Nano-Ceramic Modified Polymer Matrix Glass Composites for Impact Applications

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ABSTRACT

Ceramic materials are known for their capability of impact resistance which is the general case scenario in impact applications. The major limitation of high weight and brittleness of these materials inhibited further broad range development into integral composite systems as they interfere with the mobility range. Hence nanoceramic materials are developed and utilized in fiber reinforced composite systems to achieve the impact resistance composites. In this experimental research, the effects of low mass high velocity impact on ceramic nanoparticles modified polymer glass composites is reported. The low cost VARTM is used to manufacture 8 ply nanocomposite panels. One set consists of composite panels made with unique aluminum oxide nanofibers modified polymer reinforced with glass fibers and the other set contains composite panels made with silicon oxide nanoparticles modified polymer reinforced with glass fibers. The results of the nanocomposites which use impact height, velocity and energy as variables are compared and presented. The weight of the impactor and the type of impactor tip are not varied. The dispersion of the nanoparticles in the matrix is investigated through the SEM imaging. Concluding remarks on the impact tolerance of the nanocomposites is reported.

Keywords: Nanoceramic particles, Advanced composites, Low Velocity Impact, VARTM, Polymer Matrix Composites

1. INTRODUCTION

Fiber reinforced polymer composites consist of fibers of high strength and high modulus embedded (either as discontinuous or continuous length) in a matrix with different interfaces. The principal reinforcements in commercial use are various types of glass fibers, carbon fibers and aramid fibers. The most common form of fiber reinforced polymer composites as advanced composites for structural and high strength applications is a laminate. A laminate is sequential stacking of fibers and matrix, consolidated to a desired thickness. Due to their low density, high strength-to-weight ratios fiber reinforced polymer composites are marked superior to the metallic materials and are widely employed in advanced light weight structures [1]. Important material parameters which influence the impact energy behavior of the composites is the fiber type. Since, E-Glass fibers have high strain-to-failure ratio they have excellent impact properties. The other parameter which influence the impact energy behavior is the fiber-matrix interfacial adhesion. Higher levels of adhesion results in brittle failure of the composites under impact load. Low levels of adhesion results in catastrophic failure of the composite structures [2]. Among the polymers, polyester and epoxy resins are widely used as matrix materials to bind the fibers and fabricate composite materials. Epoxy resins are expensive than polyesters, but they are used in large fraction of high-performance polymer matrix composites because they offer dimensional stability, good interfacial adhesion, low water absorption and high service temperature limitations. Epoxy is used in most of the structural applications for one more reason of its capability to adhere to the fibers strongly. Due to this greater adhesion levels, glass fiber epoxy composites exhibit brittle failure. Glass fibers have relatively low modulus and polyesters share the same modulus range as epoxies. But due to their adhesion levels being moderate, they are expected to show a ductile failure unlike glass epoxy composites. The nanoparticles influence different properties and, in this research, the effect of the nanoparticles on the impact energy and the damage in the nanocomposites is studied. Glass fiber reinforced polymer composites are ductile in nature and the damage mechanism under impacts are tensile failure on the opposite side of the impact, deformation of fiber yarns, delamination and matrix cracking [3]. Due to the complexity of the damage mechanisms and the underlying growth mechanisms with respect to fiber reinforced composites, it is difficult to study the underlying energy absorption mechanisms with respect to nanoparticles. In this paper, effort is made to study the damage mechanisms and their interaction under low velocity impact, by varying the matrix and nanomaterials.

Table 1: Some important properties of Epoxy and Polyester:

Polymer	Density (g/mL)	Strength,σ (MPa)	Modulus, E (GPa)	Poisson's ratio, ν	Cure Shrinkage (%)
Epoxy	1.2-1.3	50-125	2.5-4	0.2-0.33	1-5
Polyester	1.1-1.4	30-100	2-4	0.2-0.33	5-12

Since its discovery in 2010, alumina nanofibers are being studied extensively in several fields such as automotive, aircrafts, wind blades, armor panels etc. A study on the impact of alumina nanofibers on different properties such as mechanical, thermal stability and flammability of the Nylon 6 thermoplastic polymers by Koo et al, reported that the mechanical properties have seen significant increase [4]. The thermal and flame-retardant properties did not significantly change. Raikitin and Grodensky reported the increase in mechanical properties by 72% by adding 0.1wt% alumina nanofibers to the epoxy resin[5]. Evidently much research must be done to study the effect of these nanoparticles in different matrix systems and its effects on various properties for composite materials. On the other side there has been considerable research done using the nanosilica, nanoclay, carbon-based nanomaterials on the impact properties of fiber reinforced composite materials. Carbon nanotubes shared a promising potential in increasing mechanical properties, but unusually strong attractive forces due to the high surface area causes agglomeration. Rahman et al studied the effect of amino functionalized MWCNT on ballistic performance of E-Glass/epoxy composites and observed a ballistic limit increase by 6.5% with a loading level of 0.3 wt%. The group also observed a decrease in the damage size [6]. Tate et al, studied the effect of nanosilica and the effect of rubber microparticle on the epoxy glass composites. The group observed mixed results of the nanomodified composites as compared to unmodified. There is an increase in the damage area though there is increase in the energy absorbed[7]. The damage mechanisms on the composite materials incorporated with multiwall carbon nanotubes is reviewed and it has been observed that the nanoparticles also contribute in energy absorption increasing the composites service life[8]. This paper also shares the objective of analysis the effect of nanoparticles on the energy absorption of the composites.

