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Investigations on the Influence of Nylon-66 Interleaving on the Fiber Matrix Interactions of Quasi-Isotropic Carbon Epoxy Composites using DMA

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Abstract

This paper presents the results of dynamic mechanical analysis of carbon fiber reinforced nylon-66 nanofiber interleaved epoxy composites. The role of nylon-66 nanofiber has been investigated with specific reference to the percentage of interleaving with nylon-66 nanofibers. For a better understanding of the fiber matrix interactions, the composites were subjected to γ-irradiation, and the resulting changes in the dynamic mechanical properties due to nylon-66 interleaving and γ-irradiation are investigated and discussed. Nylon-66 interleaving and exposure of the composites to γ-irradiation are observed to influence the dynamic mechanical properties. The study has established that 1.15% of nylon-66 interleaving of the epoxy carbon fiber composite improves the Tg and it also leads to enhancement of the dynamic mechanical properties. Individually, the improvements in dynamic mechanical properties of the base were ll nylon-66 interleaved carbon epoxy composites due to γ-irradiation is observed to be minimal.

Keywords: *Carbon Epoxy Composites, γ-Irradiation, Nylon-66 Interleaving, Storage Modulus*

1.0 Introduction

Carbon epoxy composites are extensively used in aerospace and automobile applications because of their good stiffness, impact strength, and resistance to corrosion[1]. They offer the flexibility of being manufactured into complex shapes by different manufacturing processes. However, these composites due to limitations of interlaminar strength suffer from delamination during service and are vulnerable to premature failures[2-4] under demanding operating conditions. In order to improve the interlaminar toughness, different methods like optimized stacking sequence of the layers of the composite, laminate stitching, use of braided fabrics, edge capping, and critical ply termination methods have been attempted[5-10] with good success. Interleaving a secondary material between the adjacent carbon epoxy prepreg layers is an advantageous technique[11] for improving the interlaminar strength of the carbon composites since it does not alter the planar properties of the composites[12-17].

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It is also suggested by some authors[18] that interleaving multiple layers of thin flexible polymer films instead of monolayers would increase the interlaminar strength. Further, it is also reported[19] that the use of thermoplastic particles is a better solution for improving the impact damage resistance and fracture toughness of the composites. However, the use of particles as reinforcement increases the thickness of the composites. This would be a major drawback in many applications due to a decrease in-plane stiffness and strength, and likely reduction in the values of T_g which tend to reduce the mechanical properties of the composites.

When polymer nanofibers like nylon-66 nanofibers are used, the disadvantages and limitations of particle reinforcement are avoided[20-23]. The method is distinct in that the thickness of nylon-66 nanofibers can be optimized to achieve the targeted mechanical characteristics while keeping the changes in thickness and density minimal. The concept of interleaving was primarily intended for applications providing mechanically high strength and stiffness in the aerospace and automobile industries. The primary objective of this investigation was to understand and explore and possibility of extending the use of carbon composites for other applications areas requiring high mechanical strength. In this direction, the Dynamic Mechanical Analysis (DMA)[24] is investigated and the advantages and limitations of nylon-66 nanofiber interleaving have been investigated.

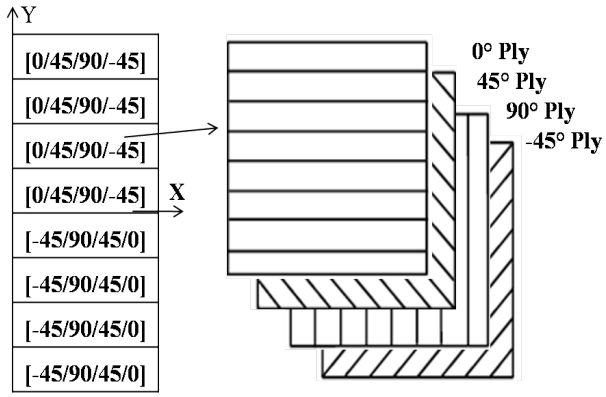


Figure 1. Base composite stacking sequence.

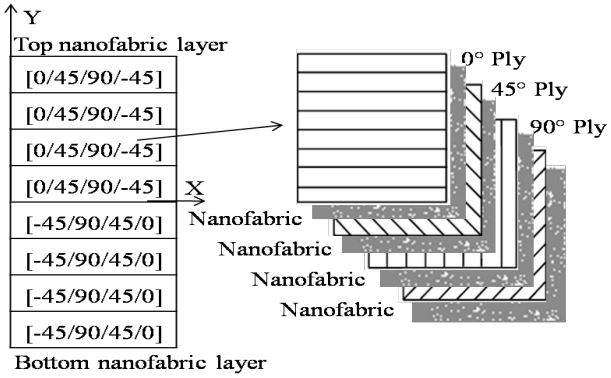


Figure 2. Interleaved composite stacking sequence.

