NUMERICAL EXPERIMENTAL STUDY ON INFLUENCE OF MULTIWALLED CARBON NANOTUBE ON INTERFACE FRACTURE OF SANDWICH COMPOSITE

Alak Kumar Patra[1], Nilanjan Mitra[2]

[1]Department of Civil Engineering, Indian Institute of Technology Kharagpur, Kharagpur, India
Email: alakpatra19@gmail.com, Web Page: http://www.dak.iitkgp.ernet.in/phd/profile.php?roll=12CE92P02
[2] Department of Civil Engineering, Indian Institute of Technology Kharagpur, Kharagpur, India
Email: nilanjan@civil.iitkgp.ernet.in , Web Page: http://www.facweb.iitkgp.ernet.in/~nilanjan/

Keywords: Carbon nanotube, epoxy resin, Foam, glass fibers, interfacial fracture, sandwich composite

Abstract

Finite element study was done with Abaqus Standard cohesive zone model and crushable foam hardening properties assuming surface to surface standard interaction between face sheet and core. Finite element study is followed by experimental investigation on interface fracture toughness of glass-epoxy (G/E) PVC core sandwich composite with and without MWCNT. Results demonstrate an improvement in interface fracture toughness values (Gc) of samples with a certain percentages of MWCNT. Dispersion of MWCNT through sonication in epoxy resin system used with vacuum resin infusion (VRI) technology in this study is an easy and cost effective methodology in comparison to previously adopted other methods limited to laminated composites. The study also identifies the optimum weight percentage of MWCNT addition in the resin system for maximum performance gain in interfacial fracture toughness. The results agree with finite element study, high resolution transmission electron microscope (HRTEM) analysis and fracture micrograph of field emission scanning electron microscope (FESEM) investigation.

1. Introduction

Sandwich composites are advantageous for their higher strength to weight ratios. Interfacial delamination between the face sheet and core is a major problem in these structures. Numerical study on debonding or crack propagation in sandwich composites are reported in literatures [1-6]. Many research works are devoted to improve the interfacial fracture toughness of nano or laminated composites through structural or constituent modifications using different toughening agents including carbon nano tubes [7-18]. Sandwich Composites are modified structurally using z-pin [19,20], stitching concept [21], peel stopper device [22,23], or, shear key concept [24]. Modification of core materials in sandwich composites are reported for varied performances [25-27]. Interface of laminates are reinforced with CNTs to change the interlaminar fracture toughness [28-31]. Mixed numerical experimental study on influence of multiwalled carbon nano-tubes (MWCNT) dispersed resin system on interface fracture of glass-epoxy PVC core sandwich composite is extremely limited.

2. Manufacturing of samples

PVC foam with density 100 kg/m^3 and 30mm thickness of trade name Divinycell H100 supplied by DIAB Inc. was used for the manuscript. PVC foam core was covered by a layer of glass fiber stitched

Excerpt from ISBN 978-3-00-053387-7

combination mat followed by a layer of woven roving mat (WRM) on both top and bottom was enclosed air-tight in a vacuum bag fitted with inlet and outlet pipes. Epoxy resin (Airstone 780E of Dow Chemicals with 1400 mPas viscosity and 1.15 g/cc density at 25 °C) and hardener (Airstone 785H of Dow Chemicals with 13 mPas viscosity and 0.94 g/cc density at 25 °C) in 30wt% of epoxy resin are mixed by stirring at 150 rpm for 15 min. In case of CNT sonicated samples, The resin is mixed with MWCNT in different wt% of epoxy resin using a sonicator (500 W, 20 kHz Vibracell Liquid processor) for 2.5 hours intermittently at room temperature (25 °C) and then mixed with the above hardener as stated above to prepare the resin system. The samples are casted through VRI technology with the prepared resin system and allowed to cure for more than 48 hours at room temperature (25 °C). Initial delamination was provided with 80 μm thick non-stick impermeable Teflon sheet by coating the upper surface of the core. The sample with required dimensions (length (L) = 170 mm, width (b)= 25 mm, and thickness(T) = 36 mm) and the pre-crack were prepared from these casted sandwich plates.

