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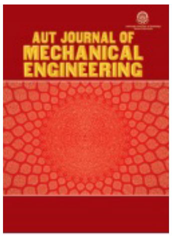

Effects of Functionalized Multi-Walled Carbon Nanotubes on the Low-Velocity Impact Response of Sandwich Plates

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ABSTRACT: One method to reduce the damage caused by low-velocity impact in sandwich composites is using nanoparticles as the reinforcement material in the face sheets. The aim of this study is to investigate the effects of different weights of functionalized multi-walled carbon nanotubes on mechanical properties of face sheets and response of sandwich plates that undergo low-velocity impact through experimental investigations. The face sheets are made of nano-modified EPIKOTE 828 with triethylenetetramine as the curing agent, and a core of polyurethane foam. The functionalized multi-walled carbon nanotubes are dispersed into the epoxy system in 0.1%, 0.3% and 0.5% weight-to-matrix. The low-velocity impact test was performed using a drop tower impact machine, at two different energy levels. The stress-strain, history of contact force, velocity-time, absorbed energy-time and force-deflection are plotted and some parameters such as elastic modulus, tensile strength, bounce time, upward velocity, peak load and maximum deflection are reported. The tensile test results show that with the slight increase in the volume fraction of carbon nanotubes, the elastic modulus and ultimate tensile strength are improved. Also, the minor amount of carbon nanotubes reduce bounce time, residual deformation, and maximum deflection and increase peak load in the sandwich plate. In addition, carbon nanotubes reduce the damaged area.

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1. Introduction

Today, sandwich plates are used in many industries, including automobile, aircraft, and rail industries, due to their low weight and high bending stiffness. Having low-strength cores and low-thickness face sheets, these structures are greatly susceptible to impact damage. Impact on sandwich plates with composite laminate face sheets and foam core can lead to damage, including matrix cracks, fiber fracture, delamination, core crushing, and so on, resulting in a sharp drop in the structural performance of the structure [1]. Increasing the strength of face sheets using reinforcing materials is one method for reducing the damage caused by impact in composite structures. In recent decades, the use of nanoparticles as reinforcement material to improve the mechanical properties of composites has developed rapidly, and many researches have been done on the effects of these particles. For example, Schadler et al. [2] found that adding 5 wt% Carbon NanoTubes (CNTs) can increase the effective stiffness of CNT-reinforced epoxy by about 40%. Breton et al. [3] could increase the Young's modulus by about 30% by adding 6 wt% Multi-Walled Carbon NanoTubes (MWCNTs) to the nanocomposite. Montazeri et al. [4] could achieve a 27% increase in Young's modulus by adding 3 wt% MWCNTs. Zhu et al. [5], studied the stress-strain response of CNT-reinforced nano-epoxies when 1-4 wt% CNTs were added, and found that the effective properties were improved by about 30-70%.

It can be seen that the presence of nanoparticles in the structure of composites generally increases their mechanical properties. The improvement in the mechanical properties of composites due to the presence of nanoparticles encouraged many researchers to investigate the effects of nanoparticles on increasing the resistance to impact and reducing the damage in composites. Nanoclay and CNTs are the most important nanoparticles used in researches to study the effects of impact on composites. For example, Avila et al. [6] investigated the effects of low-velocity impact on glass-fiber-epoxy-nanoclay laminate composites. In two other papers, researchers also examined the effects of reinforcing sandwich panels with nanoclay [7,8]. They used 65 wt% glass fibers and 0 to 10 wt% nanoclay to reinforce the face sheets. The results show that panels with 5 wt% nanoclay have the highest stiffness at low-velocity impact. They also show that a large increase in the amount of nanoclay will reduce the stiffness of the panel due to the fact that nanoparticles are not uniformly distributed in the matrix. The review paper of Hosur et al. [9,10] indicates that the core with nanoclay improves the impact response in sandwich panels. Also, their results indicate that nanoclay increases peak load, decreases the damage area, and increases the stiffness of the structure. The behavior of nanoclay-reinforced composites under low-velocity impact