2.0 Experimental Method

2.1 Materials and Fabrication

Unidirectional prepreg AS4/3501-6 was procured from Hexcel Composites USA. Nylon-66 crystals[25] (Zytel 101, MW = 20,000 g/mol, with high elongation at fracture and extraordinary bonding capabilities to epoxy matrix) were procured from DuPont USA.

A 12% homogeneous solution of nylon-66 was used for electrospinning[20-23]. In addition to the base carbon epoxy composite, three interleaved composites were fabricated with nylon-66 interlayers having thicknesses of 0.44, 1.32, and 2.22 µm by controlling the spinning duration. The bulk density of nylon-66 fabricated by electrospinning was 1.14 g/cm^3 and the electrospun nylon-66 has areal densities of 0.5, 1.5, and 2.5 g/m^2 respectively. In comparison, the base prepreg areal density alone was 216.7 g/m^2 and the average ply areal densities of the interleaved composites fabricated were 216.9, 218.5, and 219.8 g/m^2 respectively.

A quasi-isotropic lay-up stacking sequence with four symmetric sets with the sequence [-45°/90°/45°/0°] was used on either side of the midplane to form a 32-ply quasi-isotropic stacking sequence. These composites were cured in autoclave[26]. The stacking sequences of the base and interleaved composites are schematically shown in Figures 1 and 2. The bases were fabricated using the stacking sequence $[-45°/90°/45°/0°]_{4S}$ and the thickness was 4.36 mm and for convenience is identified as CEB.

Interleaved composites were prepared by placing a layer of the nanofiber in between two consecutive prepreg layers[23,27]. The thicknesses of interleaved composites

were 4.38 mm, 4.42 mm, and 4.51 mm respectively. The interleaved composite with nylon-66 nanofiber of thickness 0.44 µm is identified as CEN-1, thickness of 1.32 µm as CEN-2, and thickness of 2.22 µm is identified as CEN-3. The reason for the selection of the thickness of the nylon-66 was to ensure that the resulting changes in areal density, bulk density, and thickness of the composites were minimal. Since there is vast data on the high mechanical strength of carbon epoxy composites with quasi-isotropic stacking sequence used in this investigation[23], the same was adopted. The aerial density of nylon-66 nanofibers as a percentage of ply aerial densities is defined as the interleaving percentage of nylon-66 and it is 0.23, 0.69, and 1.15% for CEN-1, CEN-2, and CEN-3 respectively.

2.2 Details of Gamma Irradiation Source

Gamma-ray irradiation source ^{60}Co was used for irradiating the composites at room temperature in a gamma chamber (1200 cell-model GC-1200) at a fixed dose rate of 7.3 kGy/h. Though different levels of γ-irradiation were used in Table 1, the discussions in this paper on variations in the dynamic mechanical properties are confined to α γ-irradiation dose of 3000 kGy since other doses did not show any significant change as enunciated by Shore D hardness results.

Table 1. G-irradiation exposure

Irradiation Dose (kGy)	Irradiation Time (h)
500	71.428
1000	142.857
2000	285.714
3000	428.571

2.3 Details of Measurements

2.3.1 Density

Density variations are very critical while considering the replacement of non-interleaved with interleaved composites in many applications, the bulk densities of the non-irradiated and γ-irradiated composites measured in the electronic weighing machine (Mettler-Model AG 204) with ASTM D 792-13 specification. Five specimens were used for the measurements and the average value was considered for analysis.

2.3.2 Shore D Hardness

Shore D hardness testing apparatus by adopting the ASTM D 2240-05 method used to measure five samples of each composite and the average was considered for analysis.

2.3.3 Dynamic Mechanical Analysis

The DMA was conducted using a three-point bending test using Perkin-Elmer's model DMA 7 as per ASTM D-5023 (2015). From these measurements, the storage modulus (E′) and loss modulus (E″) were determined. Further, the glass transition temperature (T_g) was estimated from the peaks of the tan δ curve. The tests were done under a load of 1N, using an excitation of 1 Hz and current amplitude of 30 µA, between 25 °C to 275 °C temperature, at a heating rate of 5 °C/min.

3.0 Results and Discussions

3.1 Density

Table 2 shows the variations in ply areal density and bulk density of the composites, before and after γ-irradiation.

Table 2. Plyareal density and bulk density of the composites

Composite	Ply areal density (g/m^2)	Bulk density before γ-irradiation (g/cm^3)	Bulk density after γ-irradiation (g/cm^3)
CEB	216.7	1.59	1.59
CEN-1	216.9	1.59	1.60
CEN-2	218.5	1.58	1.59
CEN-3	219.8	1.55	1.55

Only marginal differences in ply areal density and bulk density of the composites are observed. Further, the bulk density also remains unaffected by γ-irradiation. Noticing the contribution from nylon-66 nanofibers to the bulk density variations is minimal and a marginal decrease in CEN-3. Even γ-irradiation contributes marginally to bulk density variations. The lowest bulk density is in CEN-3 both before and after γ-irradiation is observed. However, the bulk density of CEN-1 and CEN-2 are closer to the bulk density of CEB. Thus, the use of nylon-66 nanofibers does not change the physical characteristics like thickness, areal density, and bulk density[28].