2. EXPERIMENTATION

In the first stage the nanomaterials are dispersed in the resins. For epoxy-based nanocomposites, high shear mixing is employed to ensure that the alumina nanofibers and nanosilica are homogenously dispersed in the epoxy resin. A 25 min mixing at 40Hz frequency was used which provided a shear rate of about 77000 s^{-1}. Cooling jackets on the mixing chamber and hopper were used to avoid thermal curing of resin. For polyester-based nanocomposite, probe sonication is employed for 60min and is pulsed with 30s on, 15s off cycle at 40Hz. The nanomaterial dispersed matrix is reinforced with 0/90 E-Glass woven fibers using high temperature vacuum assisted resin transfer molding which uses vacuum as aid to draw the resin through the reinforcement. Fig 1 illustrates the VARTM setup, which consists of a mold and a heating pad. The layers of woven E-glass fabric coexist with the resin inlet and vacuum lines, which are placed inside the vacuum bagging. Heating pad is used to vary the temperature of the mold to reduce the viscosity of the resin, since addition of nanoparticles changes the viscosity of the resin and interferes with the flow of resin in vacuum. The details of the four types of composite panels fabricated are given in table 2. Low Velocity Impact tests were conducted on fiber reinforced composite laminates to understand the mechanism of impact failure and to examine the influence of nanomaterials on the type of failure. The readiness of woven fabrics to deform under impact make them a right choice for low velocity and intermediate velocity impact applications. The E-Glass was provided by the Owens Corning Ltd and the dry alumina nanofibers, alumina nanofibers pre-dispersed epoxy was provided by ANF technology.

The composite laminates are impacted with a striker having 12.5mm diameter hemispherical head from a height of 1.0m in the Instron 9340 free fall fully instrumented impact tester. The test was performed with a constant mass and constant height so that all the specimens are subjected to the same loading conditions. The specimens in the form of laminates had nominal dimensions of 6 in x 4 in x 0.18 in. Four different specimens are made with different resin systems and were tested under low velocity impact. Two specimens contain epoxy as matrix modified with two different nanoparticles. The other specimens are nonmodified polyester and polyester modified with 2.5 wt% loading of alumina nanofibers. The comparison of effect of nanoparticle modified epoxy to nonmodified epoxy is reported. In this research, the effect of variation in loading of nanosilica on epoxy is reported.

Table 2: Details of composite laminates

Type of laminate	Reinforcement	Matrix	Type of nanomaterial	Loading (wt%)	Dispersion Technique
Type 1	0/90 E-Glass	Epoxy	Alumina nanofiber	2.5	High Shear
Type 2	0/90 E-Glass	Epoxy	Nanosilica	20	High Shear
Type 3	0/90 E-Glass	Unpromoted Polyester	Alumina nanofiber	2.5	Sonication

Type 4	0/90 E-Glass	Unpromoted Polyester	-	-	-

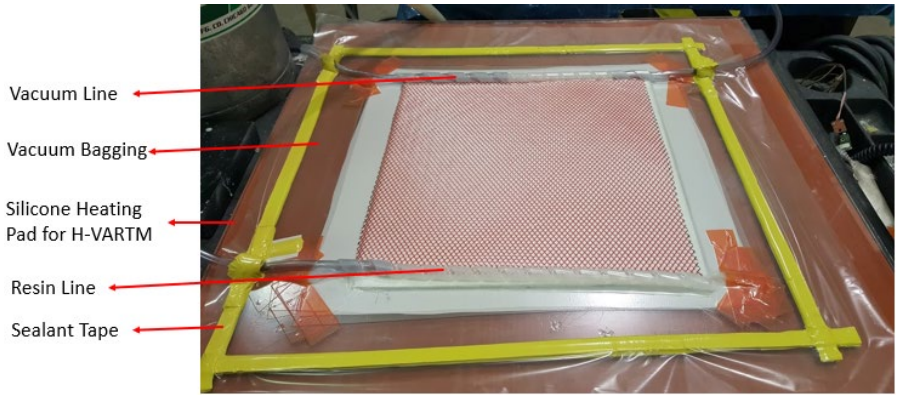

Fig 1: H-VARTM setup used to fabricate composite panels.

3. RESULTS AND DISCUSSIONS

3.1 Composite Panels

Fiber volume fraction in all the four different laminates is in the range of 57-59%. Low velocity impact properties are analyzed in terms of energy absorbed and damage area to see the effect of nanosilica and alumina nanofiber nanoparticles on the impact properties of the E-glass/epoxy and E-glass/UPE composites. The summary of the energy absorbed values are given in table 3. It can be seen from the values that the E-Glass/UPE nanocomposites have considerably higher values of energy to max load indicating than the E-glass/Epoxy nanocomposites. This indicates that the E-glass/UPE composites absorbed more energy before failure. Even when compared between the nanosilica and alumina nanofiber modified epoxy composites, the nanosilica modified epoxy composites showed greater energy absorption before failure. Obviously, improved energy absorption of composite laminates is attributed to the load transfer capability between matrix and nanoparticles. This effective stress transfer between matrix and nanoparticles is strongly dependent on the dispersion techniques. Since the E-Glass/UPE composite samples showed higher energy absorption but there was not an improvement in the energy absorption even with addition of alumina nanofiber samples, the samples were imaged using SEM. The SEM image revealed that the matrix contained agglomerated nanofibers, suggesting that the dispersion needs to be more effective.