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was surveyed in several other papers during 2009 to 2016 [11-14]. The results from these papers show that nanoclay reduces delamination as well as the damaged areas. Another type of nanoparticle used for the reinforcement of composites is the CNT. Several papers investigated the behavior of CNT-reinforced composites under low-velocity impact [15-22]. For example, Moumen et al. [18,19], in two articles, studied the impact response of polymer composite containing a random distribution of CNTs. They used 0 to 4 wt% CNT to reinforce the textile composite. The results show that a minor amount of randomly oriented CNTs can improve the dynamic properties and damage evolution in carbon/epoxy composites. The review paper of Bhuiyan et al. [20] indicated that the core with carbon nanofiber brings reinforcement to the sandwich panel at the impact load. The results show that nanoparticles increase peak load and decrease the area of damage. In addition, in low-energy impacts, the energy absorbed by reinforced panels is higher, which will be reversed with increasing energy intensity. Ramakrishnan et al. [21] added 10 wt% nanoparticles to enhance the layers of the sandwich panel containing Kevlar fiber. The results of the low-velocity impact on the samples show that nanoparticle samples require a higher level of energy to fail. Also, at the same energy level, penetration is only observed for the non-nanoparticle samples. In another study, Taraghi and Fereidoon [22] evaluated the effects of MWCNTs on the face sheets of a sandwich panel made of Kevlar fiber and foam core under the low-velocity impact. The results show that an increase in MWCNT content by 0.5 wt% improves the absorbed energy by up to 16% and decrease the damaged area.

A review of the above experimental studies shows that the presence of nanoparticles generally improves the impact properties of composites. Recently, a number of researchers have undertaken analytical studies of the effects of nanoparticles on the strength of sandwich composites at low-velocity impacts. Feli and Jalilian [23] have examined the effects of nanosilica on sandwich panel face sheets at low-velocity impact analytically and experimentally. Their analytical and empirical results show that nanosilica increases peak load, decreases maximum lateral deflection, and increases the stiffness of the structure. In other article, Salami [24] carried out an analytical analysis of the effects of CNTs on sandwich beam face sheets with foam core under impact. In this study, the Extended High Order Sandwich Panel theory was used to obtain the impact response, and the distribution of nanotubes was either uniform or functionally graded. The results show that the presence of nanoparticles increases stiffness and, consequently, increase peak load and reduce the transverse displacement of the upper face sheet. Recently in another article, Ahmadi et al. [25] investigated the impact response of beams made of CNT/Short Carbon Fiber (SCF) reinforced polymer employing finite element approach. There were revealed that the stiffness of polymer composite can be considerably improved via the hybrid CNT/SCF reinforcement. Also their results show that the impact response of polymeric beams was significantly affected by reinforcing with the combination of CNTs and SCFs.

In all of the above studies, nanoparticles have always been accompanied by other reinforcing materials in the matrix and their effects have not been studied alone. One of the serious challenges of using carbon nanotubes is their uniform distribution in composites [26].In most of the papers reviewed above, it is acknowledged that an increase in the amount of nanoparticles will cause a stop in incremental process of improving the properties of the structure, and the main reason is that CNT tend to agglomerate due to Van der Waals force [27]. One of the ways to improve the distribution of CNTs in composites is to use Functionalized carbon nanotubes [28,29]. Therefore, in this paper, COOH-functionalized MWCNTs have been used to improve the distribution of CNTs in composites.

In the present study first, the effects of different weight percentages of Functionalized Multi-Walled Carbon NanoTubes (FMWCNTs) are examined on mechanical properties of face sheets and then the response of sandwich nano plates under low-velocity impact are discussed. The face sheets were made of FMWCNT-reinforced epoxy and the core was made of polyurethane foam. The sandwich plates contained different weight percentages of FMWCNT and are subjected to impact with two different levels of energy. Finally, the effects of nanotubes on the contact force, contact area displacement, and the absorbed energy are investigated.

2. Sample Preparation

Materials

In this study, the sandwich plates made for impact testing had epoxy face sheets reinforced with FMWCNTs. Epoxy used in making the face sheets and specimens for tensile tests consists of two parts:

Part A – EPIKOTE 828. This is a medium viscosity liquid epoxy resin (32 Pa.s at 20 0C) with density 1.16 kg/L at 25 0C, produced from bisphenol A and epichlorohydrin.

Part B – TriEthyleneTetrAmine (TETA), TETA is an organic compound with viscosity 30 mPa.s at 20 0C and density 0.98 kg/L. TETA is used as an epoxy hardener.

The weight ratio proposed by the manufacturer for combining the components is 100A: 13B. The FMWCNTs used in this study were COOH functionalized MWCNTs, grade of 10-30 μm length and diameter of 10-20 nm with purity of ~98%. The FMWCNTs were supplied from US Research Nanomaterials, Inc., and were synthesized by a Chemical Vapor Deposition (CVD). The core used in making sandwich plates is a polyurethane foam and the mechanical properties are presented in Table 1 [23].