3. Numerical Investigation

Finite element analysis was done with Abaqus Standard cohesive zone model and crushable foam hardening properties assuming surface to surface interaction between face sheet and core. Two dimensional plane strain model of DCB specimen was modelled using 1892 nodes, 1615 4-noded bilinear CPE4 plane strain quadrilateral solid elements (based on convergence study) in Abaqus standard version 6.11. The dimensions and material properties of the GFRP face sheet and PVC foam core used represent those obtained from the experimental program. The modulus of elasticity and Poisson’s ratio of the GFRP face sheets and the foam core were calculated from the experimental investigations carried out on the component parts as per ASTM D3039/D3039M-14.The experimentally determined material proper ties are as listed in Table 1 below:

Table 1. Material properties used for the simulation

Description of parameters	Face sheet (Ef) MPa		PVC Core (Ec) MPa	
	Mean Value	StdDev (%RSD)	Mean Value	StdDev (%RSD)
Modulus of Elasticity	10724	5.17	70	1.44
Poisson’s Ratio (ν_{12})	0.17	9.08	0.336	1.96

Face-sheet was fabricated with two alternate layers of 995 gsm stitched combination mat (WRM stitched and assembled with Chopped Strand mats (CSM) of glass fibers) and 1161 gsm resin treated plain Woven Roving glass fiber mat (WRM). The face sheets are assumed to be isotropic with the properties shown above for the chopped strand mats are stitched with WRM. The foam core of much lower yield stress than that of glass fibers is modelled with crushable foam hardening properties for it exhibits plasticity during deformation.

Initial debond of 48 mm between the top face sheet and the core equal to that provided for experimental investigation as a pre-crack was introduced in the sample for numerical analysis also. Cohesive contact was assigned between the top face sheet and core excepting portion for initial delamination (where no contact was assigned). A tied-contact was provided between core and face sheet at bottom throughout the entire length. Assuming a cohesive layer between the top face sheet and core is a simplification of the crack propagation in a smeared layer of face sheet and core. The interaction properties were assigned through prescribing the cohesive behavior, damage properties with fracture toughness and fracture criteria and a quadratic traction.The normal fracture energy was calculated using modified compliance calibration technique [32]using a value of the exponent n as

Excerpt from ISBN 978-3-00-053387-7

2.22 (as obtained from Compliance versus crack length plot). The normal fracture energy was calculated to be 898 J/m^2 (with relative standard deviation (RSD) 1.62%) for conventional sample and 1165 J/m^2 (for particular sample) for sample with 1.5 wt% MWCNT were used for the numerical study. The boundary conditions similar to experimental set up were used for the simulation. The damage initiayion value can not be determined by the experiment and adopted to be 1.2 MPa and 1.6 MPa for conventional and CNT- samples respectively from previous simulations of the authors and found to be correlated well with the experimental results. Displacement control condition on the nodes of face sheets was adopted for the simulation. The deflected shape of the simulated DCB specimen for conventional sample and that with the parameters for sample with 1.5 wt% of MWCNT are shown in Fig.1 and Fig. 2 respectively.

