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Simulation Bending Behaviour of Shape Memory Alloy Graphene Nanotubes-Reinforced Polymers by Multiscale Finite Element Method

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A B S T R A C T

Abstract: Shape memory alloys (SMAs) have been researched and used in numerous applications. This article discusses a general methodology for the bending behavior of SMA, and the validation of this bending behavior was achieved by reinforcing polyurethane and epoxy polymers with graphene nanotubes using a finite element model. Polyurethane and an epoxy were impregnated with different amounts of graphene volume percent (25, 40, 50, 60, and 75). Some of the mechanical properties that were being studied included tensile strength, strain response, and modulus of elasticity. The results show that with the rise of graphene concentration, reductions in deformation and material are enhanced by stiffness as it changes its ductility and flexibility. An examination of the bending moment of 177 N.mm to determine the variation in the composite stiffness was also done. The results showed that the deformation always decreased with the increase in the quantity of graphene, thus proving the strengthening effect of real bending forces.

Introduction

Composite materials have gained significant attention due to their superior mechanical properties compared to traditional materials. Widely utilized to improve polymer composites, graphene is a nanomaterial noted for its extreme strength and thermal conductivity [1]–[7]. Often employed matrix in structural and functional uses are epoxy and polyurethane polymers. The inclusion of shape memory alloys (SMA) increases the adaptability and resilience of these substances, hence enabling their usage in complex engineering projects [8].

Understanding the bending behaviour in SMA graphene nanotubes strengthened polymers is essential if one wishes to maximise their mechanical performance in medical, automobile, and aviation uses. Knowing how polymer matrices and graphene nanotubes interact under bending pressures can reveal material deformation, stress distribution, and strain properties. This study aims to close the gap between computational modelling and experimental material testing so that to improve the design of high-performance composites by using a multiscale finite element technique [9].

To confirm the numerical predictions, another experimental simulation was done with a constant bending moment of 177 N.mm [10]–[14]. The loading state further renders the composite models more believable by making them act like real structures would.

In this study, composite models were formulated in this study with different ratios of reinforcement. Graphene nanotubes were used in the creation of structural models in concentrations of 0.00%, 0.01%, 0.02%, 0.03%, 0.04%, and 0.05% of epoxy and polyurethane polymers under the influence of different loading configurations and under strain response, deformation, and distribution of stress on the structure at varying levels.

Methodology

The methodology of this paper entails multiscale finite element simulation techniques to analyse the bending behaviour of graphene-reinforced SMA composites [15]-[17]. Composite structures can be precisely demonstrated by the finite element analysis (FEA) method by considering both macroscopic and microscopic properties of the materials [18]. The investigation involves mesh generation, model development, numerical analysis, and application of the boundary conditions with the help of ANSYS software [19].

Modelling the composite's microstructure of the composite as a representative volume element (RVE) was used to give a precise simulation of graphene polymer interactions [20]-[22]. Under bending stresses, the RVE based technique enables one to notice the anisotropic behaviour of the composites. A mesh sensitivity analysis was carried out to agreement the rightness of the results, the element size was adjusted till convergence in strain and stress values was attained.

New formulations of boundary conditions were carefully assigned with the bottom surface of the model fully constrained to avoid rotation and displacement. A homogeneously distributed bending force was applied on the top surface to simulate real world loading conditions [23]. The load application followed standard mechanical testing guidelines to be valid in the results. The resulting strain/stress distributions were examined to determine the influence of graphene substance on the mechanical properties of the Shape Memory Alloy composite.

The numerical solution was obtained using the finite element method, with the global stiffness matrix $[K]$ derived as:

$[\mathrm{K}]\ \{U\} = \{F\}$

where $[K]$ is the system global stiffness matrix, $\{U\}$ and $\{F\}$ are the global nodal displacement and global nodal force vectors, respectively [24]. The system was resolved using an iterative solver to confirm numerical convergence and stability.

Material System

The composite models were improved using polyurethane and epoxy as base polymer matrices, reinforced with varying weight ratios of graphene nanotubes. These materials were chosen due to their widespread industrial applications and their ability to be boosted by nanomaterial reinforcements. A RVE approach was applied to simulate the microstructure of the composite materials confirming an accurate depiction of graphene/polymer interactions at the microscopic level. This multiscale modelling technique agreed for the full evaluation of the mechanical response of the composites under bending loads.

Finite Element Simulation

Finite element modelling was conducted using ANSYS software. The models were meshed utilising tetrahedral elements, which are particularly suited for capturing the complex geometry of the composite materials and the anisotropic behaviour due to the varying graphene concentrations. The primary aim of the simulation was to ascertain the mechanical properties, specifically the bending stiffness and deformation characteristics, of the composite materials in relation to graphene content. To ensure the accuracy and reliability of the simulation results, a series of preliminary tests were carried out to select an appropriate element size, which led to the use of 1 mm tetrahedral elements. Direct element size of 1 mm is employing appropriate for modelling nanoscale fillers, as it does not capture their intrinsic scale effects. To address this limitation, a homogenization approach was adopted, in which the influence of graphene nanoscale fillers was represented through effective material properties at the macroscopic level. This strategy enabled accurate simulation of the mechanical response while maintaining computational efficiency. The revised methodology clarifies this mesh strategy and ensures that the finite element results remain both realistic and numerically stable. A mesh sensitivity analysis was performed to refine the element size until convergence was achieved for both stress and strain values. This process ensured that the results were independent of the mesh size and that the simulation was capturing the true behaviour of the material under loading conditions.

