Aero2015P460

The 14th International Conference of Iranian Aerospace Society
Communication and Space Technology, Iranian Research Organization for Science and Technology, Tehran, 3th to 5th of March, 2015.

The 14th International Conference of Iranian Aerospace Society

Reinforcing Effect of Carbon Nanotubes on Flexural Behavior of Carbon Fiber/Epoxy Grid composite Structures-Experimental Investigation

Alireza Shahrabi Farahani[1], Reza Eslami Farsani[2], Seyed Mohammad Reza Khalili[3], Mohammad Reza Zamani[4]
Center of Excellence for Research in Advanced Materials and Structures, K.N. Toosi University of Technology, Tehran, Iran
1,2- Faculty of Materials Science and Engineering, K.N. Toosi University of Technology, Tehran, Iran
3,4- K.N. Toosi University of Technology, Tehran, Iran

Abstract

The present study represents the influence of multi-walled carbon nanotubes functionalized with carboxyl groups (MWCNT-COOH) on flexural behavior of carbon fiber reinforced polymer (CFRP) grid composite structures with anisogrid lattice patterned reinforcement formed by helical and longitudinal ribs. Three-point bending test has been carried out using Hounsfield testing machine. The epoxy/MWCNT nanocomposites with different carbon nanotubes content (0, 0.1 and 0.4 wt. % of MWCNT) were used as the matrix of grid composite structures. The results of flexural test demonstrate that the maximum flexural load and energy absorption of grid samples increase from 0% to 0.4% with increasing the nanotube content. Maximum value of improvement in maximum flexural load and energy absorption are 20% and 35% for the samples with 0.4 wt. % of MWCNTs.

Keywords: *Grid composite structures- Carbon nanotubes- Nanocomposite- Three point bending test- Maximum flexural load- Energy absorption*

Introduction

Materials with excellent mechanical properties such as high strength, high stiffness and low weight are highly concerned in structural design, for this reason, composite materials are being widely used in the field of aerospace Structural efficiency is a primary concern in today's aerospace industry[1].

Grid composite structures have been developed and used for aerospace such as launch vehicle payload fairing, interstage ring, engine ducting, and for load bearing structures of satellite and civil infrastructure applications in recent years due to their high impact and fatigue resistance, high strength and stiffness to weight ratios, high energy absorption and damage tolerance. Grid composite structures provide a great potential to replace conventional metal structures by offering higher strength to weight ratio [2-5].

Grid structures are characterized by a shell (or skin) supported by a lattice pattern (or grid) of stiffeners. In these structures, the ribs are the main load-bearing members, whereas the skin is not considered as a load bearing element in design of grid structures [6].

Using stiffeners significantly increases the load resistance of structure without much increase in weight [7]. To further reduce the weight and improving the mechanical properties of the structure, both the shell and the stiffeners are made with fiber-reinforced polymers [8].

The optimum type of stiffener configuration is indicated by the type of application, the loading condition, cost, and other factors. Generally, the type of grid structure is determined by angle and direction of the grid [9]. Types of the grid are classified as Angle-grid structure, Iso-grid structure, Kagome-grid structure, Ortho-grid structure and Orthotropic-grid structure. Angle-grid structure and Ortho-grid structure consist of 2 direction grids, Iso-grid structure and anisogrid structure consist of 3 direction grids and Orthotropic-grid structure consist of 4 direction grids[1].

These structures have capabilities of plain composite structures and stiffened structures with each other. Fiber breaks, cracking and fracture of matrix, delamination, shear degradation modes, rib-skin debonding and the combination of the above, examples of failure that for this type of structures can occur[10]. It often occurs during service loading, and consequently results in structures efficiency lost before catastrophe failure [11].

Due to the critical applications of grid composite structures in the aerospace industry, it is necessary that these structures have a long life under service conditions and show more resistance against damage caused by various loading. The introduction of nanotechnology in the field of composite materials with nanoscale fillers, such as carbon nanotubes (CNTs) and carbon nanofibers (CNFs) into polymer matrices like epoxy presents a new generation of composite materials [12-16]. In fact with the use of nanoscale fillers, mechanical properties of grid composite structures can be improved which thus their efficiency will be increased.