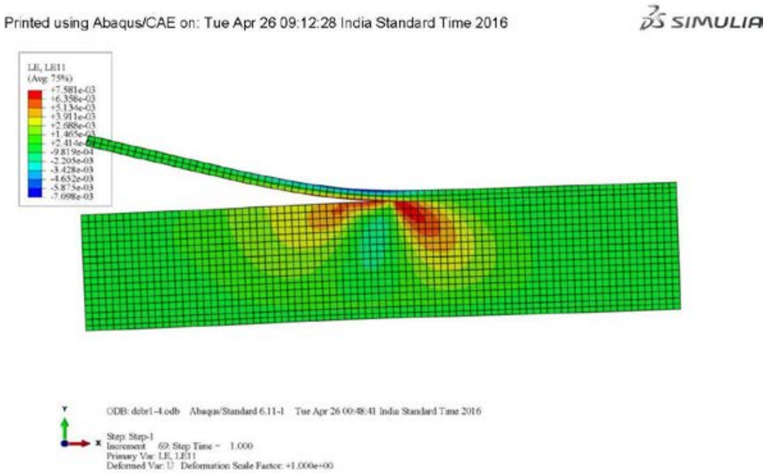

Figure 1. Deflected shape of the simulated DCB specimen for conventional sample

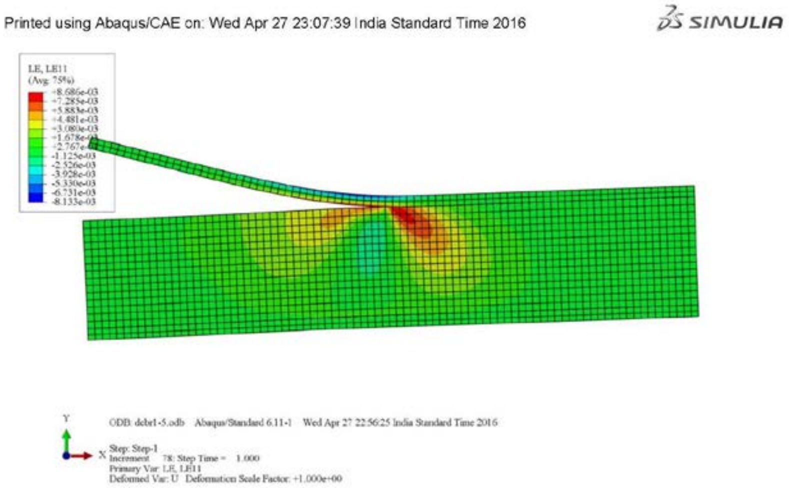

Figure 2. Deflected shape of the simulated DCB specimen for sample with 1.5wt% MWCNT

The deflected shape of the face sheet shown in figure is after 69 increments for conventional sample and 78 increments for samples with MWCNT respectively and completion of the analysis. The strain contour plot shows that the fracture is mode I dominating type associated with a slight mode mixity at the crack tip.

Excerpt from ISBN 978-3-00-053387-7

4. Experimental Investigation

Sandwich samples of dimensions 170mm X 25 mm X 36 mm were cut from the initially manufactured plates. The length of initial debond was kept within 48±1 mm. Instron Electropulse 1000 UTM with pneumatic grips and 1 kN load cell was used to apply tensile load to the specimens at a cross-head speed of 0.5 mm/min through Aluminum hinge tabs attached on both faces (top and bottom) of sandwich samples up to a crack propagation of at least 20 mm from the point of crack initiation. The load versus displacement data at discrete propagation points were recoreded by a software utility service of the computer attached to the UTM whereas the crack propagation was recorded through camera attachments. The data for the fracture of sandwich specimens with 0.5%, 1%, 1.5% and 2% MWCNT and without MWCNT were recorded for further analysis.

5. Results and discussions

The load displacement plots for the simulated DCB specimen superposed with that of the typical experimental result of the conventional sample is shown in Fig. 3.

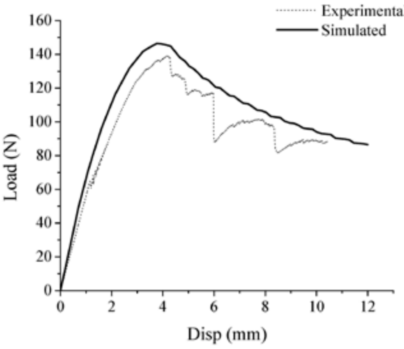

Figure 3. Simulated load-disp plot superposed with that of experimental result for neat sample

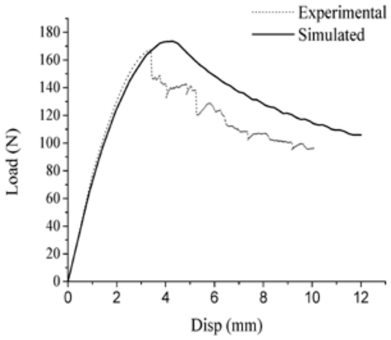

Figure 4. Simulated load-disp plot superposed with that of experimental result for sample with 1.5 wt% MWCNT

The figures show a good agreement in the initial linear portion of the plots which is an expected result. The minor difference in the non linear portion is due to the slight variation in assumptions (using mean value of normal fracture energy instead of that of the particular experimental sample superposed) made in simulation than reality and for this reason, the simulated peak load is slightly more than the

Excerpt from ISBN 978-3-00-053387-7

experimental one. The post peak stick and slip nature of the experimental plot is due to the crack propagation through smeared layer of face sheet and core which is not so prominent in the simulated plot for assuming a cohesive layer between the isotropic (as assumed in the simulation) top face sheet and the PVC core.
The superposed load displacement plots for the conventional sample and sample with MWCNT sonicated resin system for 1.5wt% (for maximum gain) is shown in Fig. 5.