Table 3: Energy absorbed before failure for the specimens

Specimen	Impact height (mm)	Thickness (mm)	Energy to max load (J)	Normalized energy to max load (J/m)
Nonmodified UPE	1000	4.8	107.57	22410.41
2.5 ANF modified UPE	1000	4.8	107.1	22312.50
20 NS modified Epoxy	1000	4.8	102.99	21456.25
2.5 ANF modified Epoxy	1000	4.8	90.01	18752.08

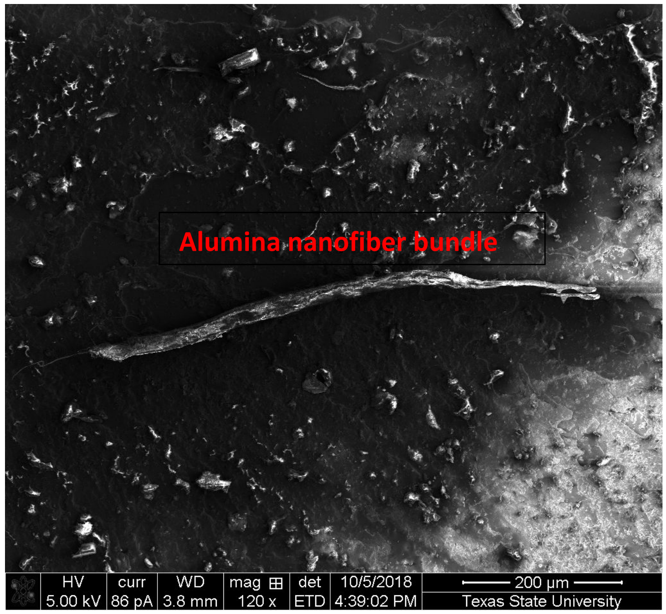

Fig 2: SEM image of alumina nanofiber modified UPE

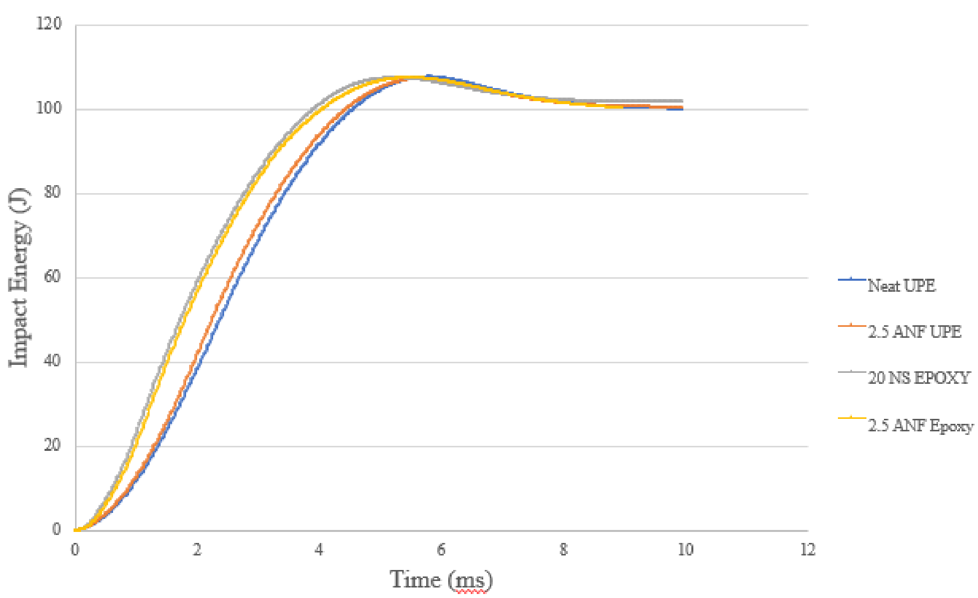

Fig 3: Impact Energy vs Time plot for all four composite samples

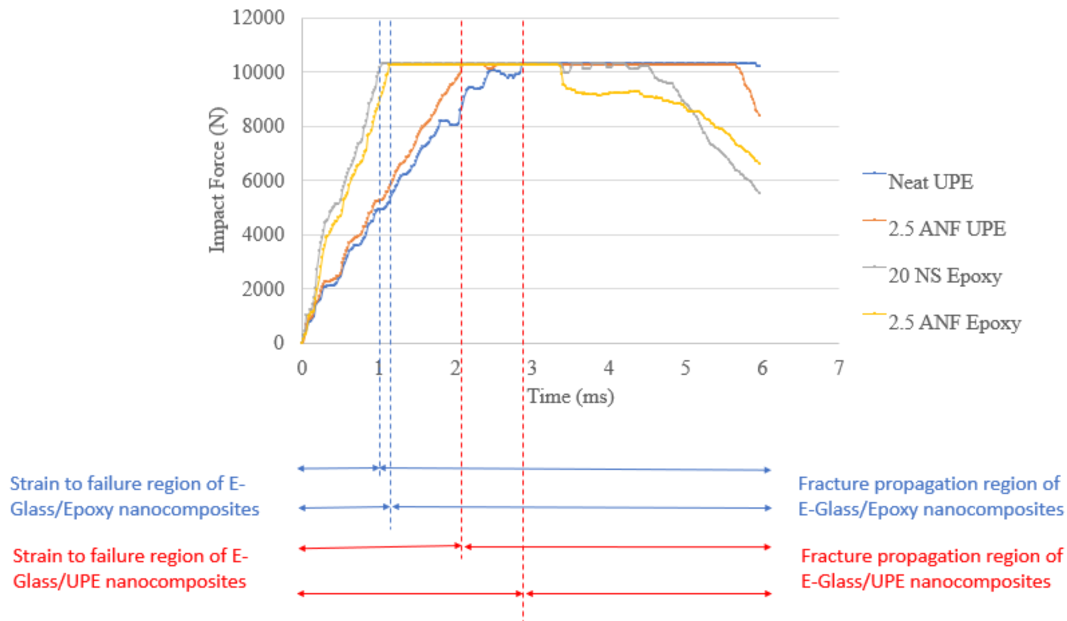

Fig 4: Impact Force vs Time plot for all four composite samples

The plots of impact energy vs time and impact force vs time are shown in Fig 3 and 4 respectively. As observed in these plots, E-Glass/UPE nonmodified composite and the E-Glass/alumina nanofiber modified UPE composites have taken a longer time to reach maximum load. This means that the E-Glass/UPE composites have greater strain-to-failure as compared to E-Glass/Epoxy nanocomposites. The additives in the form of either nanosilica or alumina nanofibers are causing brittleness in the material causing the epoxy composites to reach their maximum load earlier than polyester composites. All the four nano-composites did not show any sudden change in slope after reaching the maximum load, but instead maintained a constant value for certain period. The UPE-based composite system showed a ductile failure which is expected because of the moderate adhesion levels between the matrix and the reinforcement. A close observation at the plot of Impact Force vs Time as shown in Fig 4 UPE-based material system shows that, the addition of alumina nanofibers to the matrix has influenced the ductile behavior. The ascending curve had many changes in the slope, indicating the laminate suffered microdamage before actual failure. The ascending curve of nonmodified UPE/E-Glass composite showed greater fluctuations in the slope as compared to the other three nanocomposites indicating that most of the fiber bundles are affected during the energy dissipation. This helps in more energy absorption, but the composite must have suffered severe damage by the time. The energy corresponding to the peak load is the fracture initiation energy and the remaining energy is referred to as the propagation energy. The difference between the energy at peak load and the maximum energy from the curves of Fig 3 and Fig 4, represent the propagation energy and it is observed that the UPE-based composites have very low propagation energy and the epoxy-based composites have higher propagation energy.