---

1. M.Sc. Student
2. Assistant Professor, Tel. (+9821) 84063218, eslami@kntu.ac.ir (corresponding author)
3. Professor
4. Ph.D. Student

Carbon nanotubes have remarkable stiffness and strength, extraordinary resilience, remarkable thermal and electrical properties, their exceptionally high aspect ratio, combined with specific stiffness and strength makes carbon nanotubes an ideal candidate for reinforcement in composite materials.

One of the most critical challenges in fabricating carbon nanotubes reinforced composites is the dispersion of carbon nanotubes in polymer composites. Carbon nanotubes due to large surface area and high aspect ratio tend to agglomerate greatly. Agglomeration of carbon nanotubes may work as stress concentration zones which causing a deterioration of mechanical properties for the final nanocomposite materials [17]. Various methods to disperse nanotubes in polymer resins, such as stirring, sonication and high shear mixing have been reported in literature [18-21].

Also, the interfacial adhesion between the carbon nanotubes and polymer remains a critical issue. To have sufficient stress transfer from the matrix to the carbon nanotubes and to efficiently use the potential of carbon nanotubes as structural reinforcement, a strong interfacial adhesion between the carbon nanotubes and polymer is desired. The interfacial adhesion between carbon nanotubes and matrix was reported to improve by functionalizing carbon nanotubes [22-28].

In the current study, the influence of carbon nanotubes functionalized with carboxyl groups on flexural behavior of grid composite structures with anisogrid lattice patterned reinforcement formed by helical and longitudinal ribs. The epoxy/ MWCNT nanocomposites with different carbon nanotubes content (0, 0.1and 0.4wt.% of MWCNTs) were used as the matrix of grid composite structures. The obtained results were then used to determine the flexural properties of structures.

Raw materials

The epoxy resin used was ML-506 (Bisphenol-F) with the polyamine Hardener HA-11 was supplied by Mokarrar Engineering Materials Co, Iran. The composition of the base matrix formulation was the mixture of 15 parts by weight of the hardener with the epoxy, which provides the pot life of 20 minutes at room temperature. The resin properties based on company datasheet is shown on table1.

Table 1: ML-506 Epoxy resin properties

Density (gr/cm^3)	Viscosity (Centipoise)	Flexural strength (MPa)	Flexural modulus (GPa)
1.11	1450	96	3.6

In this research, unidirectional carbon fiber(IC-300) supplied by research and development of advanced fibers Institute Iran, was used as reinforcement of ribs. The properties of Carbon Fiber based on company datasheet are shown on table2. E-glass woven fabric supplied by Lintex International Co., Ltd, China, was used as a reinforcement of skin. Product density of fabric is 400gr/m^2.

Table 2: Unidirectional carbon fibers reinforcement characterization

Density (gr/cm^3)	Diameter (µm)	Tensile Modulus(GPa)	Tensile Strength(MPa)
1.76	7.6	180	2300

MWCNTs provided by Cheap Tubes Inc. carbon nanotubes are produced through the catalyzed chemical vapor deposition (CCVD) process. The physical properties of MWCNTs as provided by the manufacturers are shown in Table3. TEM image of multi-walled carbon nanotubes is shown on Fig. 1.

Table 3: Physical properties of MWCNTs

Diameter (nm)	Length (nm)	purity	Specific surface area (m^2/g)	COOH content (wt %)
10-20	10-30	>95%	230	2

Mold fabrication

First, with the use of CNC machine, template of grid structure was created in poly vinyl chloride (PVC) sheet. for making mold, silicon molding RTV-03325 was used. This is a two-component silicone molding and by adding hardener (6H) at a ratio of 100:4 is capable of curing at ambient temperature. Silicon molding was poured on templates and was cured for 3 hour at room temperature. The mold used for fabrication of grid structure was shown on Fig.2.

Sample preparation

To fabricate the grid composite structures, the Epoxy/MWCNT resin must be first prepared. For this purpose, the following procedure should be conducted. First, epoxy resin was diluted with acetone solvent in a ratio of 100:15. Reducing the viscosity of the resin, provides a suitable situation for disperse of carbon nanotubes into epoxy matrix. And then, the desired amount of carbon nanotubes (0,0.1 and 0.4 wt.%) was introduced into the epoxy resin and mixed well using a high speed shear mixing at a shear rate of 2000 rpm for 20 minute. after that, In order to break the residual aggregates and obtain a good dispersion of carbon nanotubes, the mixture was sonicated for 1 hour. during the sonication, the mixture container was held in water to keep the temperature around 45℃. afterwards, the mixture was vacuumed at 0.1 bar for 20 min to degass the mixture.

