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Experimental Investigation of Low-Velocity Impact Response of Plain-Weave Glass/Epoxy Composites Reinforced with Carbon Nanotubes

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Abstract

The low-velocity impact (LVI) response of the plain-weave glass/epoxy laminated composites, which were reinforced with various contents of carbon nanotubes (CNTs) was performed using a drop-weight Fractovis Plus impact machine. The nanocomposite plates were fabricated using hand lay-up (HLU) method. The effect of carbon nanotube addition into the epoxy resin is examined. The influence of the nanocarbon contents on the impact response was achieved by using 1 wt%, and 1.25 wt%. The low-velocity impact responses of the nanocomposite plates were compared, and the effect of CNT on the damaged area after impact was also discussed. The fillers adding changes the low-velocity impact (LVI) response of the plain-weave glass/epoxy laminated composites. Experimental results clearly demonstrated that the samples fabricated by various contents of carbon nanotube (CNTs), have a bigger damage area and more penetration threshold than the control samples (neat). Moreover, the plates with 1 wt % carbon nanotubes have the highest reaction force.

Keywords: Low-velocity impact, Carbon nanotubes (CNTs), Glass/epoxy laminated composites, Damaged mechanism modulus

Karbon Nano-Tüp Katkılı Düz Örgü Cam-Epoksi Kompozitlerin Düşük Hızlı Darbe Deneylerinin Deneysel Olarak İncelenmesi

Öz

Bu çalışmada, Çeşitli oranlarda karbon nanotüp katkılı düz örgü cam epoksi tabakalı kompozitlerin Fractovis Plus darbe cihazı ile düşük hızlı darbeye gösterdikleri tepki araştırılmıştır. Nanokompozit plaklar el yatırma yöntemi ile üretilmiştir. Epoksi reçine içerisine katılan karbon nanotüp etkisi incelenmiştir. Ağırlıkça %1 ve %1,25 oranları kullanılarak nanokarbon içeriğinin etkisi darbe üzerindeki etkisi elde edilmiştir. Nanokompozit plakların düşük hızlı darbe tepkileri karşılaştırıldı ve darbe deneyi sonrası hasar alanı üzerine CNT etkisi incelenmiştir. Eklenen dolgu maddeleri düz örgü cam/epoksi kompozitlerin düşük hızlı darbe tepkilerini değiştirdi. Sonuçlar çeşitli oranlarda CNT katkılı olarak üretilen numunelerin katkısız numuneye göre hem daha büyük hasar alanına hem de daha büyük penetrasyon eşik enerjisine sahip olduğunu göstermiştir. Ayrıca, ağırlıkça %1 CNT oranlı plaklar en yüksek reaksiyon kuvvetine sahiptir.

Anahtar Kelimeler: Düşük hızlı darbe, Karbon nanotüpleri (CNT'ler), Cam/epoksi lamine kompozitler, Hasar gören mekanizma modülü

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1. INTRODUCTION

In recent years, researchers have been used CNTs reinforced composite materials because of the extraordinary mechanical and physical properties of the CNTs. The CNTs reinforced composite materials have been used wide range of applications in aeronautic and astronautic technology, power plant, automobile and many other modern industries. During their service life, these composite structures have been subjected to variety of loading conditions. One of the crucial conditions that can affect their applications is the low velocity impact loading condition. For this reason, it is important accurate investigation of their mechanical behaviour under such a loading for the life assessment of composites in service conditions.

Among the most commonly used materials in industry are polymer-based composites due to high mechanical properties and significant weight reduction in structural design.

From the literature study, it is seen that extensive study has been carried out to response of fiber reinforced composite material under impact loading [1-14]. The impact resistance and damage tolerance of fiber-reinforced composites for various types of nanoparticles have been investigated a number of researches.

One of the major concerns of CFRP composite structure is the low impact resistance is because of its poor susceptibility to impact damage. In this study, the low-velocity impact response of the plain weave glass/epoxy laminated composites, which were reinforced with various contents of functionalized short length multi-walled carbon nanotubes- DWCNTs (i.e., 1wt% and 1.25wt%) was carried out by using a drop-weight impact machine. The nanocomposite beams were fabricated using by hand lay-up (HLU). The main objective of this work was to develop and study the behavior of nano modified GFRP composites under low velocity impact tests. The impact tests were carried out varying impact energy levels to examine the damage tolerance of composite laminates.

