangements were equal as follows to 90, 150 and 210 mm. The impactor for all investigation cases was the same and had the diameter of 25 mm and mass of 25 kg. The drop height depended on the required impact energy. Kinetic energy of 40 J was used, the drop height for this value reaching was equal to 160 mm and the initial velocity was equal to 1.8 m/s. As it is seen from Fig. 1, b and c, two types of sandwich composites were investigated and compared. The first of them was sandwich structure made from two FRP, i. e., woven glass fiber and polyvinylester resin, composite facesheets and polypropylene honeycomb core. The second one was made from neat facesheets material FRP. The specimen width was the same for all investigated cases and was equal to 100 mm. The composite with honeycomb included the core of 20 mm thickness. The thickness of facesheets was changed in step of 1 mm from 1 mm to 10 mm.

The mechanical properties of materials for numerical modelling were used such as they were obtained in experimental way according to applicable standard EN ISO 527-1:1994 [22]. The circumstantial description was presented in earlier study [21]. The mechanical properties of material are presented in Table. The honeycomb material was defined by *MAT_PLASTIC_KINEMATIC model; the facesheets material was defined by *MAT_COMPOSITE_ DAMAGE.

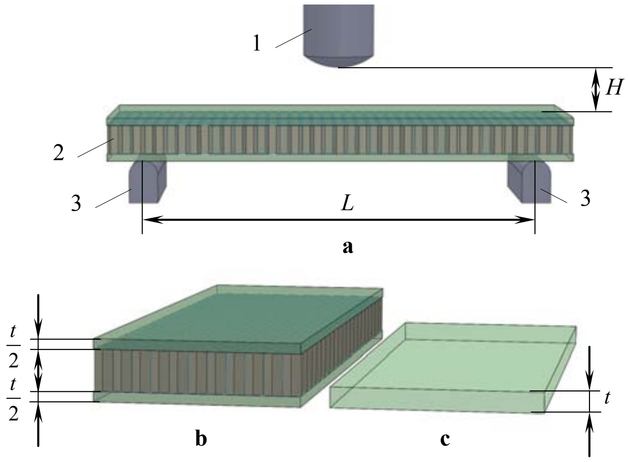

Fig. 1 Geometry, supports and impactor arrangements of the investigated model: *1* – impactor, *2* – specimen, *3* – supports, (a); model of sandwich composite with honeycomb core (b); model of sandwich composite from neat facesheets material (c); *H* – drop height, *L* – length between supports, *t* – thickness of facesheet material FRP

Changing variable parameters, i. e., length between supports and thickness of facesheet material, the dynamical properties which define dynamic stiffness and energy absorption capability were carried out for both honeycomb and neat composite structures models using FEA code LS-DYNA v.971. The typical numerical model is presented in Fig. 2.

