



Mechanical and fracture response of epoxy nanocomposites reinforced with low-concentration graphene and graphene-SiO₂ hybrids

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ABSTRACT. Epoxy adhesives are known to have good strength and chemical resistance; however, they tend to be brittle, restricting their use in structural applications. This study examines the effect of low-concentration graphene and hybrid graphene-SiO₂ reinforcement on the mechanical and fracture behaviour of epoxy nanocomposites. Composites containing 0.1–0.4 wt.% graphene and hybrid systems with 0.05–0.2 wt.% graphene combined with



SiO₂ were synthesised using in-situ polymerisation and ultrasonic dispersion to ensure uniform filler distribution. Tensile, flexural, and fracture tests were performed following ASTM standards. The mechanical properties of epoxy composites are significantly improved by adding nano fillers when used at optimal concentrations. From the single filler systems, epoxy with 0.3 wt. % graphene achieved the highest enhancement of tensile and flexural strengths compared to pure epoxy. Greater enhancement was also found in the hybrid composites with a combination of 0.15 wt.% graphene and 0.15 wt.%. SiO₂ resulted in an increase of 53% and 22% for tensile strength and flexural strength, respectively. All nano composite specimens showed a higher fracture toughness, with the best improvement of 71.1% found for the composite mix containing 0.2 wt.% graphene and 0.2 wt.% SiO₂. Scanning Electron Microscopy (SEM) images indicated stronger interfacial bonding, more crack deflection and less brittleness when the filler loadings were optimized. The excessive filler content caused agglomeration due to which the performance was lowered. The structural strength and fracture resistance of the epoxy nanocomposites were significantly improved when Graphene is combined with SiO₂ and this combination created a strong synergistic effect. A finite element simulation was carried out to understand the impact of filler addition on the flexural strength of nanocomposites and results were compared with experimental outcomes.

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KEYWORDS: Graphene, SiO₂, Mechanical, Fracture testing, SEM.

INTRODUCTION

Epoxy resins have strong mechanical properties, chemical resistance and flexible processing options. Due to these strengths, epoxy resins are frequently used as thermoset polymers. Epoxy resin is commonly utilized in aerospace, automotive as well as electronics industries where high strength and functional reliability are desired. The disadvantage of epoxy resins is their sensitivity to brittle fracture, which limits their more widespread use in high-performance structural applications. In an attempt to address the drawback of epoxy resin, there is increasing interest in adding nanofillers as a means of improving mechanical and fracture properties [1-4]. Two of the widely investigated nanofillers for improving epoxy performance are Graphene and Silica. Graphene as reinforcement filler in polymer matrix possesses the advantages of high strength, stiffness and excellent thermal conductivity. The large specific surface of graphene and strong interfacial adhesion between epoxy matrix led to the strengthening, stiffening as well as toughening of the materials. Other materials, such as hollow or core-shell microspheres and glass bubbles with intrinsic low strength to weight without high quality matrix-microsphere interfaces, may have limited promise because their sphericity and resultant higher surface energy (compared to cylindrical fibers) are likely beneficial for interfacial bonding, crack deflection, and energy dissipation. In contrast spherical silica nanoparticles exhibit high -surface energy conducive to improved interface bonding [5-8].

Akter et al. [9] showed that the epoxy nanocomposites with 0.1–0.3 wt.% tensile strength, modulus and thermal conductivity was obtained at GNP loadings of 0.3 wt.% graphene. Dileep et al. [10] reported that epoxy/PLA reinforced with hybrid graphene-SiO₂ fillers showed maximum improvements at 0.3 wt.%, increasing tensile strength, flexural strength and fracture toughness by 60%, 57% and 104%, while higher loading caused agglomeration and property deterioration. Dileep et al. [11] reported the hybrid reinforcement with 0.05 wt.% SiO₂ + 0.05 wt.% graphene exhibited the best performance, improving tensile strength by 33%, flexural strength by 24% and impact strength by 59%. Salom et al. [12] reported that adding graphene nanoplatelets to epoxy increases stiffness and storage modulus, but reduces tensile strength, strain at break, and lap-strength due to nanoplatelet agglomeration. Amine-functionalized graphene offers slightly better toughness and strength retention compared to unmodified graphene nanoplatelets.

In this paper, the effect of low content (0.1 – 0.4 wt.%) addition of graphene, and hybrid (graphene + silica nanoparticles) combinations on the fracture and mechanical performances of the epoxy nanocomposites was investigated. A systematic



characterization is performed to study the separate and synergetic contributions of these fillers to the fracture and mechanical behaviors of epoxy nanocomposites.

Despite extensive studies on graphene and SiO₂-reinforced epoxy systems, limited attention has been given to understanding the behaviour of hybrid nanofillers at ultra-low concentrations (≤ 0.3 wt.%) in relation to both mechanical and fracture responses in a unified framework. Furthermore, the role of microstructural confinement in modifying stress transfer mechanisms and fracture resistance has been recognised, where constrained environments significantly influence stiffness and strength evolution. In this context, the novelty of the present study lies in:

- (i) systematically investigating ultra-low graphene and graphene–SiO₂ hybrid loadings
- (ii) establishing structure–property relationships through combined mechanical, fracture, and SEM analyses
- (iii) implementing a staged RVE-based finite element framework to capture the synergistic behaviour of hybrid nanofillers.