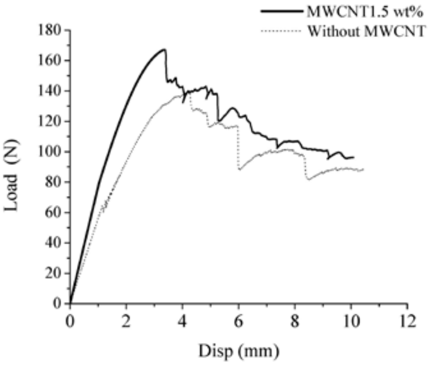

Figure 5. Load displacement plots for the conventional and sonicated CNT-sample

The plots show good match in initial portion. The greater stiffness and peak load of the CNT samples in the nonlinear part is due to the resistance offered by the MWCNT against crack initiation and propagation over that of non-CNT samples. The displacement ductility in the post peak portion is observed to be more in the CNT samples in comparison to the samples without MWCNT. The improvement in peak load carrying capacity is about 20%. Interface fracture toughness calculated on the basis of modified compliance calibration technique used in authors' paper [32] with value of exponent (n) as 2.22 calculated to be 1.20 N/mm (with 4.98% relative standard deviation) and 0.898 N/mm (with 1.62% relative standard deviation) for conventional sample and sample with 1.5wt% of MWCNT respectively. The maximum improvement in interface fracture toughness was observed for 1.5 wt% of MWCNT and calculated to be 33.6% in comparison to neat sample which is significant. Good dispersion of MWCNT was observed in HRTEM with 1.5 wt% MWCNT addition (Fig. 6) in comparison to other wt% of MWCNT as observed from Table 2. FESEM studies has also demonstrated good dispersion and fiber bridging (Fig. 7) of MWCNT in resin system. The results agree with the findings of Almuhammadi et al.[12], and Joshi&Dixit[13] for laminated composites and that of the authors[32] for sandwich composites. In addition, an easy and cost effective methodology is used for MWCNT dispersion in resin system in comparison to complex methodology used by Garcia et al. [29] for 50% improvement in mode I fracture toughness of laminates.

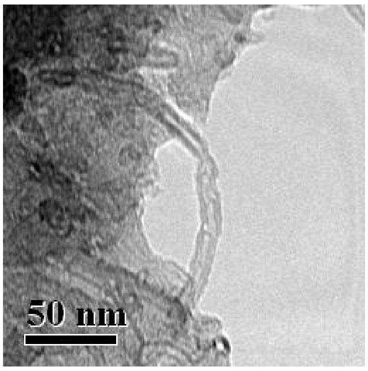

Figure 6. Magnified CNT under HRTEM for 1.5wt% MWCNT.

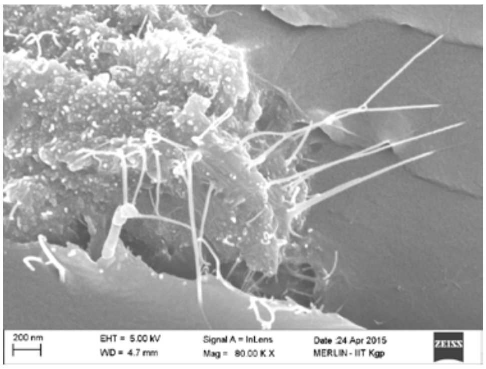

Figure 7. CNT bridging two resin systems under FESEM

Excerpt from ISBN 978-3-00-053387-7

The fracture toughness values for different wt% of MWCNT are presented in Table 2.

Table 2. Variation of Interface fracture toughness (Gc_{mcc}) with MWCNT wt%

MWCNT (wt%)	Gc_{mcc} (N/mm)	RSD (%)	Remarks
0.0	0.898	1.62	(i) mcc stands for modified compliance calibration. (ii) RSD stands for relative standard deviation.
0.5	1.11	6.73	
1.0	1.165	9.13	
1.5	1.20	4.98	
2.0	1.006	8.11	

Maximum improvement in interface fracture toughness of sandwich composite samples is observed for 1.5 wt% MWCNT in comparison to other wt% of MWCNT over samples without CNT as observed from Table 2.