The grid composite structures were manufactured using a manual filament winding method. Unidirectional carbon fiber rovings were impregnated with epoxy resin that modified with carbon nanotubes and then laid up into grooves of silicone mold layer by layer to form the ribs of grid structure. In the next step, laying up the skin using 4 layers of E-glass woven fabrics was carried out. The skin thickness of all the specimens was 1.8 mm. After completion of the manufacturing process, 3 hours at room temperature is required until curing process of resin was performed. In order to achieve maximum strength and ultimate curing, samples for 7 days were placed at room temperature. The fabricated specimens are shown in fig.3. The cross-section area of all ribs was a quadrangle with the area 6×6 mm^2. The specimens were characterized by length of 300mm and width of 125mm. Details of fabricated specimens is shown on table 4.

Table 4: Characteristics of fabricated specimens

Sample code	MWCNTs content (wt.%)	Content of carbon fibers in ribs (Vol %)	Content of glass fabric in skin (Vol%)
A0	0	20	48
A1	0.1	20	48
A2	0.4	20	48

Three-Point Bending Test

Three-point flexural test was performed to investigate the flexural properties of grid composite structures with and without of MWCNTs. Hounsfield test machine with a capacity of 25 KN was used for testing specimens. The tests were performed based on ASTM D7264. Loading rate of the machine was chosen 5 mm/min and span length kept to 250 mm. In this condition, the span-to-thickness ratio was 32:1. During the loading, the load versus the displacement curve for each specimen was recorded in the testing system. To ensure the test results, each experiment was repeated at least 3 times. Fig.4. shows the grid composite specimen in the fixture in three-point bending test.

Results and Discussion

Three-point bending test on CFRP grid composite structures was performed from the skin side until displacement of 90mm. It should be noted that under flexural loading, samples from the skin side were under compression and from the rib sides were under tension. Summary of flexural test results as a function of MWCNTs content are shown in Table5.

Fig.5. shows the Load–displacement curves of the grid composites and nanocomposites obtained from the three-point bending test.

It is evidence from fig.6 with the increase in weight percentage of MWCNTs, the maximum load bearing of the CFRP grid composite structures increases continuously. The greatest increase in the value of maximum flexural load was observed for the specimens with 0.4 wt. % of MWCNTs. In this condition, 25% increase in maximum flexural load was observed compared to the grid composites without MWCNTs. The main failure mechanisms of grid composite structures include fiber breakage of longitudinal ribs and fiber micro-buckling in skin. The enhancement in maximum flexural load by adding MWCNTs to the grid composite structures was due to the effective incorporation of MWCNTs as a result an effective load transfer from resin matrix to fibers is created. In these composites, fibers are the main load-bearing element. The presence of carbon nanotubes at the fibers reduce the stress concentration on the surface of fibers and increase the shear strength of interface between matrix and fibers As a result, improve the load-bearing capacity of grid composite structure.

According to fig.7, with increasing the weight percentage of MWCNTs, the energy absorption of grid composite structures increases continuously. It should be noted that maximum energy absorption in the grid composite structures obtained after reaching the maximum value of flexural load (initial failure). At 0.4 wt. % of MWCNTs the energy absorption of grid composite structure increases about 35%. Carbon nanotubes increase the interfacial strength and the energy required to form cracks. As a result, improve the energy absorption of grid composite structure.

Table5: Summary of the reinforcing effect of the MWCNTs on flexural behavior of the grid composite structures

Coding	Maximum flexural load (N)	Energy absorption(J)
A0	850	22
A1	890	24
A2	1050	28