2. EXPERIMENTAL PROCEDURE

2.1. Preparing Matrix

In this work, carbon nanotube fillers were dispersed in epoxy system by using ultrasonic mixer and hand lay-up techniques were used for manufacturing nano size reinforced and unreinforced composite plates. The biggest problem in nano particulate reinforced composite is agglomeration. Many methods are being used for dispersing nano particulates homogenously inside epoxy system without agglomeration. Most efficient way to overcome this problem is using ultrasonic mixer. In this method, ultrasonic sound waves distribute the agglomerated nano particle. Hielscher UP-400S brand name ultrasonic mixer was used in study. Short length multi-walled carbon nanotubes – DWCNTs was provided from Ege Nanotek Inc., İzmir, Turkey and added 0, 1 and 1.25% in weight with respect to resin. Epoxy resin and catalysts were provided from Fibermak Corporation. Before using ultrasonic mixer, CNT reinforced epoxy mixture is mixed by hand. After that the mixture was subjected to high frequency sound waves for one hour. To prevent heat rising and start self-curing in the epoxy solution, cooling cup is used. Approximately, 5^{o}C water is recirculated between cup and unit. Ultrasonic mixer and cooling device is shown in Figure 1. Fluidity and translucent color of epoxy solution is evidence for homogenous mixture.

Figure 1. Ultrasonic mixer and cooling device

2.2. Producing Composite Plate

Nano reinforced composite plates were produced from plain weave glass fiber and epoxy resin which containing carbon nanotube. Used E-glass plain weave fabrics were manufactured by Cam Elyaf Sanayi Corporation and unit weight is 200 g/m^2. Nano reinforced plates were produced using resin impregnated fabric (prepreg) and pressed under heat press machine.

Desired concentration mixture are distributed on surface of 400x400 mm size [0/90] plain weave fabric by using hand lay-up technique. 15 ply fabrics were used to obtain 2 mm thickness. Resin impregnated fabrics are left to dry at room temperature for 10 days. In this way producing prepreg glass fabrics were finished. After 10 days semi-finished fabrics were added up and wrapped with noninflammable film after that they were placed inside hydraulic heat press machine. Firstly fabrics were exposed to 100 MPa pressure after that temperature was raised from room temperature to 125^{o}C. Plate was waited for one hour with these circumstances. After one hour heater was terminated, but pressure was still applied.

Plate was slowly decreased to room temperature. To prevent thermal distortion, plate should stay in heat press until to room temperature. Approximate fiber volume fractions of plates were found 60%. Thus 2 mm in thickness and 400 mm in length square plates were manufactured. [15]. Manufacturing steps were illustrated in Figure 2. Composite plates were cut to 100 mm square specimen by using water jet cutter because composite plates were sensitive to machining

2.3. Low Velocity Impact Test

Low velocity impact test was conducted according to ASTM D5628-07. The samples were cut into 100×100mm by using a diamond cutter. Composite plates, which containing different concentration of nano fillers, were subjected to low velocity impact test at room temperature by releasing the weight. Tests were done at Dokuz Eylül University's laboratory by using Fractovis Plus test machine. Figure 3 shows the drop weight impact test machine. In this test method, impactor geometry was hemispherical nose of 12.7 mm in diameter, weight is 4.926 kg.