3.2 Hardness

The variations in the hardness before and after γ-irradiation are shown in Table 4. The hardness of CEB due to γ-irradiation showed a 1 to 4 % increase over the corresponding non-irradiated CEB. Similar results are seen in the case of interleaved composites. The maximum increase in hardness is within +4% and this is mainly due to epoxy which is affected in the non-irradiated and γ-irradiated composites. The hardness of interleaved composites is mainly due to the carbon fibers which are reinforced by nylon-66 fibers. Hence hardness is not affected by γ-radiation as reported in some studies[29].

3.3 Dynamic Mechanical Analysis (DMA)

For a better understanding of the effects of nylon-66 nanofibers, DMA parameters namely storage modulus, loss modulus, and damping factor were established. The discussions on the variations in storage modulus are based on peak value and the loss modulus peak and damping are considered at T_g.

3.3.1 Storage Modulus

The storage modulus (E′) of the composites before and after γ-irradiation are shown in Figures 3 and 4.

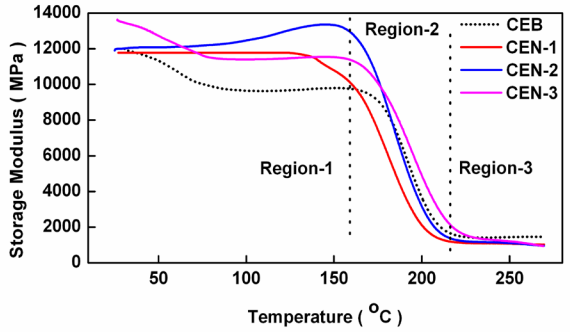


Figure 3. Variations of storage modulus of the non-irradiated composites with temperature.

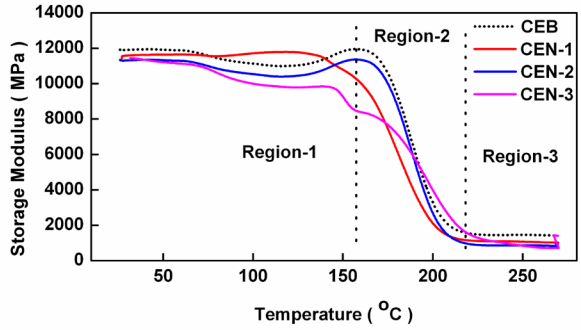


Figure 4. Variations of storage modulus of the γ-irradiated composites with temperature.

Table 3. The hardness of the composites before and after γ-irradiation

Composite	Shore D hardness values (±0.3)				
	Before γ-irradiation	After γ-irradiation (kGy)			
		500	1000	2000	3000
CEB	99.69	101.33	102.66	102.93	104.33
CEN-1	101.66	100.60	100.33	102.69	103.66
CEN-2	99.00	102.66	100.66	102.99	104.00
CEN-3	103.66	102.00	103.00	103.32	104.02

Table 4. The storage modulus of the composites before and after γ-irradiation

Composite	Storage modulus MPa (±55)		% decrease after γ-irradiation
	Before γ-irradiation	3000 kGy	
CEB	12000.34	11904.48	0.8
CEN-1	11773.87	11589.25	1.56
CEN-2	12016.41	11314.48	5.85
CEN-3	13480.35	11285.01	16.2

The E′ of the non-irradiated composites are observed to remain invariant from 30 °C up to 159 °C (Region 1). The composites thus show a glassy regime in this temperature range. With the rise in temperature above 159 °C, a sharp decrease in E′ is seen up to 216 °C (Region 2). The material structure thus transits from a glassy to a rubbery-like regime. Above 216 °C (region 3) temperature forming a rubbery regime in which the E′ is at its minimum.

To appreciate the effect of nylon-66 interleaving, the magnitude of E′ of CEN-1, CEN-2, and CEN-3 composites are compared with CEB values. The important observations from the variations in E′ are the following:

(i) E′ of CEN-1 reduces marginally by 1.88%, while it increases marginally by 0.13% in CEN-2 and increases by 12.33% in CEN-3 results of Table 4.

The relatively larger increase in E′ of CEN-3 is attributed to better reinforcement of the carbon fibers by the epoxy supported by nylon-66 nanofibers. Some authors have attributed the increase in E′ as due to a decrease in the volume fraction at the interphase leading to a decrease in effective polymer chain mobility at the interfacial regions[30]. The higher E′ values reveal the elastic nature of the composite at 1.15% of nylon-66 interleaving. Hence the composite would naturally possess better resistance to deformation[31]. A higher E′ value increases stress transfer at the fiber interface. Thus CEN-3 appears to be better than CEN-1 and CEN-2 in terms of higher E′ values.