The UPE-based composites exhibited higher initiation energy as compared to epoxy-based composites. Form this, it is evident that the nanoparticles in the epoxy and UPE matrix system acted as stress inhibitors changing their path or stopping them.

3.2 Damage Mechanism Analysis of Composites

The damage mechanisms are complex under impact loading and is a combination of matrix cracking, fiber distortion, fiber-matrix debonding, penetration and shear plugging. The damage on the impactor side and the side opposite to the impact is observed visually through transmission light technique. The backlit images also give a considerable understanding about what kind of damage occurred in the samples.

<u>Damage in E-Glass/UPE composite system:</u> Fig 5 and Fig 6 show the images of the impact side and the side opposite to impact of nonmodified UPE/E-Glass composite respectively. The images show different type of failures occurring in the composite panel after impacting with a 2.5kg mass from a drop height of 1000mm. The energy is dissipated in the sample predominantly by matrix cracking and fiber distortion. The point where the impactor has struck on the sample as shown in Fig 5, has experienced compression. The fibers offered resistance through compression strength, so the maximum energy is dissipated in order to overcome the compressive strength of the composite at the point of impact. Further this energy is dispersed to the surroundings through matrix cracking and fiber distortion. Since the impact has happened at an offset from the center, the edge closer to the impactor during impact has experienced delamination and fiber debonding as shown in the inset in Fig 6. The side opposite to the impact as shown in Fig 7 has experienced tension. The composite due to the efficient stress transfer did not undergo complete failure and has not experienced any fiber breakage or fiber pullout or penetration of the impactor. The damage in the Alumina nanofiber modified UPE/E-Glass composite on the impactor side and the opposite side of the impactor is shown in Fig 7 and Fig 8 respectively. The damage mechanisms and the damage in the later is similar to the nonmodified UPE composites. This comes as no surprise as the alumina nanofibers remained as bundles in the matrix as revealed by SEM image. The nanomaterials which is not efficiently dispersed into the matrix results in no improvement.