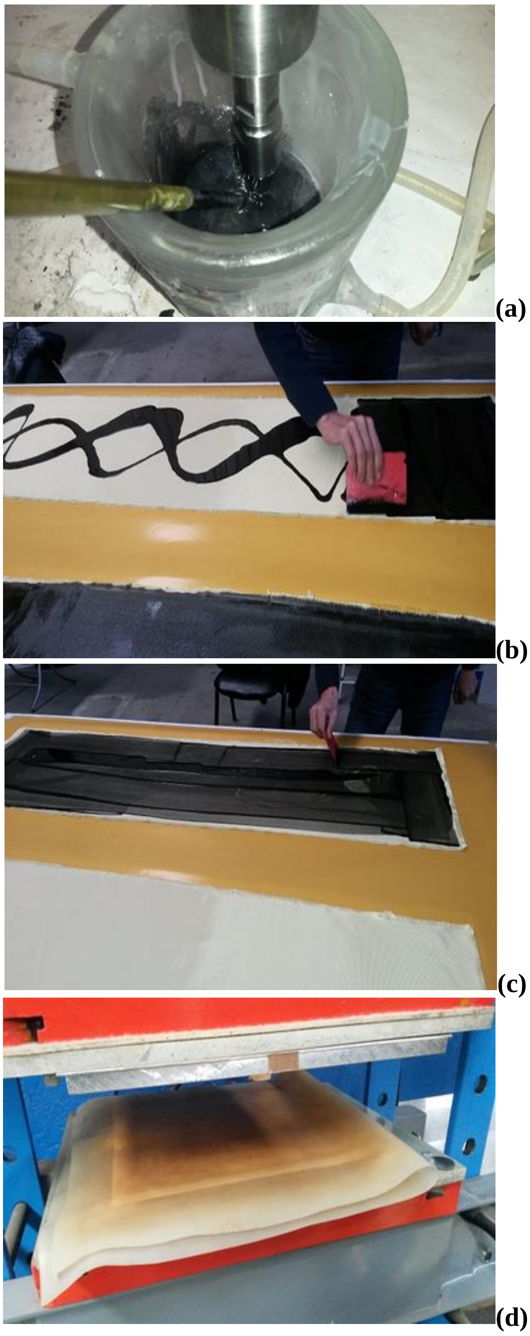


Figure 2. Manufacturing steps of nano reinforced composite plate (a, b, c, d)

(a)

(b)

Figure 3. Drop weight impact test machine (a, b)

Specimens were placed at the bottom of the machine and impact was happened in the middle of the specimen. Specimen was clamped with inner diameter 76 mm hole fixture. Fixed boundary condition was implemented. Multiple strikes were precluded by pneumatic brake. To identify rebounding, penetration and perforation threshold for different nano fillers in impact test, impact energies were changed by shifting velocity. For this work, impact energies were taken as 20, 30, 35 and 40 J.

3. RESULTS AND DISCUSSION

3.1. Force–Displacement Curves

Impact tests were done at different energy levels: 20, 30, 35 and 40 J. Figure 4(a) ve (b) and 5 show force versus displacement response of pure, 1wt% and 1.25wt% CNT laminates for 20, 30 and 40 J energy levels. Rebounding, penetration and perforation situations were identified by interpreting the curve. In these curves load was increased from beginning to a maximum value, Pmax, after that load was significantly reduced. Maximum load represent threshold value before specimen undergoing major damages [16,17]. Slope of the curve up to maximum value is called bending stiffness.

According to 20 J impact energies, adding carbon nanotubes into an epoxy matrix has increased impact resistance. The highest reaction force was shown from 1wt% CNT containing specimen. This specimen’s maximum reaction force is 5% higher than that of pure one. After maximum force point exceeded, specimen undergoes major damages, such as extensive matrix cracks, fibre breakage and delamination. First peak in force was seen around 2500 N for pure specimen. In this region, initial damages were started, such as matrix cracking and delamination. All curves are closed form. It means that impact nose was rebounded from specimens’ surface and displacement value is come back to zero value. Comparing displacement values of specimens’, the biggest value belongs to pure specimen and the lowest value belongs to 1wt% CNT containing specimen.

According to 30 J impact energies, all specimens showed similar bending stiffness. Same as 20 J impact test, 1wt% CNT containing specimen showed the highest reaction force. Peak reaction force was increased compared to previous test. Difference increased to 13% between pure specimen and 1wt% CNT containing specimen. For 1wt% CNT containing specimen's force-displacement curve ended up with certain displacement value in this energy level. This means that impact nose got stuck in specimen's surface after impact (penetration). Pure and 1.25wt% CNT containing specimens peak reaction forces were decreased compared to previous test. For these specimens curves ended up with turned towards to right and specimens were perforated. The reason for decreasing reaction force and perforation for 1.25wt% CNT containing specimen is insufficient mixing time and agglomeration.