(ii) E′ of CEB and CEN-1 decrease marginally (< 2%) due to γ-irradiation. A higher magnitude of reduction is seen in CEN-2 (5.85%) and in CEN-3 (16.2%) from the data in Table 5.

Interestingly the absence of nylon-66 fibers and its presence at 0.23% leads to minimal reduction of storage modulus. But at higher percentages of nylon-66 interleaving, indicating a higher reduction in E′.

Literature reports the different types of transitions that occur in fiber-epoxy systems, including molecular motions, and co-operative short-range diffusion motion of the chain segments[32].

Further, suggested the time scale of molecular motions involved may coincide with those of the mechanical deformation, and therefore oscillations may be converted into internal friction and non-elastic deformation may occur[33]. A similar situation may be taking place in CEN-2 and CEN-3 due to a higher percentage of interleaving and γ-irradiation[23].

3.3.2 Loss Modulus

The (E′) of the non-irradiated and γ-irradiated composites are shown in Figures 5 and 6 and the data is shown in Table 5.

The "Region 1" from room temperature to 130 °C; "Region 2" from 130 to 220 °C and "Region 3" beyond 220 °C are identified in Figure 7. The E′ increases in region 1 for all the composites and it reaches peak in region 2. However, in CEB two peaks, one at 60 °C and the other at 192 °C are observed (Figure 8) due to the carbon fibers and epoxy matrix are observed.

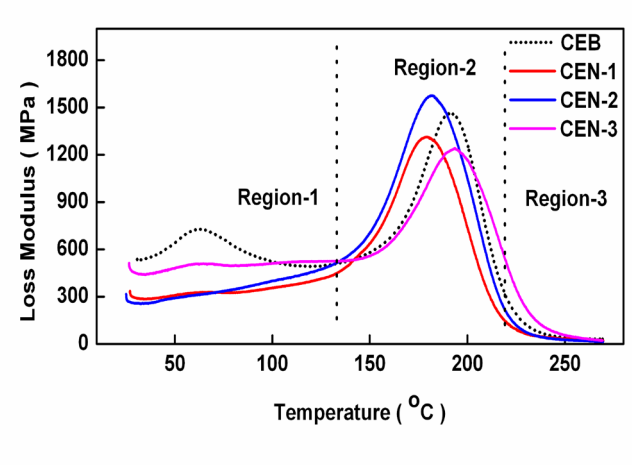


Figure 5. Loss modulus variations of non-irradiated composites with temperature.

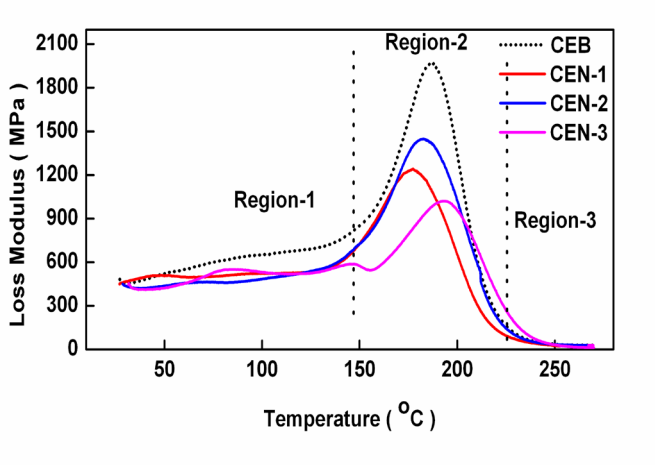


Figure 6. Loss modulus Variations of γ-irradiated composites with temperature.

Table 5. Loss modulus of the composites before and after γ-irradiation

Composite	Loss modulus (±37 MPa)	
	Before γ-irradiation	After γ-irradiation
CEB	1463.76	1964.32
CEN-1	1312.07	1236.01
CEN-2	1577.52	1467.12
CEN-3	1236.23	1023.80

The following are the important observations from the temperature variation of E′, before subjecting the composites to γ-irradiation

(i) E′ increases sharply to its peak at 192 °C in CEB, at 180 °C in CEN-1, at 183 °C in CEN-2, and at 194 °C in CEN-3.

(ii) The low-temperature peak of CEB in Region 1 vanishes due to the incorporation of nylon-66 nanofibers in the polymer system.

(iii) E″ peak decreases by 10.36% in CEN-1 and by 15.54% in CEN-3 while it increases by 8% in CEN-2 over CEB. Thus, interleaving of 0.23% and 1.15% helps in the reduction of E″ while it increases at 0.69%. The percentage of interleaving appears to control the interfacial bonding[34].