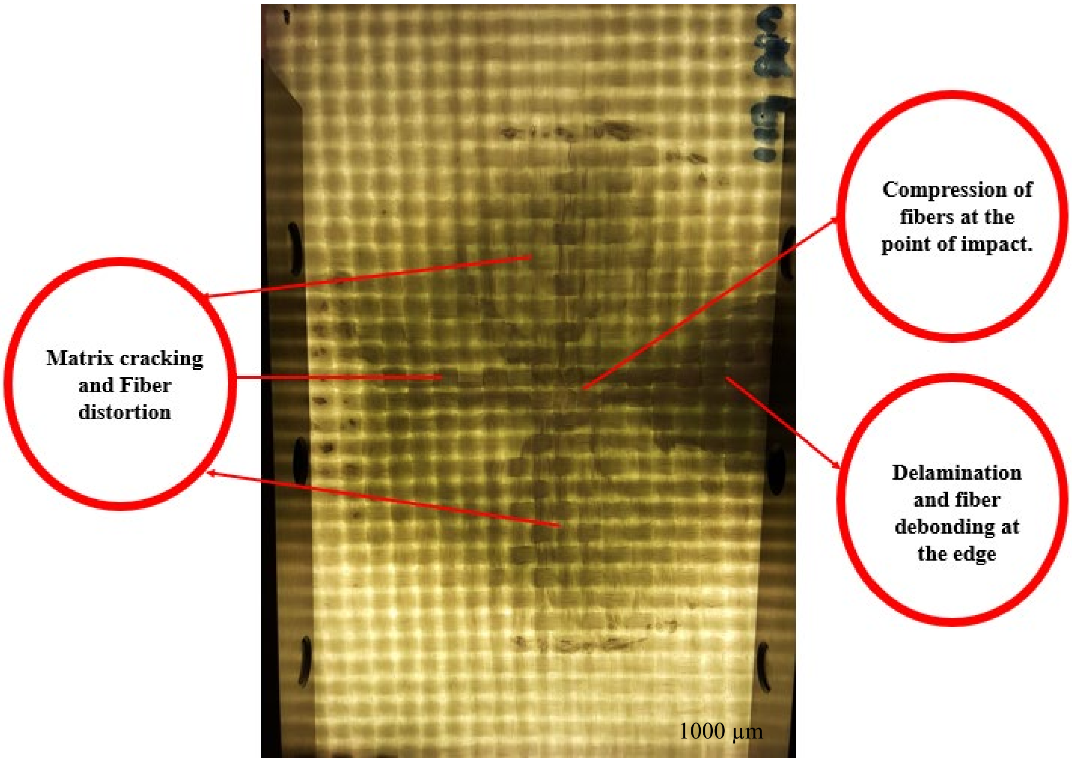

Fig 5: Damage on the impact side of the nonmodified UPE panel

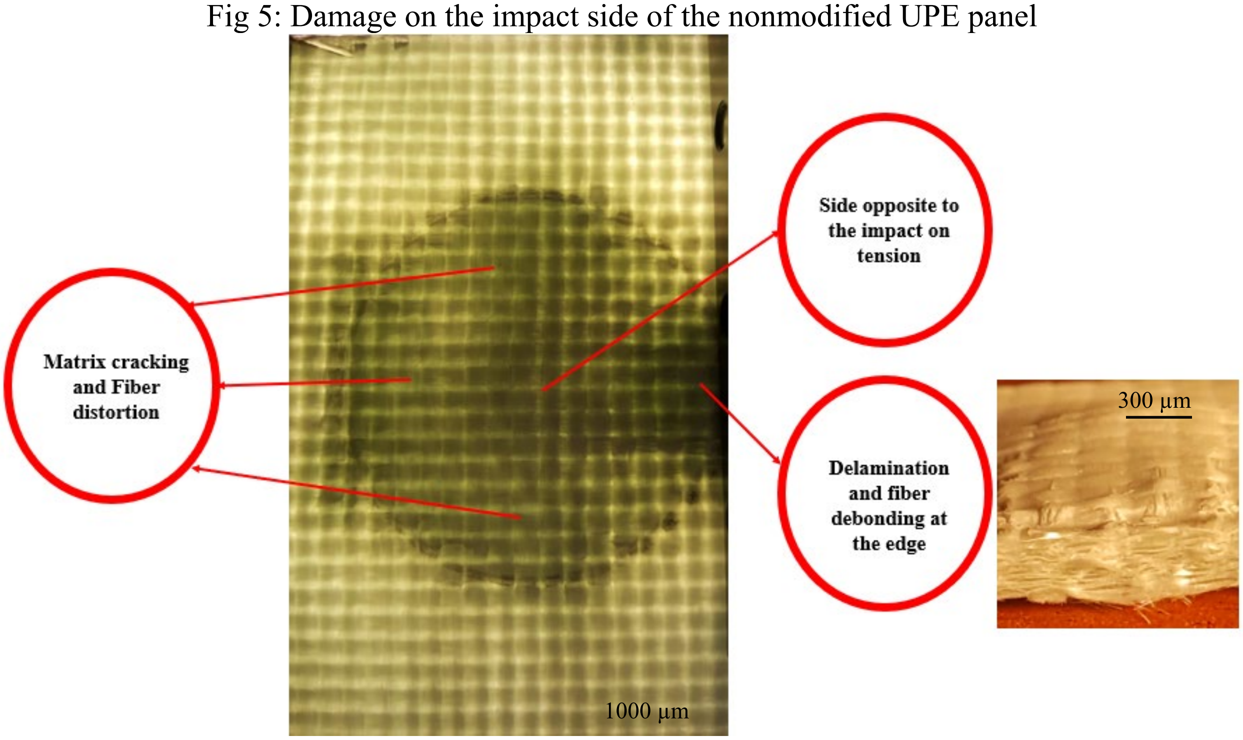

Fig 6: Damage on the side opposite to impact of the nonmodified UPE panel of size 152.4mm x 101.4 mm. The inset picture shows a closer view of cone formed on the back face.