Table 1 Mechanical properties of core

Foam	Density (kg/m^3)	Young's modulus (MPa)	Thickness (mm)	$\tilde{\delta}$
PU 180	180	156.86	20	0.28

Preparation

In order to prepare the face sheets and tension specimens, the different weight percentages of FMWCNTs were added to the epoxy resin (without hardener) and manually mixed.

The weight percentages of FMWCNTs used to make face sheets are 0.1, 0.3 and 0.5 wt%. Also, the weight percentages of FMWCNTs used to make samples for tensile test are 0.5, 1 and 1.5 wt%. Then, to have a uniform distribution of FMWCNT in epoxy, the Ultrasound Sonication method – one of the best methods for creating a uniform distribution and preventing clustering of nanoparticles – was used. The device used for this purpose was Bandelin Sonopulse Ultrasonic Homogenizers, made in Germany. Finally, after the above process was completed, part B (hardener) was slowly added to the mixture to prevent the formation of bubbles, and then it was mixed with a mechanical stirrer.

In the next step, a certain volume of the produced matrix that could create a face sheet of 3 mm thickness was poured slowly on one side of the 150*150 mm core. The core was then left in ambient temperature to be cured. The other side was prepared through the same procedure. The final mixture was also poured into a stainless steel mould and was cured at ambient temperature for making specimens for tensile test. Samples for tensile test and sandwich plate made in this way are shown in Fig. 1.

Fig. 1. . Sandwich plate sample and tensile test samples

3. Tensile and Low Velocity Impact Tests

Tensile test on specimens were performed according to ASTM D 638 using a SANTAM STM-20 at a crosshead speed of 1 mm/min.

Upon completion of the sandwich plates, a low-velocity impact test was performed using a drop tower impact machine. The machine was equipped with a hemispherical stainless steel impactor with a diameter of 15.5 mm and the weight of 0.414 kg. Energy and velocity could be adjusted at the moment of impact by changing the height and weight of the impactor. The impact energies applied to the samples were 6.65 J and 18.32 J. The dimensions of the samples were 150*150 mm, and after providing the clamping conditions on their four sides, the area exposed to impact had a dimension of 100*100 mm. The impact machine was equipped with an accelerometer (Fig. 2) that recorded the data at the 13 µs intervals. These data are used to obtain force-time history. The transverse displacement of the plate at the place of impact and the absorbed energy can be obtained using numerical integrations of force and actions in the following relations [17].

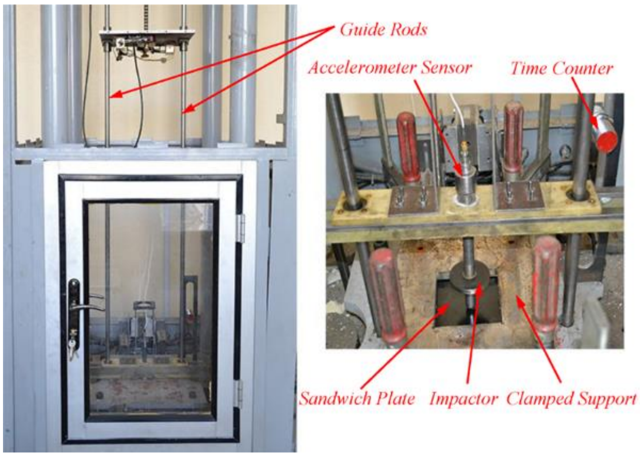

Fig. 2. Drop tower impact machine.

$$v(t)=v_i+gt-\int_0^t \frac{F(t)}{m}dt \tag{1}$$

$$\delta(t)=v_i t+\frac{gt^2}{2}-\int_0^t\int_0^t \frac{F(t)}{m}dt\,dt \tag{2}$$

$$E(t)=\frac{m\left[v_i^2-v(t)^2\right]}{2}-mg\delta(t) \tag{3}$$

where m is the applied mass, g is gravity, $v(t)$ is the velocity, $\delta(t)$ is the displacement, $E(t)$ is the absorbed energy, and $F(t)$ is the measured force. v_i is the incident velocity.