The effect of γ-irradiation leads to the following important observations:

(i) A 37% reduction in E″of CEN-1, 25% reduction in CEN-2, and 48% reduction in CEN-3 over the values of γ-irradiated CEB. Thus, the nylon-66 nanofibers aided by γ-irradiation help in considerable reduction of E″.

(ii) The E″ of CEB increases by 34.19% due to γ-irradiation but decreases by 6% in CEN-1, 7.5% in CEN-2 and 20.74% in CEN-3 before irradiation.

Thus, a higher interleaving percentage results lend better support to the system to reduce E″. The γ-irradiation results in a shift of E″ peak towards higher temperatures only in CEN-3[33]. From E″ data, CEN-3 before and after γ-irradiation appears to be better than CEB, CEN-1, and CEN-2, emphasizing the fact that at only a higher percentage of nylon-66, dissipation of mechanical energy is efficiently accomplished.

3.3.3 Damping Factor

The microscopic relaxation movements of polymer molecules[35] can be viewed from DMA analysis. The peak value of tan δ variations is closely related to T_g of the composites. The variations in tan δ of the non-irradiated and γ-irradiated are depicted in Figures 7 and 8. The T_g indicates the temperature at the peak of the tan δ. In Table 6, the T_g values and tan δ peak height.

From Figures 8 and the data of Table 6, the following inferences are drawn:

(i) The T_g of CEN-1 decreases by 5 °C in comparison with CEB. This is because of the reduction in entanglements of the carbon fibers due to nylon-66 nanofibers leading to relatively poorer interfacial strength[36]. The T_g of CEN-2 is equal to that of CEB and hence 0.69% of interleaving forms the threshold of nylon-66 interleaving percentage to compensate for the T_g reduction seen in CEN-1. With the increase in nylon-66 percentage to 1.15%, in CEN-3, the T_g increases by 9 °C above that of CEB.

(ii) Due to γ-irradiation, T_g of CEB decreases by 3 °C due to a decrease in cross-linking density. The decrease is attributed to the possible agglomerations of carbon fibers at the interphase region[37,38], in the absence of nylon-66 nanofibers.

It may also be due to a decrease in the average molecular weight of the polymer, as well as a decrease in cross-link density. Free volume is most likely to

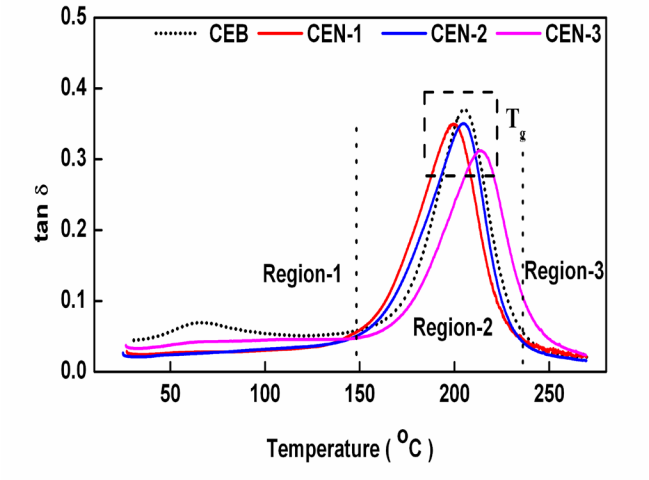


Figure 7. Variations in tan δ of composites with temperature before γ-irradiation.

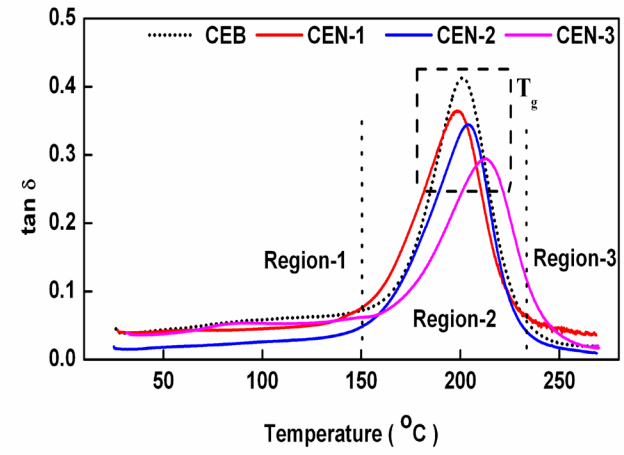


Figure 8. Variations in tan δ of composites with temperature after γ-irradiation.

Table 6. T_g values of the composites

Composite	T_g °C (±1.5)		tan δ peak height	
	Non-irradiated	γ-irradiated	Non-irradiated	γ-irradiated
CEB	205	202	0.37	0.40
CEN-1	200	199	0.36	0.36
CEN-2	205	204	0.35	0.34
CEN-3	214	213	0.31	0.29

be created due to the porosities at the interphases of adjacent carbon fibers which can facilitate polymer chain motions[39]. Results suggest the formation of chain scission and fracture of cross-link bonding during γ-irradiation.