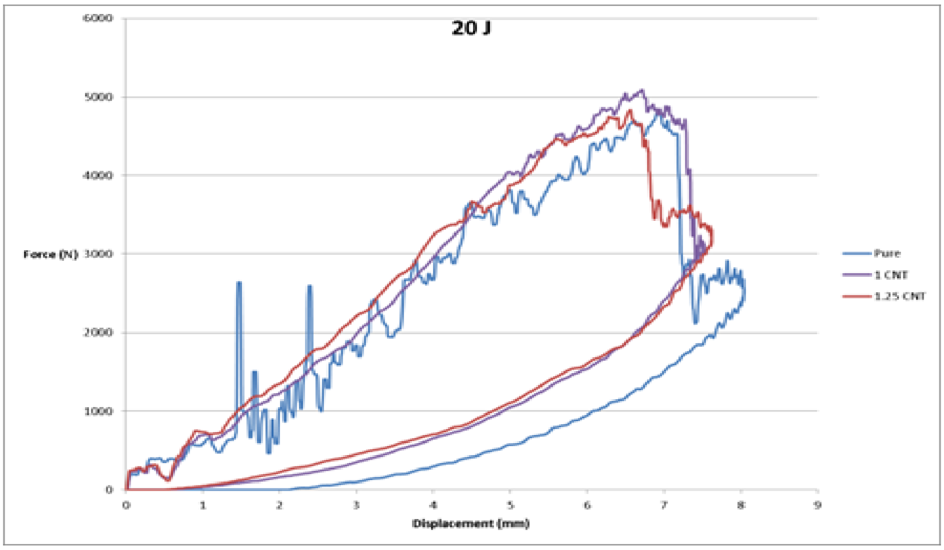


Figure 4(a). Force–displacement curves for 20 J impact level

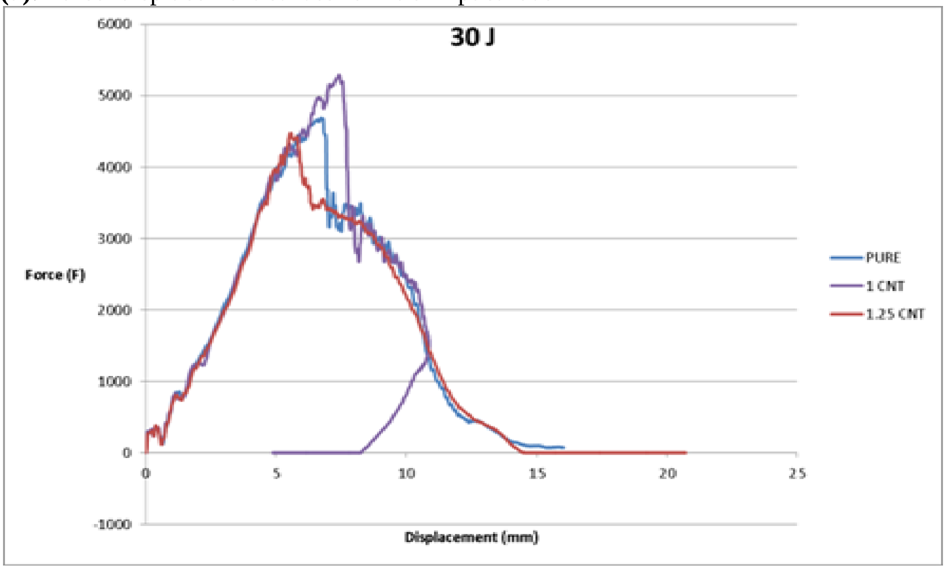


Figure 4(b). Force–displacement curves for 30 J impact level

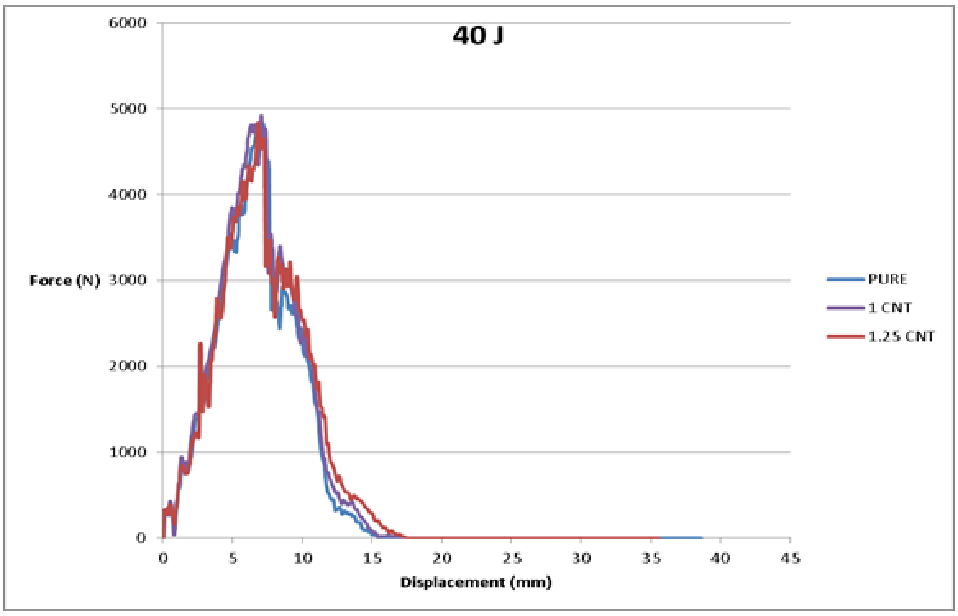


Figure 5. Force – displacement curves for 40 J impact level

All specimens were subjected to 40 J impact energy and all of them were perforated. After showing its top value in 30 J impact level, 1wt% CNT containing specimen's maximum