6. Conclusions

The results of the numerical investigation shows good correlation with that of the experimental investigation for conventional and MWCNT dispersed sandwich specimens. Significant improvement (33.6%) was recorded in interface fracture toughness of sandwich samples with 1.5 wt% MWCNT over conventional samples using simpler sonication method. Maximum improvement in interface fracture toughness of sandwich composite samples is observed for 1.5 wt% MWCNT in comparison to other wt% of MWCNT over samples without MWCNT. Good dispersion of MWCNT was observed in HRTEM with 1.5 wt% MWCNT addition. FESEM studies has also demonstrated good dispersion and fiber bridging of MWCNT in resin system. Ductility is also observed to be higher for samples with MWCNT. The results agree with the findings of previuos researchers for laminated composites and that of the authors for sandwich composites. In addition, an easy and cost effective methodology is used for MWCNT dispersion in resin system in comparison to the complex methodology used by previous researcher for 50% improvement in mode I fracture toughness of laminated composite.

Acknowledgments

This work was supported by Department of Science and Technology, India under Award No. SR/S3/MERC-035/2010. The first author would like to thank many students and technicians who had helped him for carrying out the experiments. Any opinions, findings and conclusions or recommendations expressed in this manuscript are those of the writers and do not necessarily reflect those of the Department of Science and Technology, India.

References

[1] S. Prasad, and L.A. Carlsson. Debonding and crack kinking in foam core sandwich beams—I. Analysis of fracture specimens. Engineering Fracture Mechanics, 47(6):813-824, 1994.

[2] C. Berggreen, B. C. Simonsen, and K. K. Borum. Experimental and Numerical Study of Interface Crack Propagation in Foam-cored Sandwich Beams. *Journal of Composite Materials*, 41:493-520, 2007.

[3] C. Berggreen, B.C. Simonsen, and R. Toernqvist. Modelling of debond and crack propagation in sandwich structures using fracture and damage mechanics. In *Proceedings of 6th International Conference on Sandwich Structures*. CRC Press, 2003.

[4] E.F. Rybicki, and M.F. Kanninen. A finite element calculation of stress intensity factors by a modified crack closure integral. *Engineering Fracture Mechanics*, 9(4):931-938, 1977.

[5] B.F. Sørensen, Cohesive law and notch sensitivity of adhesive joints. *Acta Materialia*, 50(5):1053-1061, 2002.

[6] D.A. Ramantani, M.F.S.F. De Moura, R.D.S.G. Campilho and A.T. Marques. Fracture characterization of sandwich structures interfaces under mode I loading. *Composites Science and Technology*, 70(9):1386-1394, 2010.

[7] A.P. Mouritz, Review of z-pinned composite laminates. *Composites Part A: applied science and manufacturing*, 38(12):2383-2397, 2007.

[8] G. Freitas, C. Magee, P. Dardzinski, and T. Fusco. Fiber insertion process for improved damage tolerance in aircraft laminates. *Journal of Advanced Materials(USA)*, 25(4):36-43, 1994.

[9] M.S. Khan, and A.P. Mouritz. Fatigue behaviour of stitched GRP laminates. *Composites Science and Technology*, 56(6):695-701, 1996.

[10] A.P. Mouritz, K.H. Leong, and I. Herszberg. A review of the effect of stitching on the in-plane mechanical properties of fibre-reinforced polymer composites. *Composites Part A: applied science and manufacturing*, 28(12):979-991, 1997.

[11] N. Sela, and O. Ishai. Interlaminar fracture toughness and toughening of laminated composite materials: a review. *Composites*, 20(5):423-435, 1989.

[12] K. Almuhammadi, M. Alfano, Y. Yang, and G. Lubineau. Analysis of interlaminar fracture toughness and damage mechanisms in composite laminates reinforced with sprayed multi-walled carbon nanotubes. *Materials & Design*, 53:921-927, 2014.

[13] S.C. Joshi, and V. Dikshit. Enhancing interlaminar fracture characteristics of woven CFRP prepreg composites through CNT dispersion.*Journal of Composite Materials*, 46(6):665-675, 2012.