(iii) T_g after γ-irradiation is seen to decrease minimally in CEN-1, CEN-2, and CEN-3 (about 1°C) compared to non-irradiated samples. The result confirms that the decrease in T_g of CEB by γ-irradiation because weakness of epoxy and overcome by nylon-66 nanofibers. It also leads to the conclusion that γ-irradiation has a lesser influence on T_g of the carbon-epoxy composites due to nylon-66 interleaving.

(iv) Significant increase of T_g of CEN-3 is due to better bonding at the interface/interphase regions which helps to reduce the mobility due to relaxation processes[40,41].

(v) The highest T_g and lowest tan δ (damping) seen in CEN-3 before and after γ-irradiation is due to the rise of restricted relaxation mobility at the interphase region consisting of the nylon-66 nanofibers, epoxy, carbon fibers, and stacking layers[42,43].

4.0 Advantages of Interleaving and Significance of γ-Irradiation

The advantages of interleaving in terms of mechanical strength have been discussed by Hiba and coworkers in depth[23,25]. Improved threshold impact strength and impact force have been demonstrated along with a decrease in impact growth rate. The higher the percentage of nylon-66 interleaving, the better improvement in these properties has been reported by the authors. From the present study, the following advantages of nylon-66 are observed:

i. From the considerations of E′, nylon-66 nanofibers help to increase the stress transfer at the carbon-nylon fiber-epoxy interface. The variations in E′ confirm that cross-linking improves in CEN-3. Further increase of T_g by 9 °C above the value of CEB confirms that CEN-3 is better than the other composites.
ii. It is observed that γ-irradiation negatively influences the loss modulus and T_g of CEB.
iii. The decrease in $_{Tg}$ of CEB after γ-irradiation by 3°C while it is minimal due to CEN-1, CEN-2, and CEN-3, outlines the importance of interleaving.

5.0 Conclusions

The study has established the importance of strong interfacial bonding of nylon-66 nanofibers and carbon fibers with the polymer matrix as the key to improving the dynamic mechanical properties. The study has highlighted the fact that the percentage of nylon-66 nanofibers and γ-irradiation have different influences on the dynamic mechanical properties. Some of the important conclusions of this study can be summarized thus:

i. The use of nylon-66 nanofibers with epoxy and carbon fibers leads to marginal variations in thickness, ply areal density, and bulk density with respect to CEB. Hence replacement of base carbon epoxy composites with nylon-66-carbon epoxy hybrid composites would not be a technical challenge.
ii. The hardness of the non-interleaved and interleaved composites shows only marginal improvement when exposed to γ-irradiation because of a relatively higher percentage of carbon fibers which remains unaffected by radiation.
iii. The dynamic mechanical properties of the composite are determined by the network of carbon fibers in the base epoxy composite (CEB) and in CEN-1 which has a lower percentage of nylon-66. At higher interleaving percentages of nylon-66, the dynamic mechanical properties of the carbon fiber epoxy matrix show significant changes.
iv. The increase in the nanofibers interleaving helps to improve storage modulus, while γ-irradiation tends to reduce the storage modulus.
v. Nylon-66 results in an increase of the loss modulus of CEN-2 but it helps in the reduction of loss modulus of CEN-1 and CEN-3 before γ-irradiation over CEB.
vi. γ-irradiation helps in the reduction of loss modulus CEN-3, followed by CEN-1 and CEN-2 in decreasing order as compared to the values of CEB.
vii. The lower margin of difference in T_g of nylon-66 interleaved composites before and after γ-irradiation shows that nylon-66 helps to retain T_g after γ-irradiation in a relatively better manner than the base carbon fiber epoxy composite.

viii. Of the composites, CEN-3 appears to be better with higher storage modulus, lower loss modulus, highest T_g, and lower damping.