reaction force was decreased. Other specimens' maximum reaction forces were increased as compared with previous test. Difference of reaction force between pure and 1wt% CNT containing specimens was only 2%. Figure 6 shows effect of CNTs of glass fiber/epoxy composites for different energy levels. As shown in Figure 6, the highest reaction force was obtained from 1wt% CNT containing specimens.

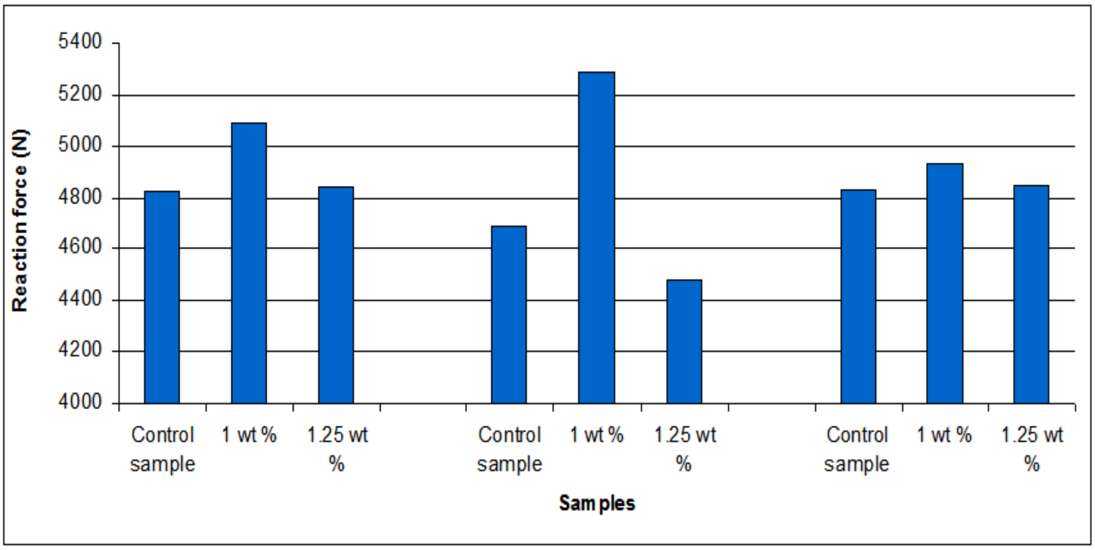
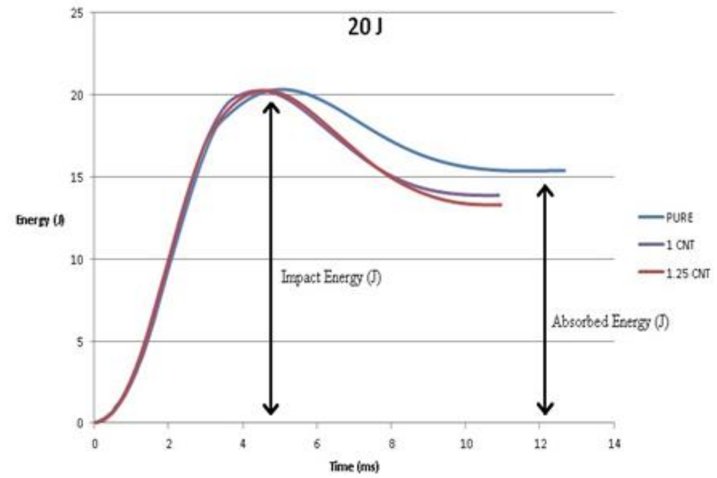