This integrated experimental–numerical approach enables a deeper understanding of the mechanisms governing strength, stiffness, and toughness in hybrid epoxy nanocomposites.

EXPERIMENTAL DETAILS

Materials used

The matrix material employed in this work was Epoxy resin (Lapox-L12) cured using K6 hardener, weight ratio of 9:1. Both the products of Polymer were procured from Atul India Ltd, Ahmedabad (Gujarat), India. The nano reinforcements used were the graphene and SiO₂ nanoparticle with a summary of its specifications depicted in Tab.1. Graphene was selected due to its high aspect ratio, exceptional tensile strength, and ability to enhance load transfer at low concentrations. SiO₂ nanoparticles were introduced to complement graphene by providing crack arrest mechanisms and improving interfacial bonding due to their spherical geometry and high surface energy. The hybrid combination is expected to promote multi-scale toughening through simultaneous crack deflection and crack pinning mechanisms.

Characteristic Property	SiO ₂	Graphene
Diameter (nm)	10-20	-
Thickness (nm)	-	3-6
Length/width (μm)	-	5-10
Density (g/cm^3)	2.4	0.24
Tensile Strength (MPa)	100	5000
Tensile Modulus (GPa)	70	1000
Purity (%)	99.5	> 99

Table 1: Specifications of Graphene and SiO₂.

Preparation of nanocomposites

Epoxy nanocomposites were fabricated using an in-situ polymerization technique illustrated in Fig. 1. Two categories of nanocomposites were prepared: epoxy reinforced with graphene and epoxy reinforced with a hybrid combination of graphene and SiO₂. Nanofillers were initially dispersed in ethanol and subjected to ultrasonication for 10 minutes to break agglomerates and achieve preliminary dispersion. The dispersed nanoparticles were then mixed with epoxy resin and further sonicated for an additional 50 minutes to ensure uniform distribution within the matrix. Subsequently, ethanol was allowed to evaporate during mixing. Finally, the hardener (K6) was added, and the mixture was poured into molds for curing. The resulting mixture was air-dried at room temperature for 24 h. The resulting composite plates were cut and demolded following ASTM standard for mechanical and fracture test measurements. The nanocomposites prepared had the compositions as shown in Tab. 2.

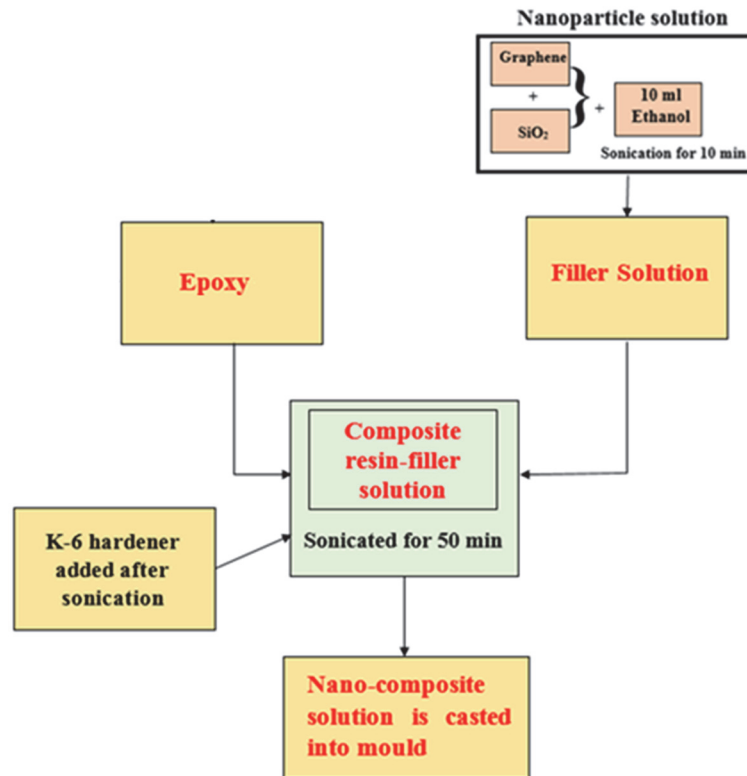


Figure 1: Steps for arrangement of epoxy nanocomposites [10].

Specimen code	Matrix (wt. %)	Graphene (wt.%)	SiO ₂ (wt.%)
PE	100	-	-
EGR1	99.9	0.1	-
EGR2	99.8	0.2	-
EGR3	99.7	0.3	-
EGR4	99.6	0.4	-
EGRS1	99.9	0.05	0.05
EGRS2	99.8	0.10	0.10
EGRS3	99.7	0.15	0.15
EGRS4	99.6	0.20	0.20

Table 2: Composition of the nanocomposites prepared.

CHARACTERIZATIONS OF COMPOSITES

A full suite of different characterization techniques was employed to determine the chemical, thermal, mechanical and fracture properties of nanocomposite materials that were manufactured in this study. The procedures for each characterization technique will be discussed in the following sections.