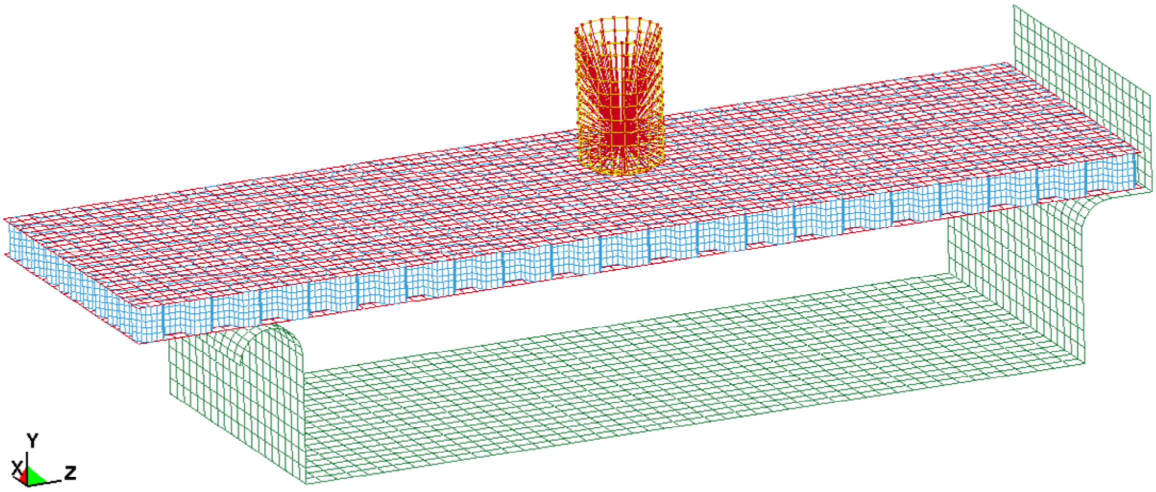

Fig. 2 Numerical model of sandwich structure

Table
Mechanical properties of sandwich structure component materials

Mechanical property	Face-sheets material, FRP	Core material, polypro-pylene
Tension strength, MPa	380	-
Compression strength, MPa	280	-
Shear strength, MPa	130	-
Young modulus, GPa	19.2	1.75
Poisson ratio	0.13	0.42
Yield stress, MPa	-	24.0
Tangent modulus, MPa	-	4.4

For both FRP composite with honeycomb core and neat FRP composite structures the dynamic stiffness K_{dyn} was calculated according to the following equation

$$K_{dyn} = \frac{F_{max}}{y_{max}} \tag{1}$$

For the comparison purposes the coefficient $k_{y_{max}}$ represented the ratio of the maximal deflection y_{max} of woven glass fiber and polyvinylester resin composite structure without honeycomb core to the maximal deflection of composite structure with honeycomb core which thickness of two facesheets was equal to this of composite without core, was used. Its expression is the following:

$$k_{y_{max}} = \frac{y_{max1}}{y_{max2}} \tag{2}$$

there y_{max1} is the maximal deflection of FRP composite; y_{max2} is the maximal deflection of FRP composite with honeycomb core.

In addition, the coefficient $k_{F_{max}}$ represented the ratio of the maximal reaction force F_{max} of composite structure without honeycomb core to the maximal reaction force of composite structure involving honeycomb core which thickness of two facesheets was equal to this of composite without core, was used as follows

$$k_{F_{max}} = \frac{F_{max1}}{F_{max2}} \tag{3}$$

there F_{max1} is the maximal reaction force of FRP composite; F_{max2} is the maximal reaction force of FRP composite with honeycomb core.

3. Results and discussion

The influence of facesheets thickness of honeycomb core sandwich composite on internal energy absorption part of honeycomb for different length between supports is shown in Fig. 3. It seems that the honeycomb core can absorb by between 45 and 95% energy of all sandwich structure. The relation between facesheets thickness and energy part absorbed by honeycomb can be defined by linear dependence, as the coefficient of

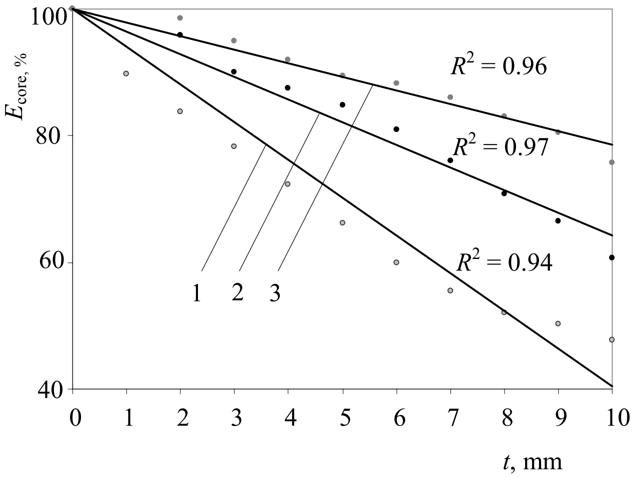

Fig. 3 Influence of facesheets thickness *t* of honeycomb sandwich composite on percentage of internal energy absorption of honeycomb E_{core}; *1*, *2*, *3* – for the length between supports respectively 90, 150 and 210 mm

determination is very high ($R^2 = 0.94 - 0.97$). The energy absorption part of honeycomb decreases as the thickness of facesheets increases. That is due to thick facesheets larger energy absorption. The significant effect of length between supports is obvious. As this length increases the honeycomb absorbed energy part increases due to large shear deformations.