4. Results and Discussions

Tensile tests are performed to evaluate the effects of FMWCNTs in mechanical properties of face sheets. Fig. 3 shows the stress–strain response curves from tensile testing for the neat epoxy and FMWCNT/epoxy composites with different weight fractions of FMWCNTs. Table 2 lists the mechanical properties of FMWCNT composite samples. The mechanical properties of FMWCNTs were obtained from the stress-strain curve. It is observed that adding FMWCNTs provide a composite with greater elastic modulus and ultimate tensile strength. Adding only 0.5 wt% FMWCNTs to epoxy, enhanced Young's modulus and tensile strength by 15.09% and 9.48%, respectively. In the case of increasing the amounts of FMWCNTs from 0.5 wt% to 1.5 wt%, we have

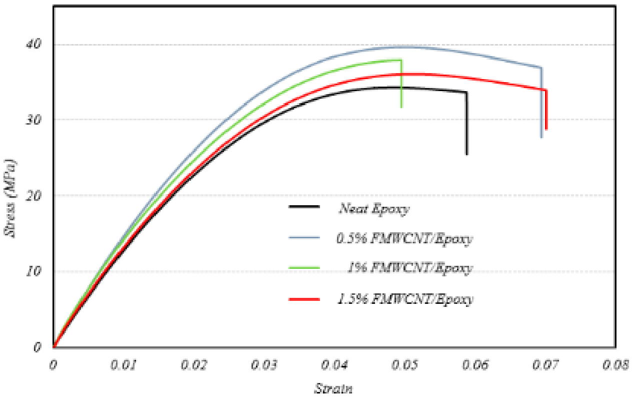

Fig. 3. Stress-strain curves for the neat epoxy and FMWCNT/epoxy

observed decrement of Young's modulus and tensile strength from 15.1% to 4 % and 9.5% to 0.6%, respectively. The lack of uniform distribution and agglomeration of nanotubes in composite are the main causes of this deterioration.

To characterize the dispersion states of FMWCNTs in the epoxy matrix, fracture surfaces of the samples were compared in Scanning Electron Microscopy (SEM) micrographs (Fig. 4). For specimen with 0.5 wt% nanotubes, dispersion is acceptable (Fig. 4(a)) but in the specimen with 1.5 wt% CNTs, distribution is not uniform and the cluster is created (Fig. 4(b)).

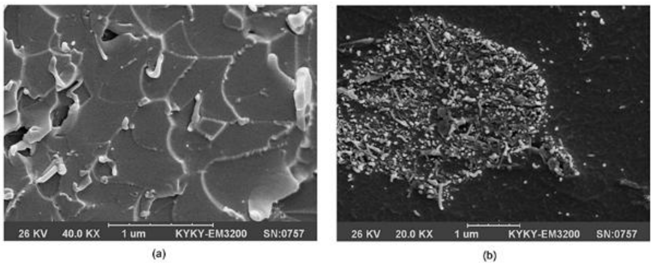

Fig. 4. SEM micrographs of the fracture surface (a) specimen with 0.5 wt % FMWCNT (b) specimen with 1.5 wt % FMWCNT.

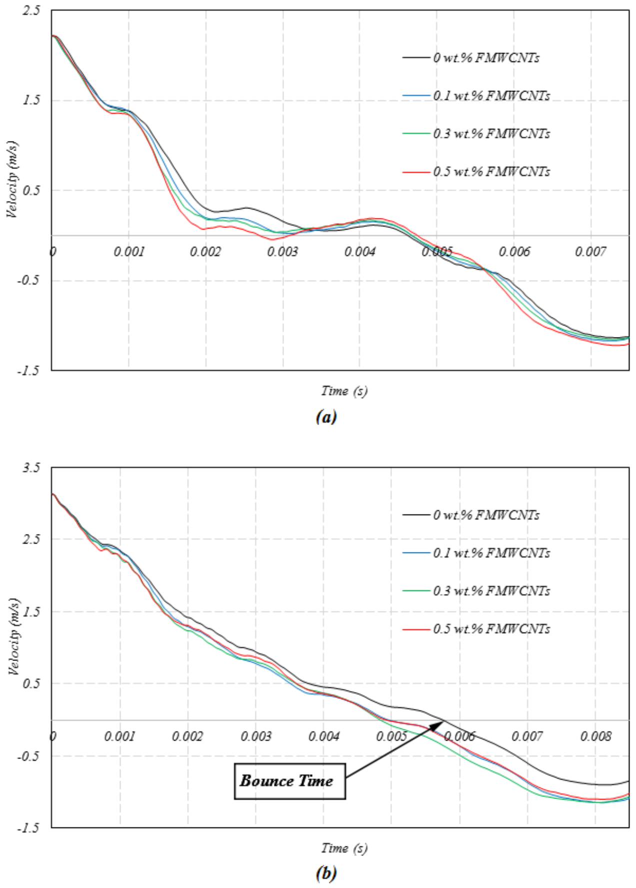

Fig. 5. Velocity- time response for various FMWCNT-modified sandwich plates, (a). Impact energy 6.65 J, (b). Impact energy 18.32 J.