Tensile testing

All samples were tested for tensile strength by means of a Tinius Olsen universal testing machine with 10 kN capacity according to ASTM D 638 [13] at a crosshead velocity of 3 mm/min. Tensile specimen dimensions are shown in Fig. 2(a). Each type of sample was verified in five specimens, and the mean value was considered as the tensile strength of composite samples.



Flexural testing

Flexural strength was performed by 3-point bending test following ASTM D 790 [14] on a Tinius Olsen universal testing machine equipped with a 10 kN loading cell at a crosshead speed of 3mm/min. The dimensions $\sigma_f = \frac{3PL}{2bd^2}$ of the flexural test sample, as shown in Fig. 2(b) were chosen, with 50 mm gauge length. The test was performed with 5 specimens for each group and the average results were used to determine the flexural strength of composite samples. The flexural strength was calculated using Eqn. (1).

$$\sigma_f = \frac{3PL}{2bd^2} \quad (1)$$

where, σ_f - flexural strength, P – Peak load, L – span length, b – width of specimen, d- depth of specimen.

Fracture test

Fracture toughness (K_{IC}) was measured referring to ASTM D5045 [15] with a single edge notch bend (SENB) sample. The tests were carried out at a crosshead speed of 1mm/min by using the Tinius Olsen UTM (10kN Capacity). The sample parameters are listed in Fig. 2(c) (support length: 48 mm). KIC was calculated based on the Eqn. (2):

$$K_{IC} = \left(\frac{P_Q}{BW^{1/2}} \right) f(x) \quad (2)$$

where $0.2 < x < 0.8$

$$f(x) = 6x^{1/2} \frac{[1.99 - x(1-x)(2.15 - 3.93x + 2.7x^2)]}{(1+2x)(1-x)^{3/2}}$$

where P_Q – Load (kN); B- thickness of specimen (cm); W- width of specimen (cm); a - crack length in cm, and $x = a / w$.

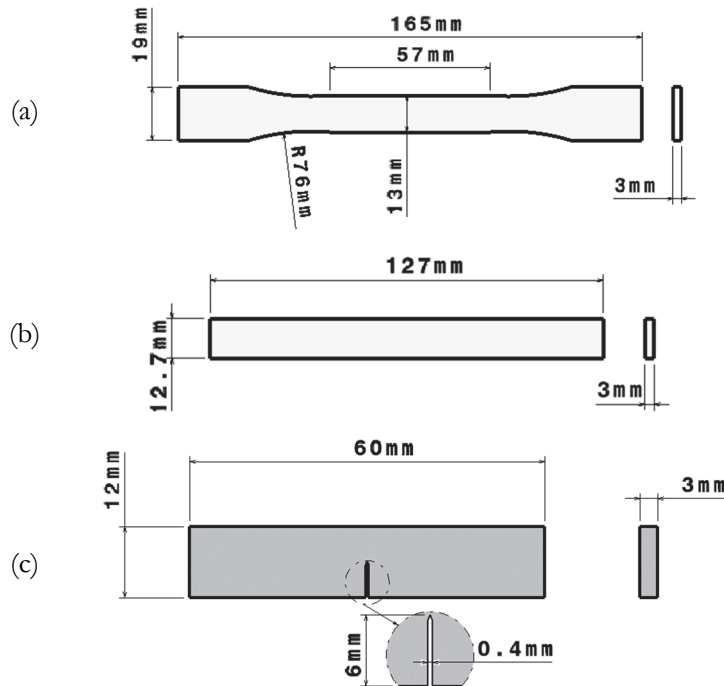


Figure 2: Dimensions of specimens for (a) Tensile (b) Flexural (c) Fracture tests.



For each composite formulation, five specimens were tested, and the mean value was reported. The experimental variability was assessed using the standard deviation and coefficient of variation (COV), calculated as the ratio of the standard deviation to the mean value. The COV values ranged from 3.4% to 13.2%, indicating acceptable experimental repeatability and reliability of the measured data.

RESULTS AND DISCUSSIONS

Tensile tests

The tensile strength of PE and all nanocomposites is shown in Fig. 3. The tensile strength of neat epoxy (PE) was measured at 23.07 MPa. Upon addition of the graphene, a progressive increase in tensile strength was observed up to 0.3 wt.%. The EGR1, EGR2 and EGR3 nanocomposites exhibited tensile strengths of 25.1 MPa, 28.69 MPa and 33.68 MPa, respectively, representing improvements of 8.8%, 24.3% and 46% over PE. However, at 0.4 wt.% graphene loading (EGR4), the strength dropped sharply to 20.33 MPa, falling below the PE baseline. This reduction at higher filler loading is due to an excessive likelihood of graphene agglomeration, and hence, disrupted stress transfer and premature failure. Among the epoxy-Graphene (EGR series) specimens, EGR3 displayed the highest tensile strength, proving that 0.3 wt.% graphene delivers the most effective reinforcement.