The influence of FRP thickness on dynamic stiffness for both honeycomb and neat FRP composite was found out. It is presented in Fig. 4. The dynamic stiffness increases as the thickness of FRP increases for all investigated cases. For low thickness values, the dynamic stiffness of honeycomb structure is higher than this of neat FRP composite. The value of thickness as the dynamic stiffness has the same value exists but it is different depending on the length between supports. As $L = 90$ mm this value is about $t = 4 - 5$ mm, as $L = 150$ mm $t = 5 - 6$ mm, as $L = 210$ mm $t = 7 - 8$ mm. Above this thickness value the dynamic stiffness of neat FRP becomes higher than this of honeycomb core composite. In the case of $L = 90$ mm the dynamic stiffness is significantly higher than in the cases of $L = 150$ mm and especially of $L = 210$ mm. But in the most extreme case as the thickness of FRP is equal to 10 mm the dynamic stiffness of neat FRP composite is about two times higher than this of honeycomb structure for all investigated length between supports cases.

The dynamic stiffness of composite with honeycomb core can be approximated by the following function

$$K_{dyn,1}(L,t) = \left(a_1 + b_1\, e^{-L/c_1}\right) e^{t/(d_1 + e_1\, L)} \tag{4}$$

there $a_1 = 0.156$; $b_1 = 5.743$; $c_1 = 24.02$; $d_1 = 0.783$; $e_1 = 0.0307$.

The dynamic stiffness of neat FRP composite can be approximated as follows

$$K_{dyn,2}(L,t) = \left(a_2\, e^{-L/b_2}\right) t^{(c_2 + d_2 \cdot L)} \tag{5}$$

there: $a_2 = 0.4389$; $b_2 = 29.67$; $c_2 = 2.053$; $d_2 = 0.0060$.

However, the evaluation of optimal thickness value by dynamical stiffness is not quite clear because, the same value of dynamical stiffness can be obtained for different F_{max} and y_{max} values. So, the influence of thickness on separate F_{max} and y_{max} values was investigated.

The dependences of coefficients $k_{y_{max}}$ and $k_{F_{max}}$ defined by respectively F_{max} and y_{max} values upon the thickness of FRP for different length between supports are presented in Fig. 5. It is clear that the maximal deflection decreases as the thickness of FRP increases and the length between supports decreases. The significant influence on the deflection value of honeycomb core presence was found out only as the FRP thickness is low and the length between supports is high. The values of coefficient $k_{y_{max}}$ cannot be defined for low values of thickness t due to too little stiffness of neat FRP composite. In comparison for t equal to 5 mm (at this value the honeycomb height is 80%) of the total composite thickness [10, 11]) the deflection of honeycomb core FRP composite is 1.1, 1.7, and 2.5 times lower than this of neat FRP composite as the length between supports is respectively 90, 150 and 210 mm. However, as t is equal to 10 mm the deflections of honeycomb core FRP and neat FRP composites are of similar value and the coefficient $k_{y_{max}}$ is near to one.