In the following, impact responses of sandwich plates are evaluated. Figs. 5(a) and 5(b) show the time histories of the impactor velocity variations at two energy levels of 6.65 J and 18.32 J for different FMWCNT percentages. Positive values indicate the downward movement of impactor, while negative ones indicate its upward movement do to impactor rebound. Bounce point indicates the moment at which the velocity of impactor approaches zero. Bounce time and the ultimate velocity of the impactor at the end of the impact event (upward velocity) depend on the stiffness of the plate. At the end of the impact events, the higher the separation velocity is, the lower the damage in the plate will be. This is due to the fact that less energy is absorbed by the plate. It can be seen from Fig. 5(a) that at the low impact energy, FMWCNTs do not have significant effect on bounce time and upward velocity.

If the energy level increases (Fig. 5(b)), FMWCNTs reduce bounce time and increase upward velocity. It is also observed that the decreasing rate of velocity grows with the increase in FMWCNT content. This results indicates that the FMWCNTs are capable to increase the stiffness of the sandwich plate under impact loading. Table 3 lists the bounce time and upward velocity variations for different FMWCNT percentages. It is seen from Table 3 that adding 0.3 wt% FMWCNT to the face sheets improves bounce time and upward velocity by up to 16% and 26.7%, respectively, at the energy level of 18.32 J. We, furthermore, have noticed stopping in the improvement of bounce time and upward velocity in case of higher amounts of MWCNTs and the main causes of this deterioration comes from the lack of uniform

Table 2. Mechanical properties of FMWCNT/epoxy composite

wt % FMWCNT	Young's modulus (GPa)		Tensile strength (MPa)	
	Experimental	% Improvement	Experimental	% Improvement
0	1.312	---	33.77	---
0.5	1.510	15.09	36.97	9.48
1	1.481	12.88	37.94	12.44
1.5	1.365	4.04	33.96	0.56

Table 3. Bounce time and upward velocity for different FMWCNT percentages

wt% CNT	Impact Energy 6.65 J		Impact Energy 18.32 J			
	Bounce time (ms)	upward velocity (m/s)	Bounce time (ms)	% Decrease	upward velocity (m/s)	% Increase
0	4.63	1.13	5.76	---	0.90	---
0.1	4.68	1.17	4.95	14.1	1.14	26.7
0.3	4.68	1.15	4.84	16	1.14	26.7
0.5	4.76	1.22	4.93	14.4	1.10	22.2

distribution and agglomeration of nanotubes.

Fig. 6 shows the contact force history for different percentages of FMWCNTs at two energy levels of 6.65 J and 18.32 J. It can be observed that the contact force curve is not smooth, having many sharp drops and rises. The main causes of these sharp load drops are damage of the top face sheet and failure of the core in the impact area. At the beginning of the impact, force increases rapidly until the top face sheet suffers from damage and causes a drop in the force. Next, force increases again due to stiffness of core and bottom face sheet. By increasing the contact force, the core will undergo crushing and another sharp load drop will occur. Figs. 6 and 7 show that increasing the amount of nanotubes increases the maximum peak load, which is due to the increased face sheets stiffness. A comparison of Figs. 6(a) and 6(b) shows that by growing the impactor energy, the impact duration is prolonged, which is due to the higher damage to the plates. Table 4 lists maximum peak loads for different FMWCNT percentages. The results show that adding 0.3 wt% FMWCNT to face sheets mounted maximum peak load at energy levels of 6.65 J and 18.32 J by up 52% and 41.4%, respectively. Also, we have observed stopping in the improvement of pick load in case of higher amounts of FMWCNTs and the main causes of this deterioration comes from the lack of uniform distribution and agglomeration of nanotubes.

Fig. 7 shows the force-displacement response of sandwich plates with different percentages of FMWCNTs at two energy levels of 6.65 J and 18.32 J. Fig. 7 shows that increasing the amount of nanoparticles increases the gradient and peak force. Moreover, it is observed that the maximum deflection and residual displacement (dent) are reduced by increasing the amount of nanotubes. Table 5 lists the maximum deflection for different FMWCNT percentages. The results show that adding 0.3 wt% FMWCNT to face sheets decreased maximum deflection at energy levels of 6.65 J and 18.32 J by up 11% and 10.4%, respectively. The deflection is a qualitative indication of the stiffness of the material. It is seen from table 5 that the neat samples had higher deflection.