The tensile strength of the EGRS series (Epoxy-Graphene-SiO₂) was 26.36 MPa for EGRS1, 30.70 MPa for EGRS2, and 35.35 MPa for EGRS3 with an increase in tensile strength by 14.26%, 33.07%, and 53.23% over neat epoxy (PE). This indicates a considerable enhancement was realized up to 0.3 wt. % filler concentration. A mix of 0.15 wt.% graphene and 0.15 wt.% SiO₂ is added to 99.7 wt.% Epoxy to form specimen EGRS3 and this specimen gave the highest tensile strength of 35.35MPa. This clearly depicts that the combination of 2D graphene with spherical SiO₂ particles, when mixed with epoxy (99.7 wt%), gives the desired results. This mixture emerges to have effective stress transfer by improving mechanical interlocking and connecting the polymer matrix more effectively. The tensile strength suddenly dropped to 19.31MPa for the EGRS4 specimen when the filler content was further increased to 0.4 wt.% (0.20 wt.% graphene and 0.20 wt.% SiO₂). A comparable trend is noticed in graphene-only composites (EGR series) as shown in Fig. 3. This decline in tensile strength is mainly due to the agglomeration of filler particles and weaker adhesion at the interface at higher concentrations, i.e. 0.4 wt.% (0.20 wt.% graphene and 0.20 wt.% SiO₂).

At every comparable loading, the hybrid EGRS composites outperformed EGR composites (those reinforced with only graphene), which depicts that having both graphene and SiO₂ appears to more effectively mitigate crack propagation, delay plastic deformation and enhance load-sharing mechanisms. From these results, it is evident that there is not a simple linear relationship between filler loading and tensile performance, with optimal reinforcement occurring within a narrow concentration range. Epoxy nanocomposites reinforced with 0.3 wt.% graphene (EGR3) and the hybrid formulation containing 0.15 wt.% graphene + 0.15 wt.% SiO₂ (EGRS3) exhibited the highest tensile strengths of 33.68MPa and 35.35MPa, representing increase of 46% and 53%, over pure Epoxy (PE).

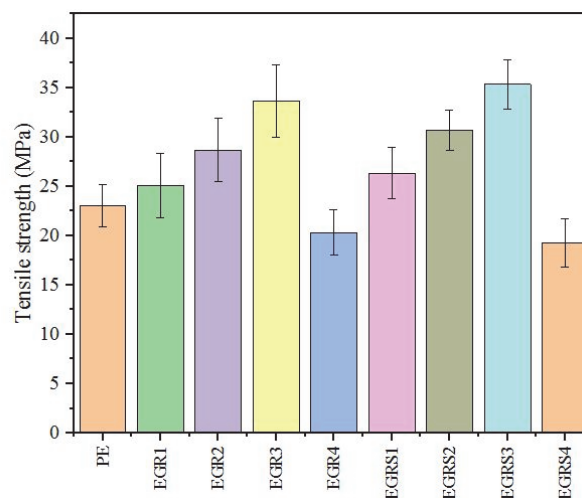


Figure 3: Tensile Strength Comparison of Neat Epoxy and Nanocomposites.

Analysis of Scanning Electron Microscopy (SEM) images

The SEM micrographs of the fractured tensile specimens for PE, EGR3, EGR4, EGRS3 and EGRS4 are shown in Fig. 4. The influence of graphene and hybrid graphene-SiO₂ reinforcement on fracture morphology and interfacial behaviour can be depicted through these images. The pure epoxy (PE) specimen (Fig. 4(a)) displays a smooth, featureless surface characteristic of brittle fracture, with minimal plastic deformation. The absence of microcracks, voids or shear ridges indicates poor energy absorption and little resistance to crack propagation in the pure Epoxy (PE).

In contrast, when the 0.3 wt% graphene is added to 99.7 wt% Epoxy (EGR3), a rougher fracture surface is observed (Fig. 4(b)), with well-developed cleavage planes, micro-ridges, and localized crack deflections. Therefore, enhanced adhesion between graphene and the polymer matrix contributes to suppressing crack propagation and effective load transferring. The actual enhancement in tensile and flexural strengths observed was justified by Crank bridging and pinning mechanisms justifiably. The fracture morphology for the EGR4 sample (0.4 wt% graphene) is different, this time as observed in Fig. 4c; irregular lumps of graphene and smooth patches can be seen, which undoubtedly reflect the agglomeration of graphene. As a result of agglomeration, stress concentration is intensified and the filler-matrix interface is compromised so as to initiate cracks at an early stage. The stiffness and flexural responses reduction of EGR4 compared with that of EGF3 shows the unsatisfactory dispersion and loss of mechanical properties when the amount of filler is greater than 0.3 wt%.

When compared with the EGR series, the EGRS series gave a positive morphology as shown in Fig. 4d. The combination of Graphene and silica particles in the EGRS series promoted crack deflection and uniform stress distribution. A densely interconnected morphology with fine micro texture is observed with uniformly distributed cleavage planes. In the combination of Graphene and SiO₂, Graphene induced crack deflection, whereas SiO₂ assisted crack arrest, contributing to enhanced toughness and strength.

However, at 0.4wt% filler loading, the surface morphology again shows agglomeration with smooth fracture regions (Fig. 4(e)), indicating particle clustering and insufficient wetting of the fillers by the epoxy. This explains the decline in tensile and flexural properties recorded for EGRS4, confirming that filler content beyond 0.3 wt% leads to poor dispersion and the drop in mechanical performance.