[14] F. Mujika, G. Vargas, J. Ibarretxe, J. De Gracia, and A, Arrese. Influence of the modification with MWCNT on the interlaminar fracture properties of long carbon fiber composites. *Composites Part B: Engineering*,43(3):1336-1340, 2012.

[15] M. Yoonessi, H. Toghiani, R. Wheeler, L. Porcar, S. Kline, and C.U. Pittman. Neutron scattering, electron microscopy and dynamic mechanical studies of carbon nanofiber/phenolic resin composites. *Carbon*,46(4):577-588, 2008.

[16] S. Aldajah, and Y. Haik. Transverse strength enhancement of carbon fiber reinforced polymer composites by means of magnetically aligned carbon nanotubes. *Materials & Design*, 34:379-383, 2012.

[17] M.M. Rahman, S. Zainuddin, M.V. Hosur, C.J. Robertson, A. Kumar, J. Trovillion, and S. Jeelani. Effect of NH 2-MWCNTs on crosslink density of epoxy matrix and ILSS properties of e-glass/epoxy composites. *Composite Structures*, 95:213-221, 2013.

[18] A. Montazeri, and N. Montazeri. Viscoelastic and mechanical properties of multi walled carbon nanotube/epoxy composites with different nanotube content. *Materials & Design*, 32(4):2301-2307, 2011.

[19] U.K. Vaidya, S. Nelson, B. Sinn, and B. Mathew. Processing and high strain rate impact response of multi-functional sandwich composites. *Composite Structures*, 52(3):429-440, 2001.

[20] D. D. Cartié, and N.A. Fleck. The effect of pin reinforcement upon the through-thickness compressive strength of foam-cored sandwich panels. *Composites Science and Technology*, 63(16):2401-2409, 2003.

[21] J.H. Kim, Y.S. Lee, B.J. Park, and D.H. Kim. Evaluation of durability and strength of stitched foam-cored sandwich structures. *Composite structures*, 47(1):543-550, 1999.

[22] J. Jakobsen, E. Bozhevolnaya, and O.T. Thomsen. New peel stopper concept for sandwich structures. *Composites Science and Technology*, 67(15):3378-3385, 2007.

[23] J.L. Grenestedt. Development of a new peel-stopper for sandwich structures. *Composites science and technology*, 61(11):1555-1559, 2001.

[24] N. Mitra. A methodology for improving shear performance of marine grade sandwich composites: Sandwich composite panel with shear key. *Composite Structures*, 92(5):1065-1072, 2010.

[25] M.K. Yeh, and T.H. Hsieh. Dynamic properties of sandwich beams with MWNT/polymer nanocomposites as core materials. *Composites Science and Technology*, 68(14):2930-2936, 2008.

Excerpt from ISBN 978-3-00-053387-7

[26] M.V. Hosur, A.A. Mohammed, S. Zainuddin, and S. Jeelani. Impact performance of nanophased foam core sandwich composites. *Materials Science and Engineering: A*, 498(1):100-109, 2008.

[27] M.C. Saha, E. Kabir, and S. Jeelani. Study of debond fracture toughness of sandwich composites with nanophased core. *Materials Letters*, 62(4):567-570, 2008.

[28] G. Lubineau, and A. Rahaman. A review of strategies for improving the degradation properties of laminated continuous-fiber/epoxy composites with carbon-based nanoreinforcements. *Carbon*, 50(7):2377-2395, 2012.

[29] E.J. Garcia, B.L.Wardle, and A.J. Hart. Joining prepreg composite interfaces with aligned carbon nanotubes. *Composites Part A: Applied Science and Manufacturing*, 39(6):1065-1070, 2008.

[30] N.A. Koratkar, B. Wei and P.M. Ajayan. Multifunctional structural reinforcement featuring carbon nanotube films. *Composites Science and Technology*, 63(11):1525-1531, 2003.

[31] S.S. Wicks, R.G. de Villoria, and B.L. Wardle. Interlaminar and intralaminar reinforcement of composite laminates with aligned carbon nanotubes. *Composites Science and Technology*, 70(1):20-28, 2010.

[32] A. Patra, and N. Mitra. Interface fracture of sandwich composites: Influence of MWCNT sonicated epoxy resin. *Composites Science and Technology*, 101:94-101, 2014.

Excerpt from ISBN 978-3-00-053387-7