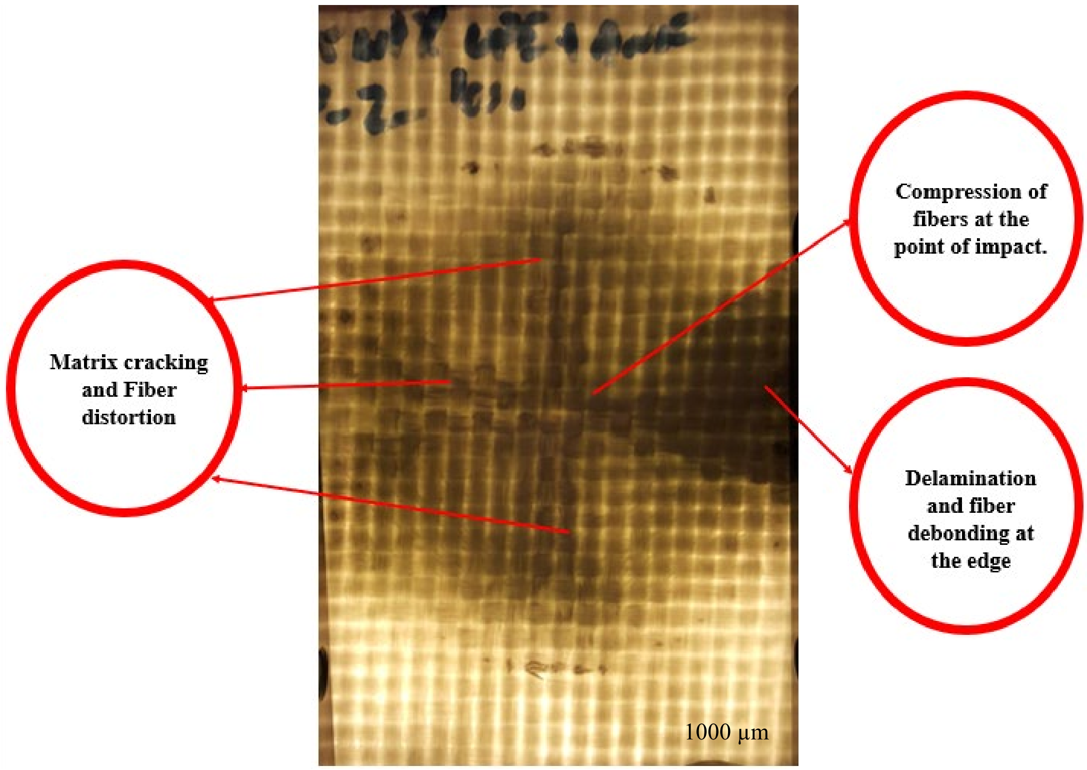

Fig 7: Damage on the impact side of the 2.5 wt% alumina nanofiber modified UPE panel

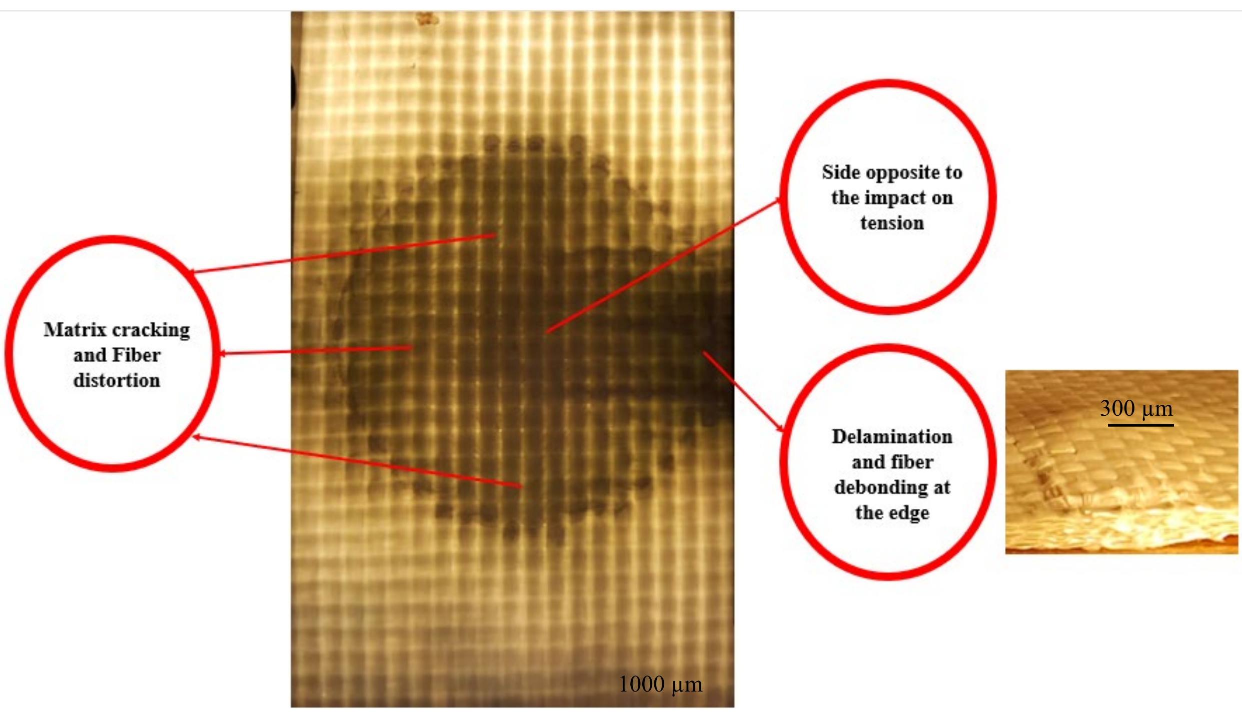

Fig 8: Damage on the side opposite to impact of the nonmodified UPE panel

Damage in E-Glass/Epoxy composite system: The 2.5wt% alumina nanofiber modified epoxy glass composites and 20 wt% nanosilica modified epoxy glass composites have failed completely. In both the material systems, the energy dissipation is very inadequate, and the damage is restricted to the region close to the impactor. The alumina nanofiber and nanosilica changed the matrix fiber interface that the damage progression was arrested, and the energy is spent in damaging the sample in through thickness direction. The back face in the epoxy-based nanocomposites experienced extensive damage showing clear penetration with fiber breakage. No widespread delamination, matrix cracking or fiber distortion in the epoxy-based nanocomposites is observed. Fig 9 and Fig 10 show the impactor side and back side damage in the 2.5wt% alumina nanofiber modified epoxy glass composites respectively. The impactor side image reveals that the impact energy was absorbed mainly to overcome the compression below the impactor. The image also reveals that the cracks are initiated and propagated in all the four directions but are limited around the impactor. The matrix crack and delamination are also observed to be around the impactor region. Fig 11 and Fig 12 show the damage in front side and back side of 20wt% nanosilica modified epoxy glass composites respectively.