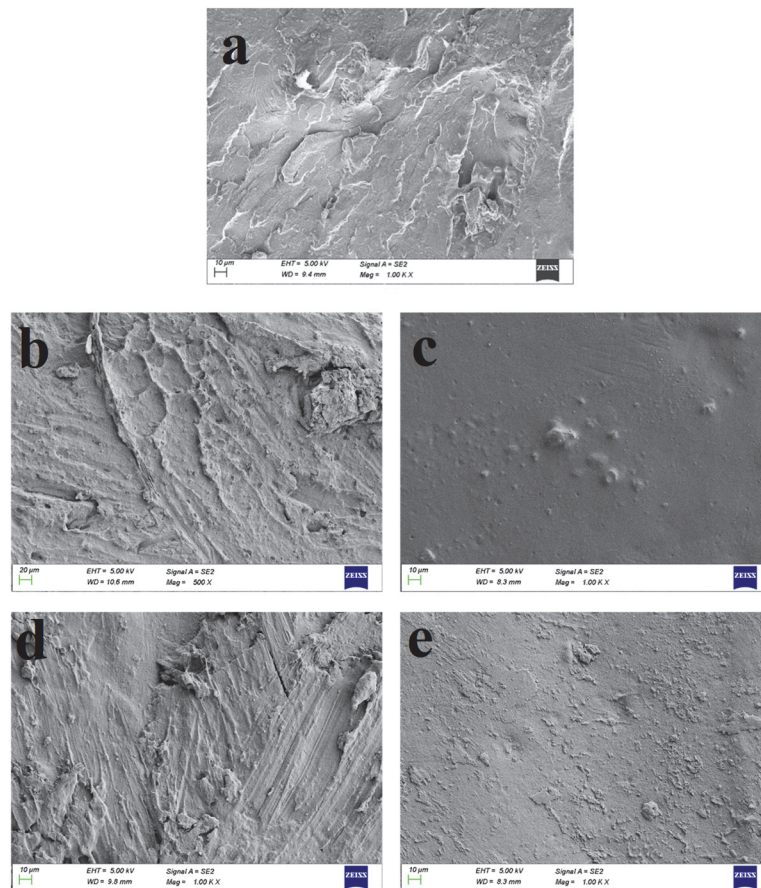


Figure 4: SEM micrographs of (a) PE, (b) EGR3, (c) EGR4, (d) EGRS3, (e) EGRS4.



Microstructural analysis

Microstructural evaluation is necessary to characterize the polymer nanocomposites synthesized and validate the micromechanisms that cause fracture and mechanical performance in the analysis of fracture-oriented studies. Accordingly, post-fracture scanning electron microscope (SEM) analysis is performed for the purpose of directly correlating microstructure with observed damage progression of samples subjected to tensile loading, and further flexural loading, and fracture toughness testing is carried out. For tensile loading, mechanisms governing damage include interfacial debonding and initiation of micro-cracks, with enhanced filler dispersion within the holding polymer matrix for improved stress transfer and avoiding agglomeration resulting in premature fracture. For flexural loading, the primary mechanisms governing damage are crack formation within the matrix and localized shear damage. Optimal filler contents yield deflected cracks and/or redistributed load. For fracture toughness testing, the mechanisms controlling crack growth include extrinsic toughening mechanisms such as crack deflection, crack arrest, and bridging of micro-cracks. There is strong agreement between the mechanisms of damage for each test and the fracture morphology observed, thereby establishing a consistent relationship between microstructure, damage, and the mechanical properties of the materials in question. This clearly establishes an unequivocal connection between the mechanical tests conducted.

Flexural tests

The flexural strength of PE and all nanocomposites is shown in Fig. 5. The pure epoxy (PE) exhibited a flexural strength of 56.8 MPa. Upon addition of the graphene, a progressive increase in flexural strength was observed up to 0.3 wt.%. The flexural strengths of EGR series specimens (Epoxy-Graphene) were measured at EGR1 (59.22 MPa), EGR2 (64.14 MPa), and EGR3 (73.72 MPa), representing an increase in flexural strength by 4.26%, 12.92%, and 29.78% when compared with neat epoxy (PE). This confirms that 0.3 wt. % graphene is the best reinforcement for flexurally loaded nanocomposite. However, at 0.4 wt. % graphene loading (EGR4) the flexural strength significantly dropped to 45.66 MPa, which was lower than the PE baseline of 56.8 MPa. This decrease is attributed to the agglomeration of graphene that proves matrix discontinuities, and therefore escalating inefficiency in the stress transfer which leads to deterioration in flexural properties. A similar trend was observed in the case of the epoxy-graphene-SiO₂ (EGRS) samples. The flexural strengths of EGRS series samples were: 60.26 MPa (EGRS1), 65.51 MPa (EGRS2) and 69.30 MPa (EGRS3) and model with improvement in flexural strengths by 6.05%, 15.3% and 22.15% relatively to PE sample respectively. This finding demonstrates that the synergistic effect of the combination of 2D graphene platelets and spherical SiO₂ particles improves crack deflection, strengthens interfacial adhesion, and increases load sharing between the matrix. At 0.4 wt. (EGRS4) bend strength sharply declined to 49.71 MPa further confirming that any amount of filler exceeding 0.3 wt. % results in clumping of the nanoparticles and premature cracking.