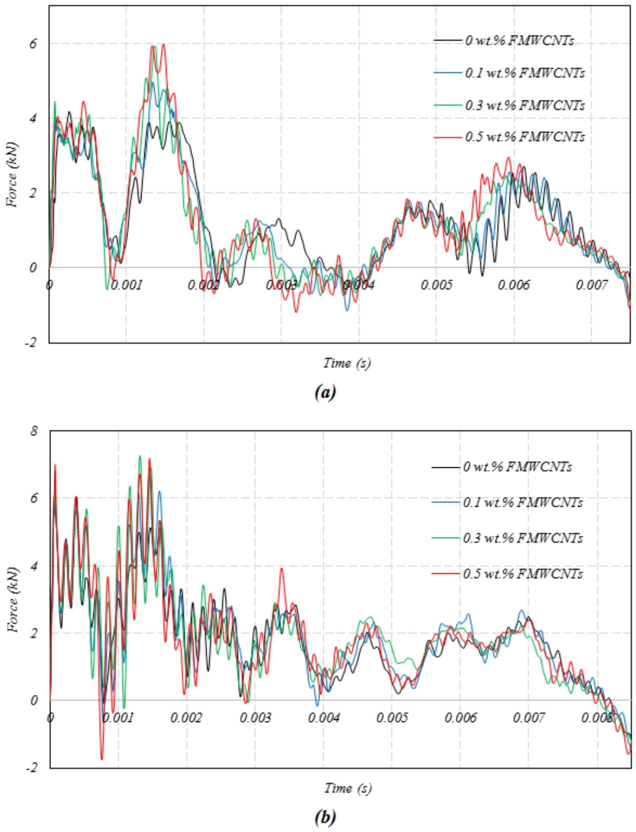

Fig. 6. Force-time response for various FMWCNT-modified sandwich plates, (a). Impact energy 6.65 J, (b). Impact energy 18.32 J.

The absorbed energy was calculated as the difference between kinetic energy of the impactor at the beginning of the impact event and at the end of the impact events. Impact energy is a principal measure of the severity of the impact event. Absorbed energy would increase with impact energy. Absorbed energy is related to the damage in the specimen. Changes in the absorbed energy at two energy levels of 6.65 J and 18.32 J for different percentages of FMWCNTs

Table 4. Maximum peak load for different FMWCNT percentages.

wt% FMWCT	Impact Energy 6.65 J		Impact Energy 18.32 J	
	Peak load(kN)	% Increase	Peak load(kN)	% Increase
0	3.90	---	5.14	---
0.1	4.96	27.2	6.71	30.5
0.3	5.93	52.1	7.27	41.4
0.5	5.92	51.8	7.19	39.9

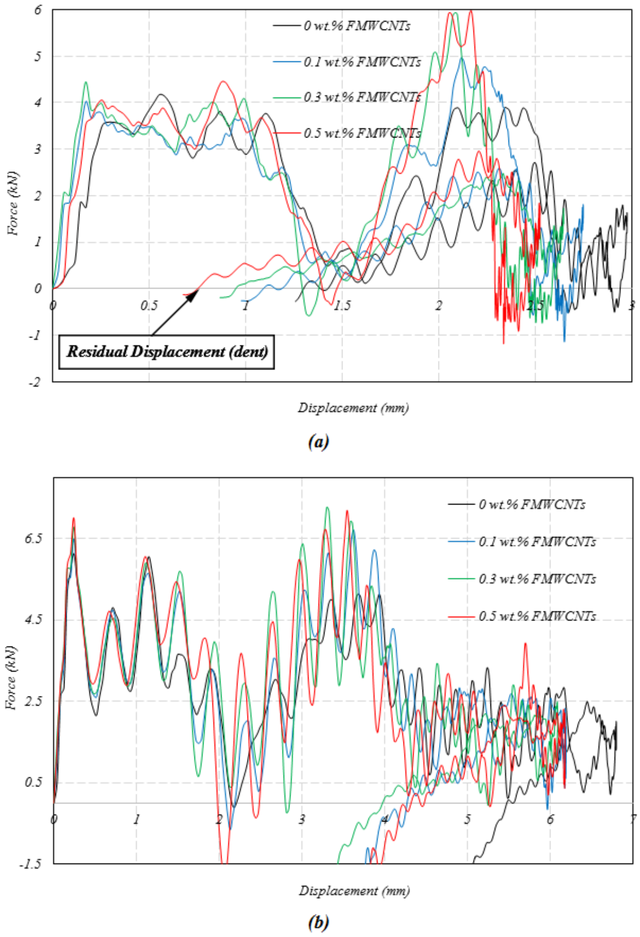

Fig. 7. Force-displacement response for various FMWCNT-modified sandwich plates, (a). Impact energy 6.65 J, (b). Impact energy 18.32 J.