Conclusions

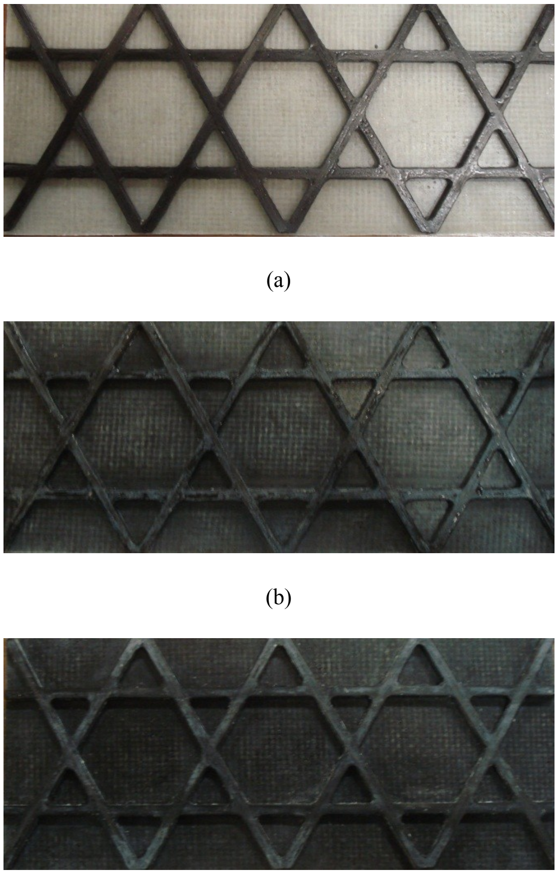
In the current study, the influences of MWCNTs that functionalized with carboxyl groups on flexural behavior of unidirectional carbon Fiber/ epoxy anisogrid composite structures formed by helical and longitudinal ribs are studied experimentally. The following conclusions can be drawn:

1- With addition of 0.4wt. % of MWCNTs the maximum flexural load of grid composite increases 25% in comparison to the grid composite structure without carbon nanotubes.
2- The maximum energy absorption was observed for specimens containing 0.4wt.% of carbon nanotubes.
3- Improvement of flexural properties at 0.4wt.% of MWCNTs was due to improvement in the interfacial properties and effective load transfer from resin matrix to fibers.

Figures and Drawings

Fig. 1: TEM image of multi-walled carbon nanotubes that functionalized with carboxyl groups.

Fig. 2: Silicone mold used for fabrication of grid composite structures.



(a)

(b)

(c)

Fig. 3: Grid composite structures a) Without MWCNT. b) Filled with 0.1wt% MWCNT. c) Filled with 0.4wt% MWCNT.

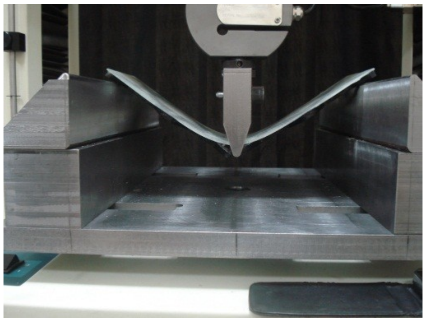
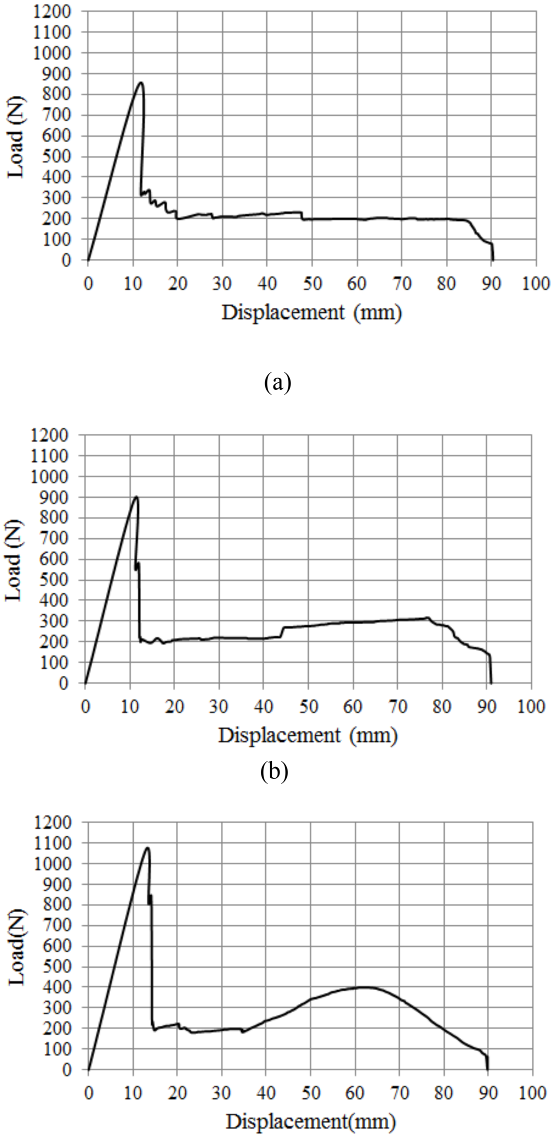


Fig. 4: The grid composite specimen in fixture in three-point bending test.