Both EGR and EGRS overall showed a nonlinear relationship between filler content and flexural property. The most preferred range of flexural strength is 0.2-0.3 wt. % for graphene and 0.1–0.15 wt. % each for hybrid fillers. EGR3 displayed the maximum flexural strength, suggesting that controlled dispersion and uniform filler loading are factors of prime importance for obtaining the best possible mechanical response in epoxy nanocomposites

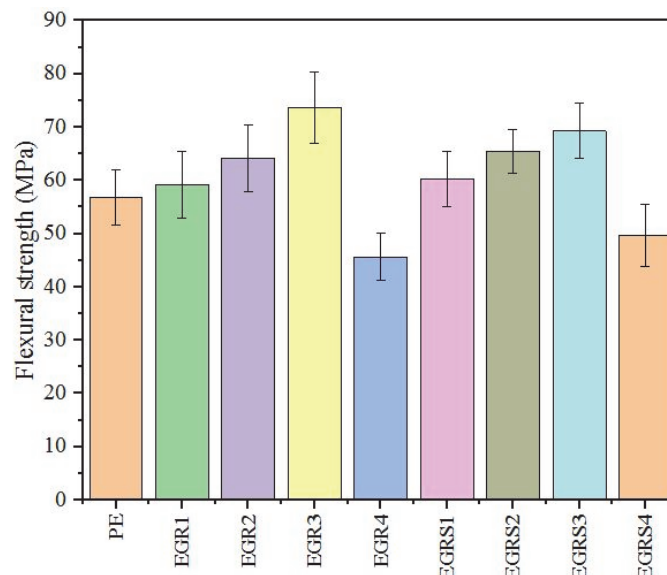


Figure 5: Flexural strength of PE and nanocomposites.



Fracture toughness

The fracture toughness values of PE, EGR1, EGR2, EGR3 and EGR4 were shown in Fig. 6. The fracture toughness values of EGR specimens improved by 22.8 %, 36.7%, 42.2% and 65% over PE. While excessive filler loading (beyond 0.3 wt.%) adversely affected tensile and flexural properties, fracture toughness continued to increase with an increase in graphene wt.%. This trend clearly describes the graphene's power to establish multiple toughening mechanisms, including crack deflection and energy dissipation via microcrack formation and pull-out, which become prevalent at improved loadings. The fracture toughness values for PE, EGRS1, EGRS2, EGRS3, and EGRS4 are shown in Fig.6, corresponding to improvements of 28.3%, 42.8%, 48.9% and 71.1%, respectively, when compared with neat epoxy (PE). The highest fracture toughness among all samples was observed for EGRS4, indicating a strong synergetic toughening effect. The combination of 2D graphene and spherical SiO₂ nano particles enhances resistance to crack propagation by promoting multi-scale crack interruption, particle-matrix frictional sliding and localised plastic deformation.

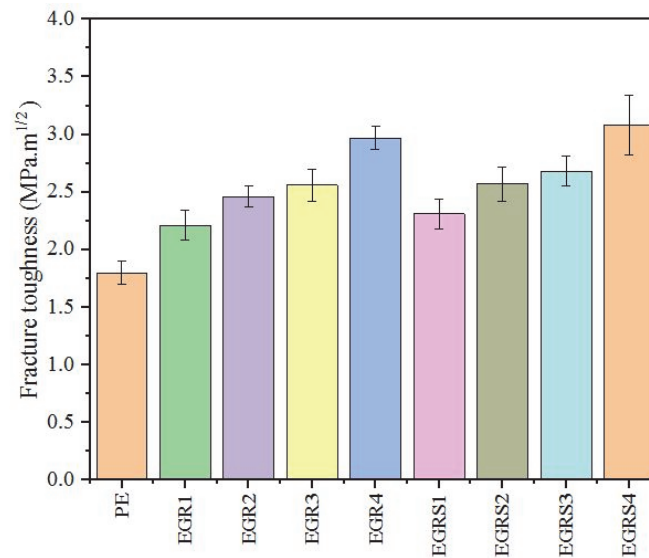


Figure 6: Fracture toughness of PE and all nanocomposites.

The reduction in tensile and flexural strengths at higher filler loadings (0.4 wt.%) is primarily attributed to nanoparticle agglomeration, which induces stress concentration sites and weakens interfacial bonding, thereby leading to premature failure under static loading conditions. In contrast, fracture toughness continues to increase due to the activation of additional energy dissipation mechanisms such as crack deflection, particle pull-out, crack bridging, and microcrack formation. At higher filler concentrations, even though agglomerates negatively influence strength, they act as crack arresters and increase the tortuosity of crack paths, thereby enhancing resistance to crack propagation. Thus, strength is governed by stress transfer efficiency and flaw sensitivity, whereas fracture toughness is governed by energy absorption mechanisms, explaining the observed divergence in trends.