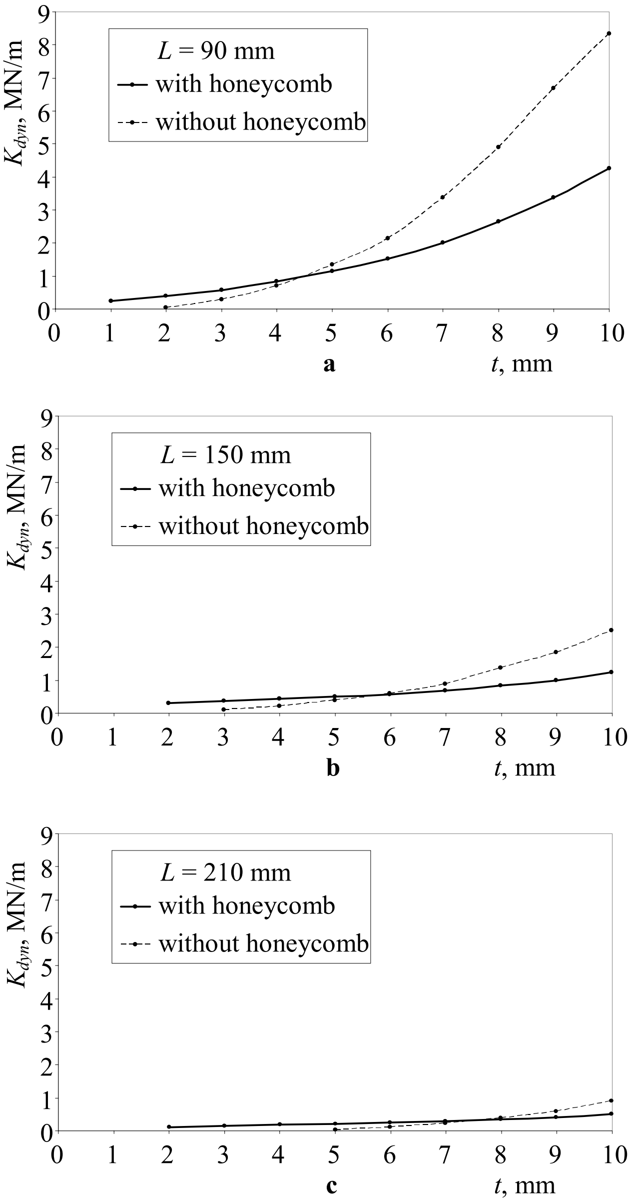

Fig. 4 Influence of FRP thickness t on dynamic stiffness K_{dyn}; a, b, and c – for length between supports respectively 90, 150 and 210 mm

The similar effect of FRP thickness is obtained on the maximal reaction force F_{max} of composite, also. From Fig. 5 it seems that, the significant influence on the reaction force value of honeycomb core presence was found out only as the FRP thickness is low. As the thickness of FRP increases and the distance between supports decreases the reaction force increases. In the case of low thickness, the reaction force of honeycomb core FRP composite is higher than this of neat FRP composite for all the investigated length between supports cases. But for the higher values of thickness the situation reverses and reaction force of honeycomb core FRP composite becomes lower (up to two times) than this of neat FRP composite.

The effective honeycomb core composite structure can be found out evaluated the fact that coefficients $k_{y_{max}}$ and $k_{F_{max}}$ must be higher than one. In Fig. 5 the range of FRP thickness where this condition is sustained is marked. It seems that this range depends upon the distance between supports and as this distance increases, the higher value of FRP thickness is needed and the wider range can be used.