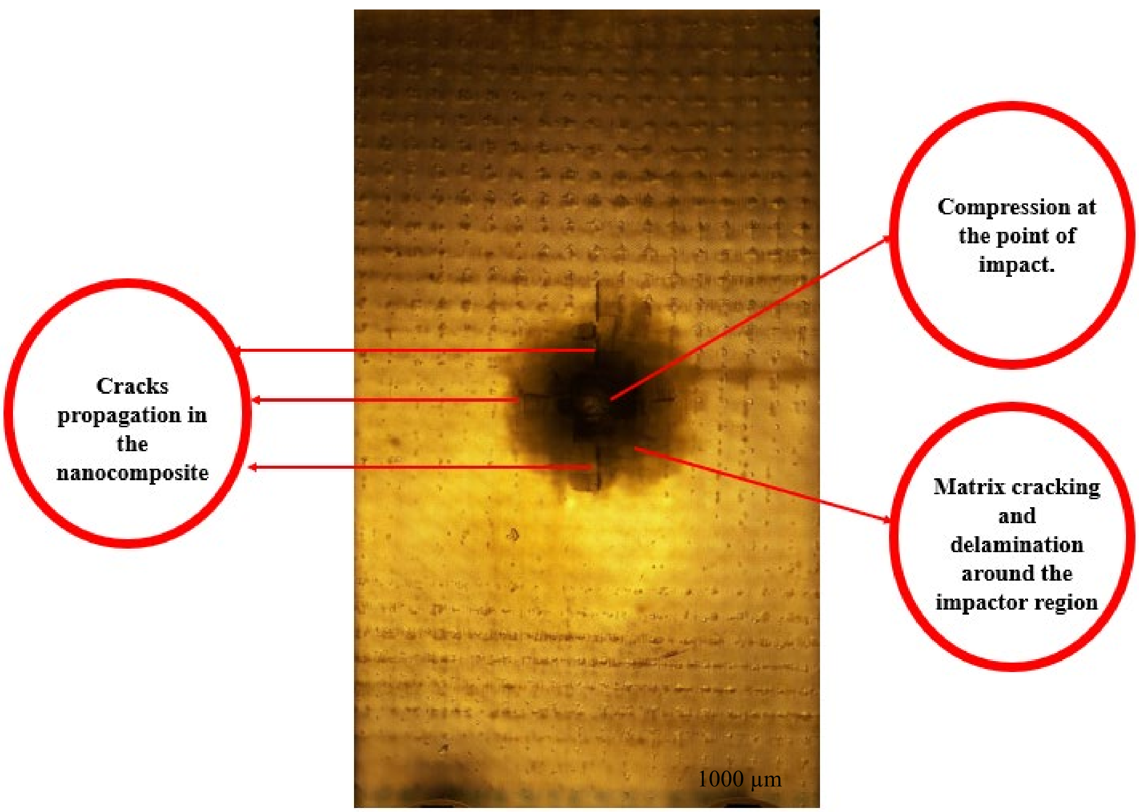

Fig 9: Damage on the side of impact of the 2.5wt% modified epoxy glass composite panel