Overall, both single-fibre and hybrid nano-composites demonstrated substantial improvements in fractured toughness, with hybrid systems exhibiting better performance. The nonlinear rise in toughness with filler loading suggests that fracture behaviour is governed not only by interfacial adhesion but also by the ability of fillers to activate multiple extrinsic mechanisms. The highest improvement of 71% was achieved by the hybrid EGRS4 composite, confirming the efficiency of the combined graphene in SiO₂ to reinforcement in enhancing crack resistance in epoxy matrices.

SIMULATION STUDIES OF NANOCOMPOSITES

Finite element (FE) simulation is performed to forecast the mechanical behavior of the composites, and the results were then compared with experimental findings.

Creating a material and three dimensional model

A two-step finite element (FE) simulation was used to simulate how hybrid fillers (SiO_2 with Graphene) affect the properties of the composites. The overall simulation procedure is shown in Fig.7.

First, a representative volume element (RVE) of the nanocomposite was created in ANSYS Workbench using the material properties (Tab. 1) and weight percentages (Tab. 2) of the matrix and fillers (Graphene). From this step, the elastic properties of the nanocomposite were calculated.

In the second step, the same RVE method was used again. The nanocomposite properties obtained in Step 1 were used as a new matrix material (called the effective matrix), and SiO_2 was added as the filler. This two-stage process was used to determine the final properties of the hybrid nanocomposites. The epoxy matrix, graphene-modified epoxy, and hybrid nanocomposites were assumed to behave as homogeneous, isotropic, and linearly elastic materials. The stress–strain relationship was defined according to Hooke's law using experimentally determined elastic properties.

Model creation and boundary conditions

For simulation, a three-dimensional part was modelled in CATIA V5 based on the specimen dimensions shown in Fig. 2. The model was meshed using Hex20 elements with 1 mm mesh size, as shown in Fig. 8(a) and the boundary conditions used for the simulation is shown in Fig. 8(b). The specimen was supported at both ends and a load was applied at the center. Maximum load sustained by the specimen before failure were used as for the FE simulation. The three-point bending test for the EGRS3 specimen was simulated by applying a vertical load of 71 N at the center, and the resulting stress distribution is shown in Fig. 9. Tab. 3 compares the bending strengths obtained from experiments and FE simulations for all specimens. The FE simulation results showed very close agreement (within $\sim 1\%$) with experimental values, validating the adopted modeling approach.

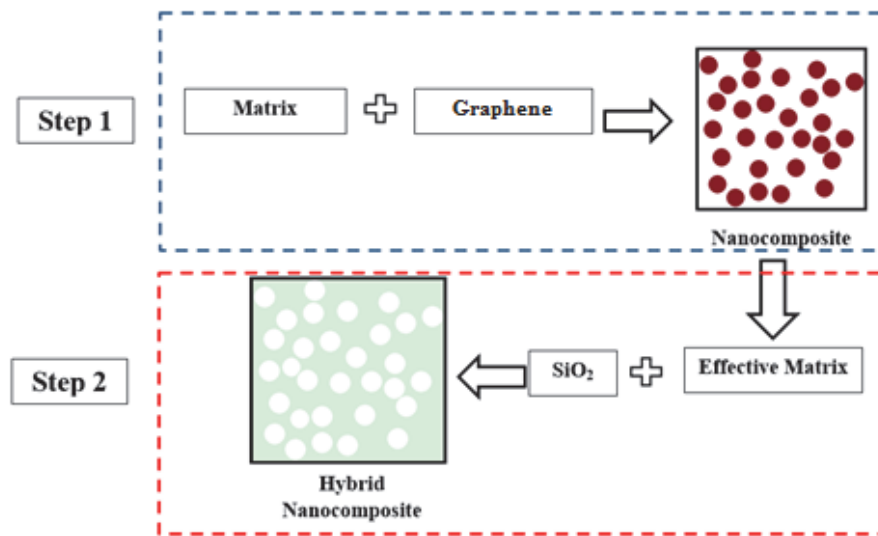


Figure 7: Steps to evaluate mechanical properties of hybrid nanocomposites [10,11].

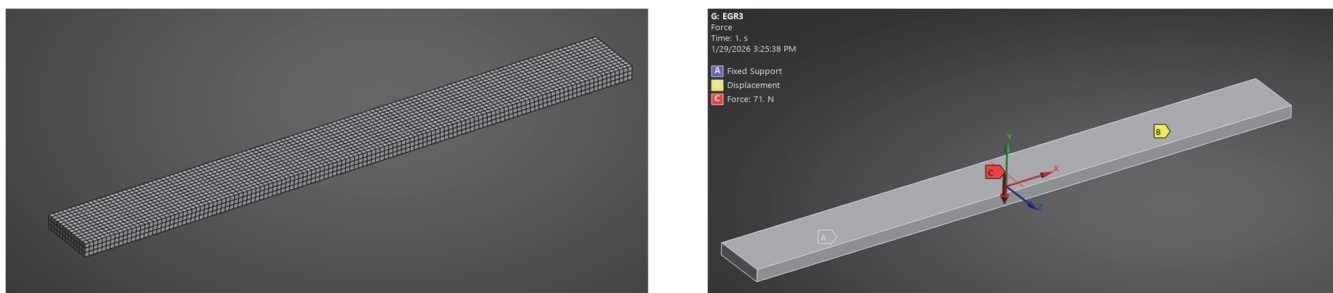


Figure 8: (a) Meshed model of flexural model (b) Boundary conditions during FE simulation.