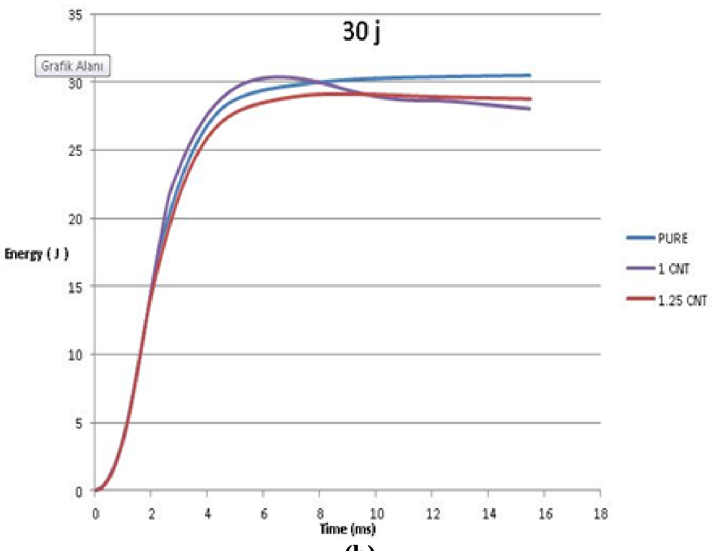
Figure 6. Effect of CNTs of glass fiber/epoxy composites for different energy levels

3.2. Energy–Time Curves

Energy–time curves could be used for identify how much energy is absorbed by specimen after impact. Absorbed energy could be found by substituting elastic energy, which was given back to the impact nose from specimen, from maximum impact energy. Decrease in elastic energy means that specimen is getting close to penetration threshold energy and specimen takes more damages [16,17]. Various concentrations of CNT containing composite plates' energy–time responses are shown in Figure 7 (a,b) and 8 for different impact energies.



(a)



(b)

Figure 7. Energy–time curve for 20 J and 30 J impact level (a, b)

In 20 J impact energy test, energy was increased to maximum value, which was impact energy, after this point energy decreased to permanent certain value. The difference between these two levels was given back to system. Impact noses for all tests were touched to surface and rebounded. The biggest absorbed energy was shown from pure specimen. The higher absorbed energy means that specimen took more damages. The lowest absorbed energy was obtained for 1.25wt% CNT containing specimen. This specimen absorbed 66% of subjected energy and rest of the energy was given back to system. This value was come to 70% for 1wt% CNT containing specimen.

Absorbed energies increased after impact energy was arranged 30 J so elastic energy value decreased. Damage area got bigger. 1.25wt% CNT containing specimen did not reach to impact energy. This specimen perforated before absorbed enough energy. Penetration threshold lay between 20 J and 30 J for this specimen. The reason for this situation is specimen's rigidity increased and also embrittlement increased with addition of CNT. Pure specimen did not decrease after maximum value and perforated. Only 1wt% CNT containing specimen showed small decrease after maximum point. In 40 J impact energies, none of the specimens reached impact energies.

They could not show elastic energies. The biggest energy absorption was shown from 1.25wt% CNT containing specimen and the lowest energy absorption was shown from pure specimen.

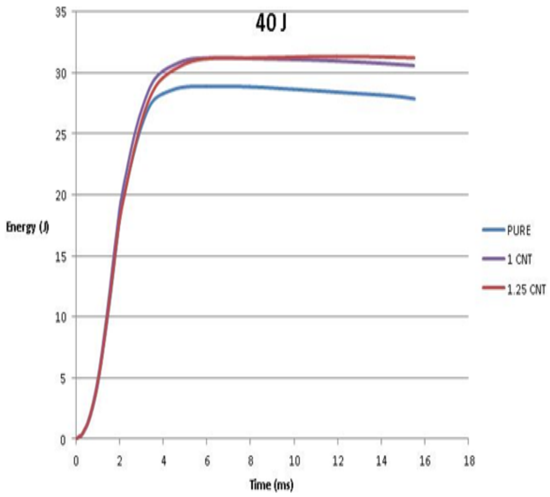
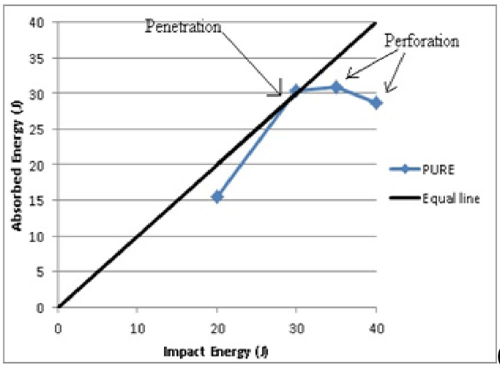