6.0 Acknowledgements

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7.0 References

1. Bhattacharya. Radiation and industrial polymers. Prog Polym Sci. 2000; 25:371–401. https://doi.org/10.1016/S0079-6700(00)00009-5
2. O'Brien TK. Characterization, analysis, and prediction of delamination in composites using fracture mechanics. ICF10, Honolulu (USA) 2001; 2013.
3. Abrate S. Impact on Composite Structures. Cambridge University Press; 1998. https://doi.org/10.1017/CBO9780511574504
4. Abrate S. Impact Engineering of Composite Structures, Springer; 2011. https://doi.org/10.1007/978-3-7091-0523-8
5. O'Brien TK. Towards a damage tolerance philosophy for composite materials and structures. ASTM Special Technical Publication. 1990; 1059:7. https://doi.org/10.1520/STP24105S
6. Pagano NJ, Pipes RB. The influence of stacking sequence on laminate strength. J Compos Mater. 1971; 5:50-7. https://doi.org/10.1177/002199837100500105
7. Mignery LA, Tan TM, Sun CT. The use of stitching to suppress delamination in laminated composites. ASTM STP 876, American Society for Testing and Materials. 1985; 371–85. https://doi.org/10.1520/STP36315S
8. Dow MB, Dexter HB. Development of stitched, braided, and woven composite structures in the ACT program and Langley Research Center. NASA TP-97-206234; 1997.
9. Howard WE, Gossard T, Jones Jr, RM. Reinforcement of composite laminate free-edges with U-shaped caps. AIAA Paper No.86-0972; 1986. https://doi.org/10.2514/6.1986-972
10. Chan WS, Ochoa OO. Edge Delamination Resistance by a Critical Ply Termination. Key Engineering Materials. 1989; 37:285–304. https://doi.org/10.4028/www.scientific.net/KEM.37.285
11. Shivakumar K, Panduranga R, Sharpe M. Interleaved Polymer Matrix Composites - A Review. 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference. American Institute of Aeronautics and Astronautics. 2013. https://doi.org/10.2514/6.2013-1903
12. Palazzetti R, Zucchelli A, Trendafilova I. The self-reinforcing effect of Nylon-66 nanofibres on CFRP laminates subjected to low-velocity impact. Compos Struct. 2013; 106:661–71. https://doi.org/10.1016/j.compstruct.2013.07.021
13. Hamer S, Leibovich H, Green A, Avrahami R, Zussman E, Siegmann A, Sherman D. Mode I and Mode II fracture energy of MWCNT reinforced nanofibril mats interleaved carbon/epoxy laminates. Compos Sci Technol. 2014; 90:48–56. https://doi.org/10.1016/j.compscitech.2013.10.013
14. Hamer S, Leibovich H, Green A, Intrater R, Avrahami R, Zussman E, Siegmann A, Sherman D. Mode I interlaminar fracture toughness of Nylon 66 nanofibrilmat interleaved carbon/epoxy laminates. Polym Compos. 2011; 32:1781–9. https://doi.org/10.1002/pc.21210
15. Lu, Zheng G, Dai K, Liu C, Chen J, Shen C. Enhanced mechanical properties of polyethylene composites with low content of electrospun nylon-66 nanofibers. Materials Letters. 2015; 140:131–4. https://doi.org/10.1016/j.matlet.2014.10.151
16. Clark Jr RL, Craven MD, Kander RG. Nylon 66/poly (vinyl pyrrolidone) reinforced Composites: 2: Bulk mechanical properties and moisture effects. Composites Part A: Applied Science and Manufacturing. 1999; 30:37–48. https://doi.org/10.1016/S1359-835X(98)00083-9
17. Dzenis Y, Reneker DH. Delamination-resistant composites prepared by small diameter fiber reinforcement at ply interfaces. U.S. patent, Editor 7/24/2001, board of regents, university of Nebraska-Lincoln: USA. p.18.
18. Joo J, Lee CY. High-frequency electromagnetic interference shielding response of mixtures and