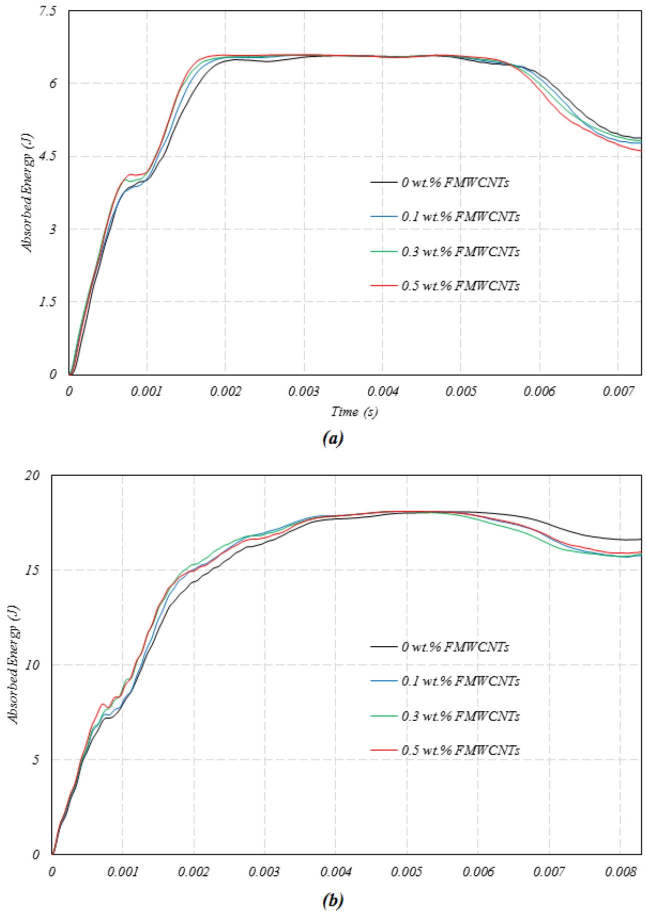

Fig. 8. Energy-time response for various FMWCNT-modified sandwich plates, (a). Impact energy 6.65 J, (b). Impact energy 18.32 J.

are shown in Fig. 8. It can be seen from the figures that at the end of the impact, the absorbed energy decreases with the increase in the amount of nanotubes, which indicates less damage in nanotube-reinforced sandwich plates. Table 6 lists the absorbed energy at the end of the impact event for different FMWCNT percentages. It is observed that the amount of energy absorbed is significantly increased by the increase in the impactor energy and results in a more severe damage on the plates.

For further investigation, a top and a section view of the damaged area for the impact energy of 18.32 J is shown in Fig. 9. The top view shows that failure has occurred in precisely the area receiving the impact, which is due to the brittle structure of the face sheets. The section view shows that penetration occurred in all top face sheets, and the core was crushed at the area below the impact point. For a closer examination of the damage and effects of nanotubes, we consider the damage area as in Fig. 10. The width (b) and depth of indentation (h), as shown in Fig. 10, characterize the impact damage area. Table 7 shows the width and depth of damage by FMWCNT content. The results show that

Table 6. Absorbed energy at the end of the impact event for different FMWCNT percentages.

wt % FMWCNT	Impact Energy 6.65 J	Impact Energy 18.32 J
	Absorbed energy(kN)	Absorbed energy(kN)
·	4.88	16.60
0.1	4.78	15.70
0.3	4.82	15.72
0.5	4.62	15.90

Table 5. Maximum deflection for different FMWCNT percentages.

wt % FMWCNT	Impact Energy 6.65 J		Impact Energy 18.32 J	
	Maximum Deflection(mm)	% Decrease	Maximum Deflection(mm)	% Decrease
0	2.98	---	6.80	---
0.1	2.75	7.7	6.19	9
0.3	2.65	11	6.09	10.4
0.5	2.53	15	6.18	9.1