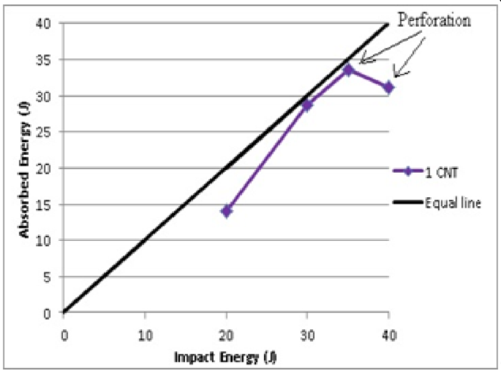
Figure 8. Energy–time curve for 40 J impact level

3.3. Energy Profile Diagram (EPD)

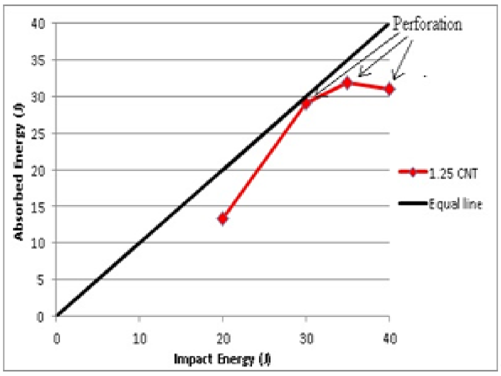
Energy profile diagram (EPD) is useful for identifying penetration and perforation threshold energies [3]. In this diagram, equal line is drawn for determine the penetration threshold. When absorbed energy is equal to impact energy and coincides with equal line this specimen's situation is called penetration. Higher impact energies than penetration energy causes perforation [16,17].



(a)



(b)



(c)

Figure 9. Energy profile diagrams for various concentration of CNT (a,b,c)

Figure 9 (a,b,c) show different concentrations of CNT's energy profile diagrams. According to diagram, pure and 1.25wt% CNT reinforced specimens got penetrate and perforate earlier than 1wt% CNT containing specimen. Control specimen's penetration threshold is around 28 J, interestingly 1.25wt% CNT containing specimen do not approach to equal line so it is hard to obtain penetration threshold value, but in the light of force-displacement and energy-time curves, it should be located between 20 and 30 J levels. Highest penetration value was shown from 1wt% CNT containing specimen, which was between 30 and 35 J levels.

3.4. Characterization of Impact Damage

Short length multi-walled carbon nanotubes–DWCNTs containing plates' damage mechanisms were shown from Figure 10–12. As shown in Figure 10, it was investigated by visual inspection for 20 J impact energies response. Perforation situations were not seen for any of the specimens, but desired transverse crack could only be seen from 1wt% CNT containing specimen.