(a)

(b)

(c)

Fig. 5: Load-displacement curve of the composite a) for A0 samples b) for A1 samples c) for A2 samples subjected to flexural load.

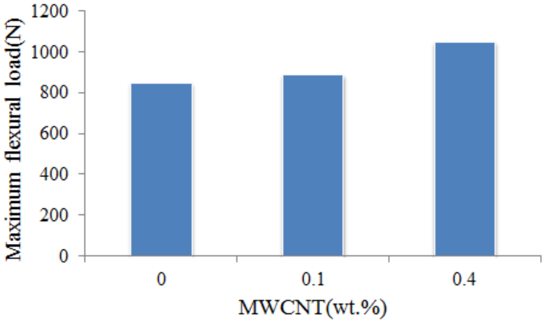


Fig. 6: Maximum flexural load of CFRP grid composite structures at different MWCNTs content.

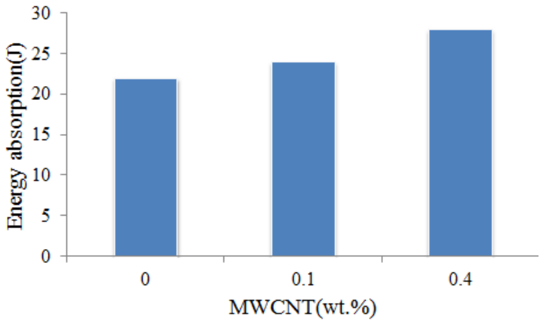


Fig. 7: Energy absorption of CFRP grid composite structures at different MWCNTs content.

References

1- Kanghee Lim, Wei He, Zhidong Guan, Buckling Analysis of Advanced Grid Stiffened Composite Cylinders, *Advanced Materials Research*, Vols. 875-877,2014, pp. 755-762.

2- E.V. Morozov, A.V. Lopatin, V.A. Nesterov, Finite-element modelling and buckling analysis of anisogrid composite lattice cylindrical shells, *Composite Structures*, 93, 2011, 308–323.

3- V.V.Vasiliev, V.A.Barynin, A.F.Razin, Anisogrid composite lattice structures-Development and aerospace applications, *Composite Structures*, 94, 2012, 1117–1127.

4- H.Kanou, S.M.Nabavi, J. E. Jam, Numerical modeling of stresses and buckling loads of isogrid lattice composite structure cylinders, *International Journal of Engineering, Science and Technology*, Vol. 5, No. 1, 2013, pp. 42-54.

5- Hualin Fan, Daining Fang, Fengnian Jin, Mechanical properties of lattice grid composites, *Acta Mech Sin*, 2008, 24,409–418.

6- V.V.Vasiliev and A.F.Razin, Anisogrid composite lattice structures for spacecraft and aircraft applications, *Composite Structures*, 76, 2006, 182–189.

7- G.Totaro, Local buckling modelling of isogrid and anisogrid lattice cylindrical shells with hexagonal cells, *Composite Structures*, 95, 2013, 403–410.

8- Jafar Eskandari Jam, Milad Noorabadi, Hossein Taghavian, Masoud Mohammadi, Nader Namdaran, Design of Anisogrid Composite Lattice Conical Shell Structures, *Researches and Applications in Mechanical Engineering (RAME)*, Volume 1, Issue 1, December 2012.

9- Eyassu Wodesenbet, Samuel Kidane, Su-Seng Pang, Optimization for buckling loads of grid stiffened composite structures, *Composite Structures*, 60, 2003, 159–169.

10- M. Hedayatian, GH.H.Liaghat, GH.H. Rahimi, M.H. Pol, M. Khoshsorour, Experimental study on dynamic response of grid cylindrical composite structures under high velocity impact, *Modares Mechanical Engineering*, Vol. 14, No. 2, pp.41-46, 2014 (In Persian).

11- He Jingxuan, Ren Mingfa, Sun Shiyong, Huang Qizhong b, Sun Xiannian, Failure prediction on advanced grid stiffened composite cylinder under axial compression, *Composite Structures*, 93, 2011, 1939–1946.

12- Shafi Ullah KHAN and Jang-Kyo Kim, Impact and Delamination Failure of Multiscale Carbon Nanotube-Fiber Reinforced Polymer Composites: A Review, *Int'l J. of Aeronautical & Space Sci*, 12(2), 2011, 115–133.