multilayer films based on conducting polymers. J Appl Phys. 2000; 88:513–8. https://doi.org/10.1063/1.373688
19. Hojo M, Matsuda S, Tanaka M, Ochiai S, Murakami A. Mode I delamination fatigue properties of interlayer-toughened CF/epoxy laminates. Compos Sci Technol. 2006; 66:665–75. https://doi.org/10.1016/j.compscitech.2005.07.038
20. Shivakumar K, Lingaiah S, Chen H, Akangah P, Swaminathan G, Russell L. Polymer nano fabric interleaved composite laminates. AIAA J. 2009; 47:1723–9. https://doi.org/10.2514/1.41791
21. Akangah P, Lingaiah S, Shivakumar K. Effect of nylon-66 nanofiber interleaving on the impact damage resistance of epoxy/carbon fiber composite laminates. Compos Struct. 2010; 92:1432–9. https://doi.org/10.1016/j.compstruct.2009.11.009
22. Akangah P, Shivakumar K. Impact damage resistance and tolerance of polymer nanofiber interleaved composite laminates. 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference; 2012. https://doi.org/10.2514/6.2012-1374
23. Ahmed HA, Shivakumar KN. Effect of amount of nylon-66 nanofiber interleaf on impact performance of AS4/3501-6 carbon epoxy composite laminate. 57th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference; 2016. https://doi.org/10.2514/6.2016-0932
24. Motoc, Bou SF, Gimeno RB. Effects of fiber orientation and content on the mechanical, dynamic mechanical, and thermal expansion properties of multi-layered glass/carbon fiber-reinforced polymer composites. J Compos Mater. 2014.
25. Akangah P, Shivakumar K. Assessment of impact damage resistance and tolerance of polymer nanofiber interleaved composite laminates. Greener J Chem Sci Tech. 2013; 2:39–52.
26. Umashankar M, Renukappa NM, Shivakumar K, Sundara Rajan J. Electromagnetic Shielding Effectiveness of Nylon-66 Nanofiber Interleaved Carbon Epoxy Composites. IEEE Trans Electromagn Compat. 2018.
27. Lingaiah S, Shivakumar KN, Sadler R. Electrospinning of nylon-66 polymer nano-fabrics. Proceedings of 49th AIAA/ASME/ASCE/AHS/ASC Structural Dynamics and Materials Conference. 2008. https://doi.org/10.2514/6.2008-1787
28. Ozbek S, Isaac DH. Strain-induced density changes in PAN-based carbon fibers. Carbon. 2000; 38:2007–16. https://doi.org/10.1016/S0008-6223(00)00060-9
29. Hoffman EN, Skidmore TE. Radiation effects on epoxy/carbon-fiber composite. J Nucl Mater. 2009; 392:371–8. https://doi.org/10.1016/j.jnucmat.2009.03.027
30. Rahman MM, Zainuddin S, Hosur MV, Malone JE, Salam MBA, Kumar A, Jeelani S. Improvements in mechanical and thermo-mechanical properties of E-glass/epoxy composites using amino-functionalized MWCNTs. Compos Struct. 2012; 94:2397–406. https://doi.org/10.1016/j.compstruct.2012.03.014
31. Wen Y, Song J, Chen J, Sun Y, Yang W. Synergistic conductivity and electromagnetic interference shielding effectiveness of epoxy/carbon fiber and epoxy/carbon black composites via mixing with bamboo charcoal. BioRes. 2017; 12:1288–99. https://doi.org/10.15376/biores.12.1.1288-1299
32. Ornaghi Jr HL, Silva HSP, Zattera AJ, Amico SC. Hybridization effect on the mechanical and dynamic mechanical properties of curious composites. Mater Sci Eng A. 2011; 528:7285–9. https://doi.org/10.1016/j.msea.2011.05.078
33. Kumar S, Satapathy BK, Patnaik A. Visco-elastic interpretations of erosion performance of short aramid fiber reinforced vinyl ester resin composites. J Mater Sci. 2011; 46:7489–500. https://doi.org/10.1007/s10853-011-5719-x
34. Romanzini D, Lavoratti A, Ornaghi Jr HL, Amico SC, Zattera AJ. Influence of fiber content on the mechanical and dynamic mechanical properties of glass/ramie polymer composites. Mater Design. 2013; 47:9–15. https://doi.org/10.1016/j.matdes.2012.12.029
35. Gao Y, Jiang SL, Yang DZ, He SY, Xiao JD, Lixing ZJ. A study on radiation effect of <200keV protons on M40J/epoxy composites. Nucl Instrum Methods Phys Res B. 2005; 229:261–8. https://doi.org/10.1016/j.nimb.2004.11.030
36. Shin JW, Jeun JP, Kang PH. Fabrication and characterization of the mechanical properties of multi-walled Carbon nanotube-reinforced epoxy resins by e-beam irradiation. J Ind Eng Chem. 2009; 15:555-60. https://doi.org/10.1016/j.jiec.2009.01.012
37. Fan Z, Hsiao K-T, Advani SG. Experimental investigation of dispersion during the flow of multi-walled carbon

nanotube/polymer suspension in fibrous porous media. Carbon. 2004; 42:871–6. https://doi.org/10.1016/j.carbon.2004.01.067

38. Murayama T. Dynamic mechanical analysis of polymeric material. Elsevier Scientific Publishing Company, Amsterdam, The Netherlands; 1978.
39. Davis DC, Wilkerson JW, Zhu JA, Ayewah DOO. Improvements in mechanical properties of a carbon fiber epoxy composite using nanotube science and technology. Compos Struct. 2010; 92:2653–62. https://doi.org/10.1016/j.compstruct.2010.03.019
40. Unal HY, Oner G, Pekbey Y. Comparison of the experimental mechanical properties and DMA measurement of nano clay hybrid composites. European Mechanical Science. 2018; 2:31-6. https://doi.org/10.26701/ems.356823
41. Shin BS, Shin JW, Jeun JP, Kim HB, Oh SH, Kang PH. Effect of gamma-ray irradiation on the mechanical and thermal properties of MWNTs reinforced epoxy resins. J Radiat Res. 2011; 5:137–43.
42. Martin-Gallego M, Hernandez M, Lorenzo V, Verdejo R, Lopez-Manchado MA, Sangermano M. Cationic photocured epoxy nanocomposites filled with different carbon fillers. Polym J. 2012; 53:831–8. https://doi.org/10.1016/j.polymer.2012.02.054
43. Almeida Jr JHS. Study of hybrid interlaminates curaua/glass composites. Mater Des. 2012; 42:111–7. https://doi.org/10.1016/j.matdes.2012.05.044