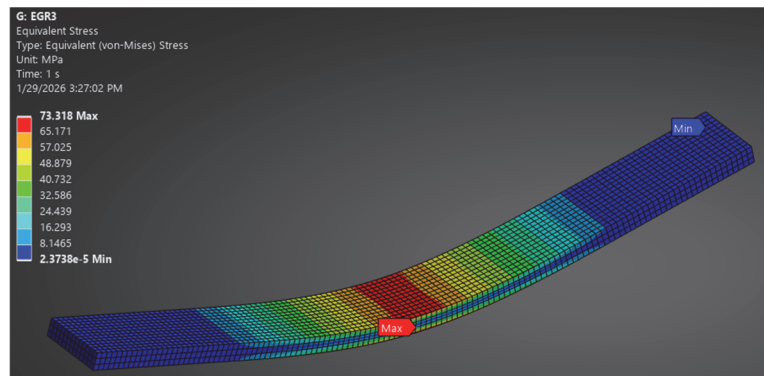


Figure 9: Maximum equivalent stress from simulation of Flexural test (EGRS3)

Nanocomposites	Flexural strength results from FE simulation (MPa)	Flexural strength results from experiment (MPa)
PE	56.46	56.80
EGR1	58.88	59.22
EGR2	63.78	64.14
EGR3	73.31	73.72
EGR4	56.49	56.80
EGRS1	59.90	60.26
EGRS2	65.13	65.51
EGRS3	68.91	69.30
EGRS4	49.43	49.71

Table 3: Comparison of flexural strength results obtained from experimentation and FE simulation.

The main goal of this numerical study is not solely to determine flexural strength test results obtained via experimental means, but rather to validate how hybrid nanocomposite materials undergo load transfer behaviour through finite element modelling based on physics-based concepts (two-stage RVE). In this work, information was obtained regarding the methodology used to simulate the process of flexural strength of the hybrid nanocomposites (graphene-modified epoxy and silica (SiO_2) particles), by describing the rationale behind the sequentially-homogenised modelling method adopted. The properties of the graphene-modified epoxy are modelled first to determine the matrix material properties and then this values are used as an effective matrix to continue modelling SiO_2 particle reinforcement. The methodology allows us to isolate the individual and synergistic contributions of 2D graphene and spherical SiO_2 as independent components of the hybrid nanocomposites while still being included in a single modelling framework. Therefore, numerical results are presented as further validation of the multi-scale modelling method adopted to produce numerical results in comparison with experimental results, rather than just a numerical simulation exercise. The novelty of the numerical simulation lies in the demonstration of using both experimental and numerical approaches to effectively represent staged homogenisation of a hybrid filler system, thereby accurately representing the flexural response of the hybrid filler system. This demonstrates unique aspect of the simulation adopted, therefore positioning the numerical simulation as a complementary tool to help validate experimentally-derived structure–property relationships.

CONCLUSIONS

The study showed that the combination of graphene and hybrid graphene- SiO_2 leads to an appreciable improvement in the mechanical and fracture performance of epoxy-based nanocomposites, especially at low filler contents. Composite materials infiltrated with graphene reinforcement achieved their optimum physical attributes at 0.3 wt% of graphene content. These composites demonstrated approximately 46% superior tensile strength and almost 30% higher



flexural strength than the corresponding ratios of the epoxy without graphene. However; increasing the amount of graphene beyond this optimum concentration caused the development of agglomerates, which degraded the mechanical properties of the composite. EGRS3, which contains 0.15 wt. % graphene and 0.15 wt. % SiO₂ exhibited the highest tensile and flexural strengths with enhancements of 53.23% and 22.15%, respectively. For the fracture toughness, all samples showed an increase in their value but the highest (71.1%) was achieved for EGRS4. This papers on the strong toughening synergy of 2D graphene with spherical SiO₂ nanoparticles. SEM also indicated that less than 0.3 % nanofillers, which resulted in stronger adhesion at the interface, effective crack deflection and rough fracture surfaces that could promote energy dissipation and/or extensive toughening. In contrast, for 0.4 wt. %, particle agglomeration took place and stress concentrations reduced the material, thereby affecting the mechanical properties. Overall, these findings confirm that carefully tailored low-concentration (up to 0.3 wt. %) hybrid nanofillers can greatly enhance the stiffness and fracture toughness of epoxy composites. Controlled use of graphene and SiO₂ at a proper ratio yields effective stress transfer as well as crack-stopping, thus hybrid nanocomposites are considered to be candidate materials for high-performance applications. The experimental results were validated by the numerical analysis, and variation in the bending strength within 1%.

Future work will focus on exploring the fatigue behaviour and long-term durability of hybrid nanocomposites under cyclic loading conditions. Additionally, the influence of functionalised nanoparticles and surface treatments on interfacial bonding will be investigated. The extension of the numerical framework to nonlinear and damage-based modelling is also envisaged to better capture failure mechanisms. Furthermore, scaling the developed materials for industrial structural applications remains an important direction for future research.

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