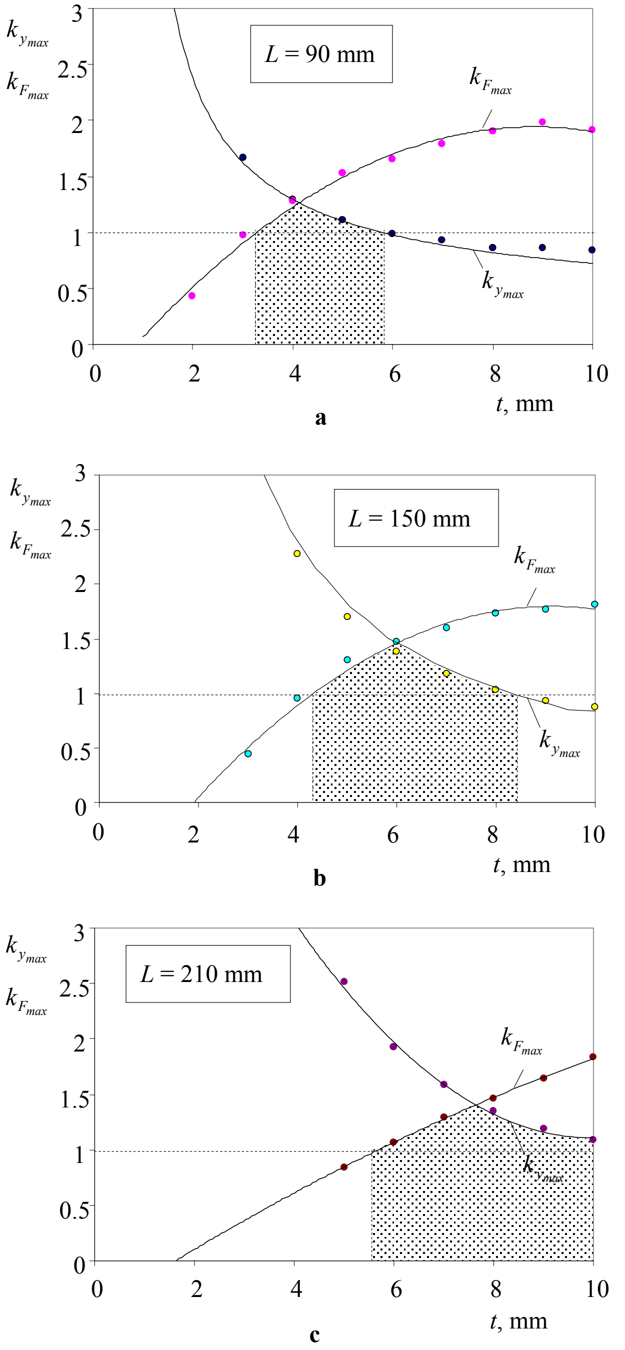

Fig. 5 Influence of FRP thickness t on coefficients $k_{y_{max}}$ and $k_{F_{max}}$; a, b, and c – for length between supports respectively 90, 150 and 210 mm

4. Conclusions

The dynamical behaviour of woven glass fiber and polyvinylester resin composite structure both with polypropylene honeycomb core and without it were obtained and compared using the numerical modelling.

It was found out that the use of honeycomb core in sandwich composite system is very effective because the honeycomb can absorb by between 45 and 95% of energy of all the sandwich structure. The relation between facesheets thickness and energy part absorbed by honeycomb can be defined by linear dependence. This energy part decreases as the thickness of facesheets increases.

The results of assessment of dynamic stiffness, maximal deflection and maximal reaction force show that effective value of FRP thickness in honeycomb core composite depends upon product structure geometry first of all. It is to be considered to the length between supports because the facesheet thickness very depends upon it and this thickness not always coincides with this proposed in literature for general cases.

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PLUOŠTU ARMUOTŲJŲ SLUOKSNIUOTŲ KOMPOZITŲ SMŪGINĖS ELGSENOS TYRIMAS SKAITINIU METODU

Reziumė

Skaitiniu baigtinių elementų metodu tirta saugai svarbių sluoksniuotųjų struktūrų iš austinio stiklo pluošto ir polivinilesterinės dervos kompozito laminuojančiųjų sluoksnių bei polipropileno taisyklingo šešiakampio formos korinės šerdies elgsena smūginio apkrovimo metu, nustatytos sluoksniuotosios struktūros dinaminės savybės, apibūdinančios energijos sugėrimą ir dinaminį standumą.

Gauti smūginės energijos sugėrimo ir dinaminio standumo priklausomybių nuo konstrukcijos geometrinių parametrų dėsningumai leidžia vertinti ir prognozuoti smūginių apkrovų veikiamų sluoksniuotųjų konstrukcijų saugai svarbius parametrus, o kartu efektyviai naudoti medžiagas.

D. Zeleniakienė, P. Griškevičius, V. Leišis, D. Milašienė

NUMERICAL INVESTIGATION OF IMPACT BEHAVIOUR OF SANDWICH FRP COMPOSITES

Summary

Finite element simulations were performed to study the behaviour under impact loading of the sandwich composite made from woven glass fiber and polyvinylester resin composite facesheets and polypropylene hexagonal honeycomb core that can be used for safety important structures. The layered structure dynamical properties associated with energy absorption and dynamical stiffness was investigated.

The obtained impact energy absorption and dynamical stiffness dependences of geometric parameters of the structure allow the assessment and the prediction of sandwich structures safety important parameters under impact loading and ensuring the efficient material expenditures.

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Д. Милашене

ИССЛЕДОВАНИЕ ПОВЕДЕНИЯ ВОЛОКНОМ АРМИРОВАННЫХ СЛОИСТЫХ КОМПОЗИТОВ ПОД ВОЗДЕЙСТВИЕМ УДАРНОЙ НАГРУЗКИ С ПОМОЩЬЮ ЧИСЛЕННЫХ МЕТОДОВ

Резюме

Методом конечных элементов выполнен динамический анализ поведения важных для безопасности структур, изготовленных из слоев стекломата с полиэфирной смолой и структурного сотового заполнителя, под воздействием ударной нагрузки. Установлены динамические свойства слоистой структуры для поглощения энергии динамической жесткости.

Полученные зависимости поглощения энергии и динамической жесткости от геометрических параметров конструкции дают возможность оценить и прогнозировать важные для безопасности параметры слоистых конструкций, от влияния ударных нагрузок, а тем самым сэкономить затраты на материал.

Received July 21, 2010
Accepted October 11, 2010