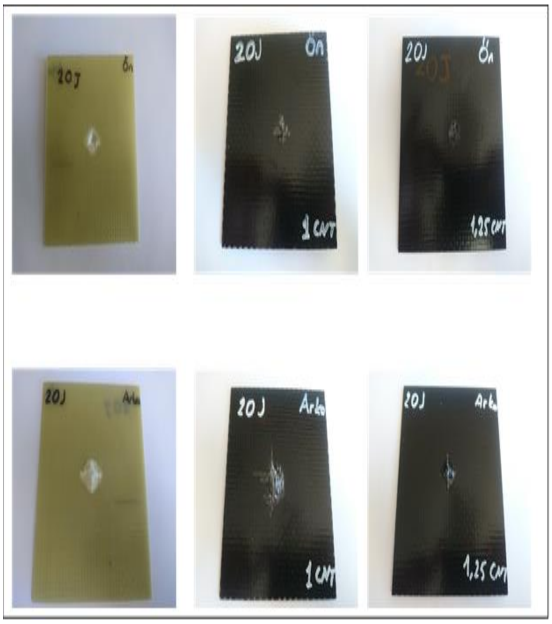


Figure 10. Damage areas for various concentration of CNT in 20 J impact energy

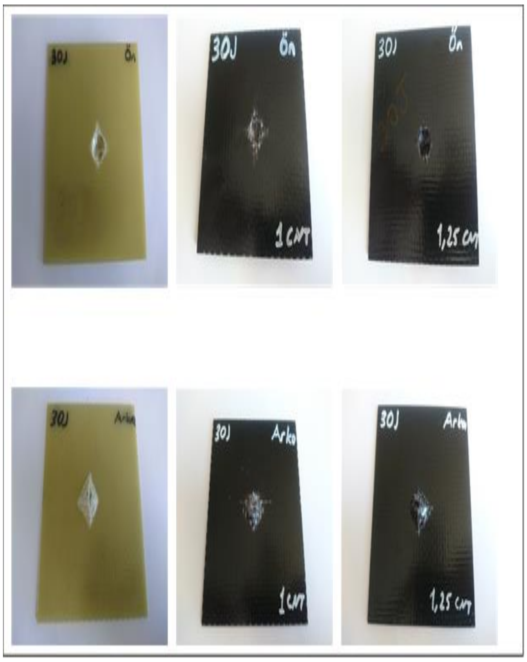


Figure 11. Damage areas for various concentration of CNT in 30 J impact energy

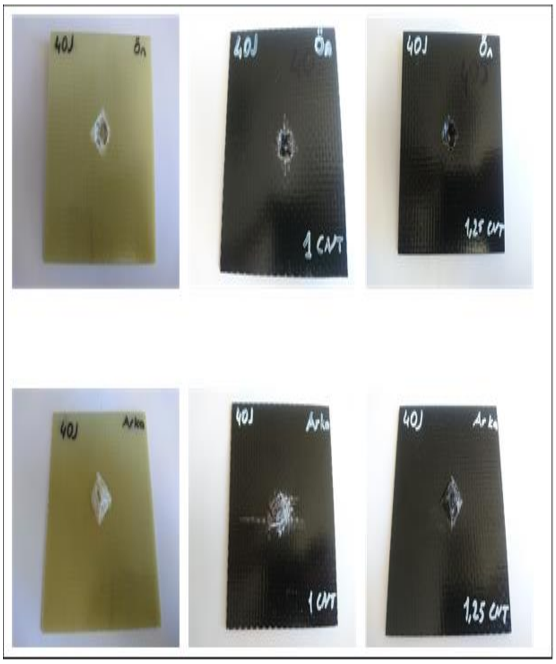


Figure 12. Damage areas for various concentration of CNT in 40 J impact energy

The smallest damage area was shown from 1.25wt% CNT containing specimen. The results are completely matched with force-displacement curve.When impact energy increased to 30 J, damage area also increased. The biggest damage area was seen from 1wt% CNT containing specimen. Impact energy was absorbed in longitudinal direction after that crack propagation occurred through thickness direction.

Perforation was occurred for pure and 1.25wt% CNT containing specimens.After impact energy increased to 40 J in drop weight impact test, all specimens could not absorb the load and specimens perforated. Fiber breakage and delamination was main failure mechanism. 1wt% CNT containing specimen showed deformation through fiber direction, it means transverse direction. Other specimens' showed circular impact damage.

4. CONCLUSION

The low-velocity impact (LVI) tests on composite plates that were reinforced with different loadings of short length multi-walled carbon nanotubes–DWCNTs were experimentally investigated. Two different content of short length multi-walled carbon nanotubes–DWCNTs (0, 1 and 1.25wt%) were used to evaluate their effects on the response of the low velocity impact loading.

In this experimental work, 1 and 1.25wt% short length multi-walled carbon nanotubes–DWCNTs added into epoxy matrix and compared with pure one. Plain weave E-glass fabrics were used for producing composite plates. Impact properties were investigated at room temperature. Tests have done at 20 J, 30 J, 35 J and 40 J impact energies. Penetration and perforation threshold was identified by using force–displacement, energy–time and energy profile diagram. According to tests results the lowest penetration threshold energy and the biggest penetration energy was seen from pure and 1wt% CNT containing specimens, respectively. 1wt% CNT containing specimen showed the highest reaction force and the lowest displacement value. Impact nose was rebounded from specimen surface at 20 J impact energies and were perforated at 40 J impact energies for all specimens. Main failure mechanisms for specimens' were fiber breakage and delamination.

5. ACKNOWLEDGEMENTS

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