13- M.T. Kim, K.Y. Rhee , S.J. Park, D. Hui, Effects of silane-modified carbon nanotubes on flexural and fracture behaviors of carbon nanotube-modified epoxy/basalt composites, *Composites*, Part B, 43, 2012, 2298–2302.

14- Qi Chen, Weidong Wu, Yong Zhao, Min Xi, Tao Xu, Hao Fong, Nano-epoxy resins containing electrospun carbon nanofibers and the resulting hybrid multi-scale composites, *composites*, part B, 58, 2014, 43–53.

15- Y. X. Zhou1, P. X. Wu, Z-Y. Cheng, J. Ingram1, S. Jeelani, Improvement in electrical, thermal and mechanical properties of epoxy by filling carbon nanotube, *Express Polymer Letters*, Vol.2, No.1, 2008, 40–48.

16- Fawad Inam, DorisW. Y.Wong, Manabu Kuwata, Ton Peijs, Multiscale Hybrid Micro-Nanocomposites Based on Carbon Nanotubes and Carbon Fibers, *Journal of Nanomaterials*, 2010, 12 pages.

17- S.A.Meguid, J.M. Wernik, F.Al Jahwari, Toughening mechanisms in multiphase nano composites, *Int J Mech Mater Des*, 2013, 9,115–125.

18- S.G. Prolongo1, A. Jiménez-Suárez1 , B. G. Melitón1, M. Campo1, A. Ureña1, Optimum Dispersion Technique of Carbon Nanotubes in Epoxy Resin as a Function of the Desired Behaviour, *Journal of Nano Research*,Vol. 26, 2014, pp. 177-186.

19- Yan Yan Huang and Eugene M. Terentjev, Dispersion of Carbon Nanotubes: Mixing, Sonication,Stabilization, and Composite Properties, *Polymers*, 4, 2012, 275-295.

20- Peng-Cheng Maa, Naveed A.Siddiqui, Gad Marom, Jang-Kyo Kim, Dispersion and functionalization of carbon nanotubes for polymer-based nanocomposites: A review, *Composites*, Part A, 41, 2010, 1345–1367.

21- A.A.Sinar , M.A.NurAzni1 , Z.Firuz1 , M.A.Hazizan , M.S.Siti Shuhadah , H.A.Sahrim , Treatment methd for dispersion of carbon nanotubes: A review, *Materials Science Forum,* Vol. 803, 2015, pp 299-304.

22- S. Zainuddin , A. Fahim, T. Arifin, M.V. Hosur, M.M. Rahman , J.D. Tyson , S. Jeelani , Optimization of mechanical and thermo-mechanical properties of epoxy and E-glass/epoxy composites using NH_2-MWCNTs acetone solvent and combined dispersion method, *Composite Structures*, 110, 2014, 39–50.

23- M.T. Kim, K.Y. Rhee a, J.H. Lee, D. Hui, Alan K.T. Lau, Property enhancement of a carbon fiber/epoxy composite by using carbon nanotubes, *Composites*, Part B, 42, 2011, 1257–1261.

24- Merlin Theodore, Mahesh Hosur, Jonathan Thomas, Shaik Jeelani, Influence of functionalization on properties of MWCNT–epoxy nanocomposites, *Materials Science and Engineering*, A, 528, 2011, 1192–1200.

25- Zhiqiang Chen, Xiujuan J. Dai, Kevin Magniez, Peter R. Lamb, David Rubin de Celis Leal, Bronwyn L. Fox, Xungai Wang, Improving the mechanical properties of epoxy using multiwalled carbon nanotubes functionalized by a novel plasma treatment, *Composites*, Part A, 45, 2013, 145–152.

26- Leonel Matias Chiacchiarelli, Mariano Martin Escobar, Jose Maria Kenny, Luigi Torre, Analia Vazquez, The Role of the Interphase on the Shear Induced Failure of Multiwall Carbon Nanotubes Reinforced Epoxy Nanocomposites, journal of applied polymer sciences, vol.132, issue 4,2015.

27- Vikas Mittal, Carbon Nanotubes Surface Modifications, An Overview, John wiley, 2011.

28- Soo-Jin Park, Seul-Yi Lee, Fan-Long Jin, Surface Modification of Carbon Nanotubes for High-Performance Polymer Composites, Handbook of Polymer nanocomposites. Processing, Performance and Application, 2015, pp 13-59.