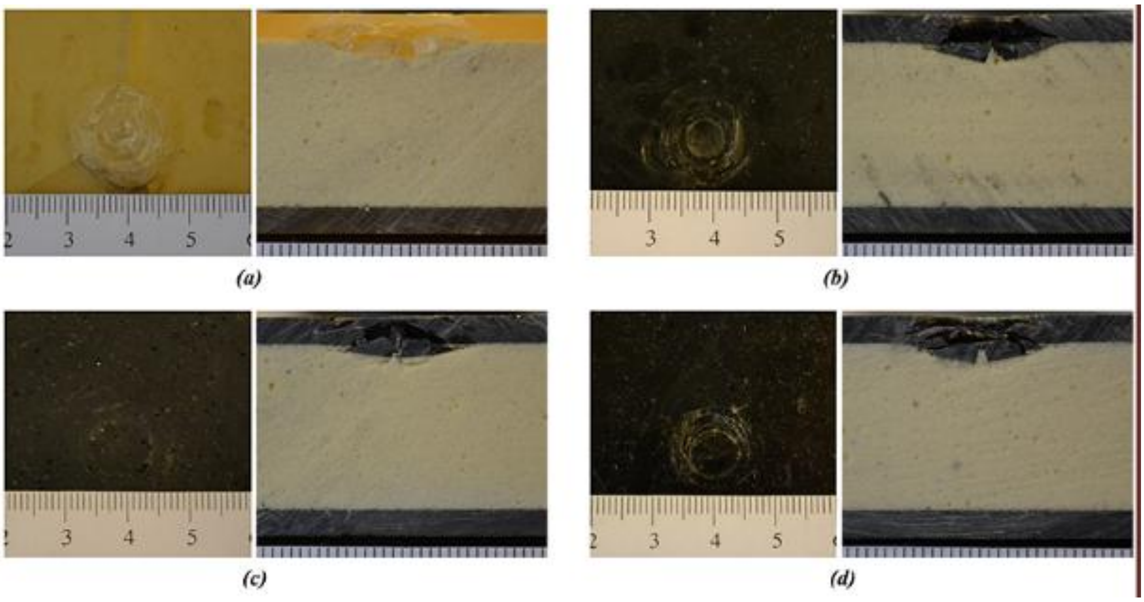

Fig. 9. Impact surface, (a). Neat, (b). 0.1 wt%, (c). 0.3 wt%, (d). 0.5 wt% FMWCNT face sheet at the impact energy 18.32 J.

FMWCNTs are reduced width and depth of damage; for example, 0.3 wt% FMWCNT reduced the width and depth by 20.8% and 12.9%, respectively.

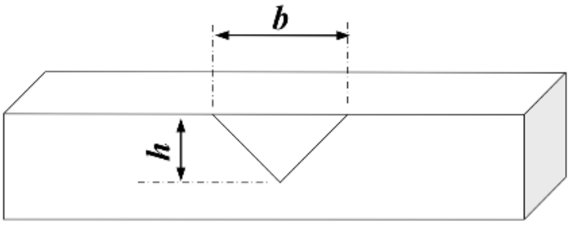

Fig. 10. A schematic picture of the damaged area.

5. Conclusions

In this research, the effects of FMWCNTs as the only reinforcing component in the sandwich plates under low-velocity impact were studied through experimental investigations. The samples contained 0 wt%, 0.1 wt%, 0.3 wt%, and 0.5 wt% FMWCNTs and the impact energy level applied was 6.65 J and 18.32 J. The results show that a minor amount of FMWCNTs, about 0.3 wt%, enhances the impact resistance of the specimens. It is also observed that with more than 0.3 wt% FMWCNTs, improvement of properties will stopped and even will reduced.

The findings can be summarized as follows:

1. Adding 0.3 wt% FMWCNTs to the face sheets reduce the bounce time and increase the upward velocity by up to 16% and 26.7%, respectively.
2. Adding 0.3 wt% FMWCNTs to face sheets increased maximum peak load at the energy levels of 6.65 J and 18.32 J by up to 52% and 41.4%, respectively.
3. Adding 0.3 wt% FMWCNTs to face sheets decreased maximum peak load at the energy levels of 6.65 J and 18.32 J by up to 11% and 10%, respectively.
4. The damaged area decreased with the increase in FMWCNT content.

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Table 7. Damage dimensions at the impact energy 18.32 J.

wt % FMWCNT	Width, *b*(mm)	% Decrease	depth, *h*(mm)	% Decrease
0	21.1	---	7	---
0.1	17.2	18.5	6.5	7
0.3	16.7	20.9	6.1	12.9
0.5	16.9	19.9	6.3	10

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