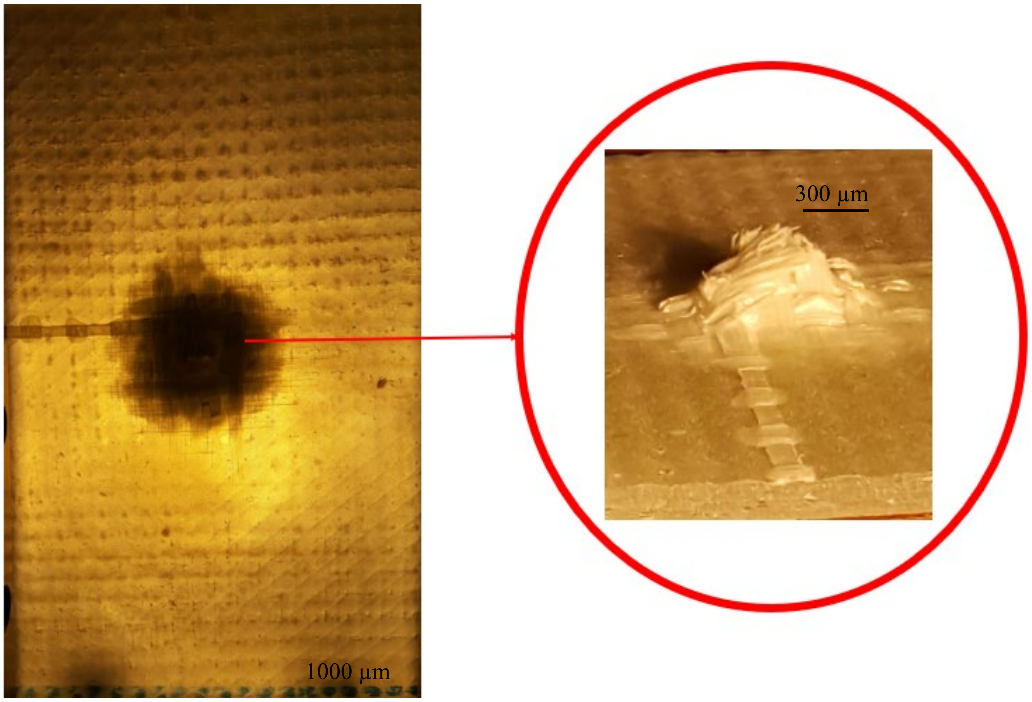

Fig 10: Damage on the opposite side of impact of the 2.5wt% alumina nanofiber modified epoxy glass composite panel. The image in the inset showing fiber fracture.

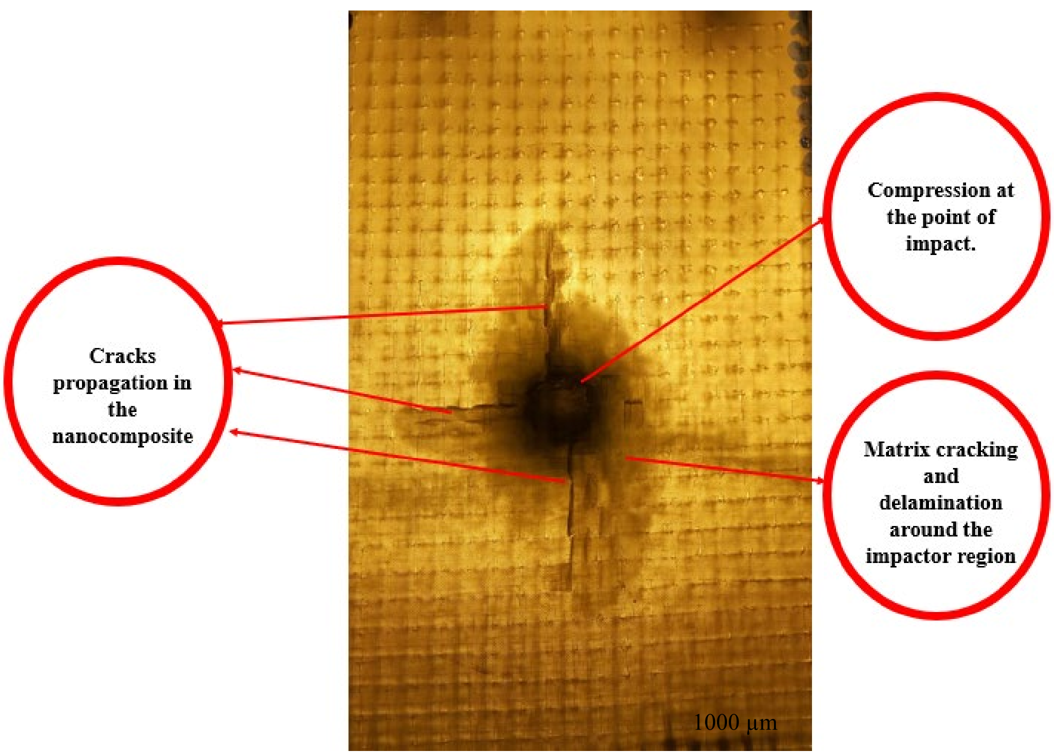

Fig 11: Damage on the side of impact of the 20wt% nanosilica modified epoxy glass composite panel.

Fig 12: Damage on the opposite side of impact of the 20wt% nanosilica modified epoxy glass composite panel. The image in the inset showing fiber fracture.

In comparison between alumina nanofiber modified epoxy glass composite and the nanosilica modified epoxy glass composite the damage is more widespread in the later as opposed to the restricted damage area in the earlier. The fiber morphology of the alumina nanofibers has shown greater extent of damage restriction by constraining the cracks to propagate further along the axial direction in the nanocomposite. The spherical morphology of the nanosilica particles have less area for the crack to deviate and propagate further.

4. CONCLUSIONS

The nonmodified UPE glass composites and the alumina nanofiber modified UPE glass composite showed good impact energy absorbing capacity when compared to the epoxy-based nanocomposite panels. The damage area is wide spread in the case of UPE-based composites and the damage is more restricted around the impactor region in the case of epoxy nanocomposites. The E-Glass/UPE composites exhibited greater strain-to-failure as compared to E-Glass/Epoxy nanocomposites and the nanofillers are supposedly causing increase in brittleness in the epoxy composites to reach their maximum load earlier than polyester composites. The UPE-based composites exhibited greater times to reach maximum load leading to higher initiation energy as compared to epoxy-based composites. The absorbed energy and the damage area of samples are directly correlating with each other. The UPE based laminates absorbed energy through delamination, matrix cracking, fiber distortion and fiber matrix debonding. The epoxy-based laminates absorbed energy through matrix cracking, cracks propagating along the fibers and fiber fracture followed by penetration on the back side. Since the laminates have been penetrated by the impactor, the impactor still had some kinetic energy which is not completely transferred to the laminate. So, an increase in the laminate thickness or through thickness reinforcement in the epoxy-based composites might result in complete energy absorption and prevent penetration into the laminates resulting in more advanced impact resistant structures.

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