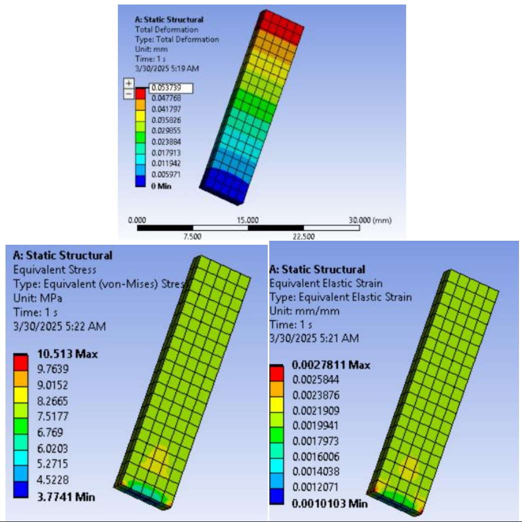
Boundary conditions were applied with the bottom surface of each model fully constrained to prevent both displacement and rotation, replicating a fixed boundary condition. A uniformly distributed bending force was applied along the top surface to simulate practical loading scenarios as seen in experimental testing. This setup was designed to mimic real-world mechanical conditions as closely as possible, where bending moments and shear forces are applied in composite structures during use.

The material properties for each model, including modulus of elasticity and Poisson's ratio, were assigned based on experimental results obtained from testing different graphene concentrations. Specifically, the elastic modulus of the epoxy and polyurethane matrices were adjusted based on the graphene content to simulate the reinforcement effect. The values for the modulus of elasticity were as follows:

- Epoxy-based composites: The modulus ranged from 59.526 MPa at 25% graphene content to 59.413 MPa at 75% graphene content.
- Polyurethane-based composites: The modulus ranged from 59.817 MPa at 25% graphene content to 59.980 MPa at 75% graphene content.

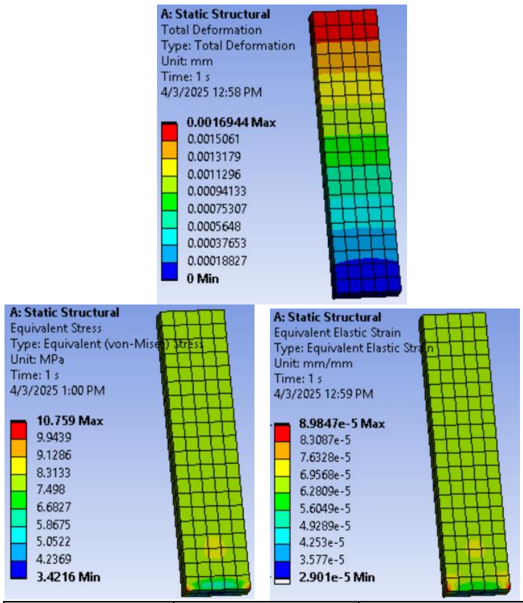
The global stiffness matrix [K] for the system was derived based on the material properties and geometry of the models. The system of equations was solved iteratively using an iterative solver to ensure numerical stability and convergence of the results.

Calculation of the tensile strength of epoxy resin under an applied tensile force of 98.1N:



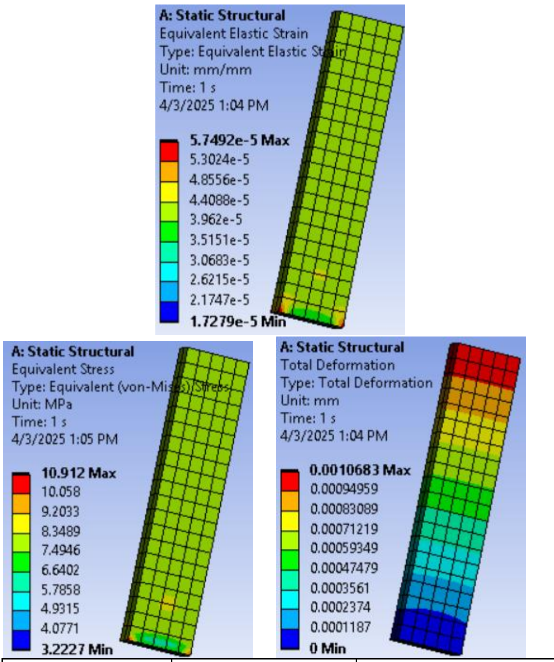
0.00278	0.0027811	0.053739

Figure 1 The results of the tensile strength for Epoxy resin 100% model.



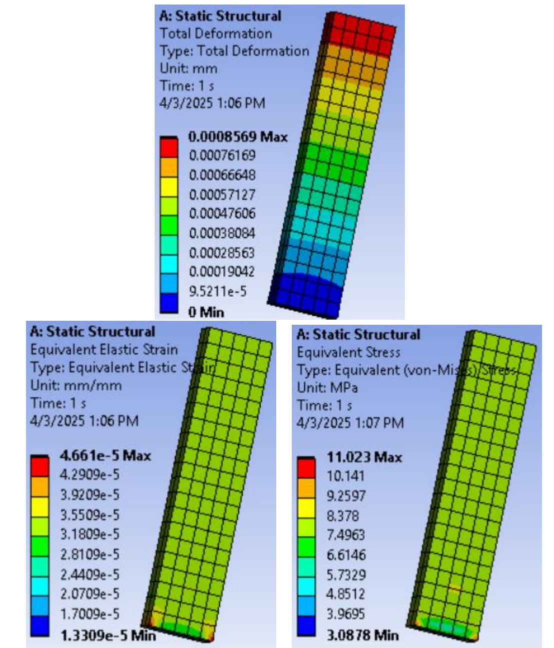
10.759	8.9847e-5	0.0016944

Figure 2 The results of the tensile strength for model: 75% epoxy and 25% graphene by volume.



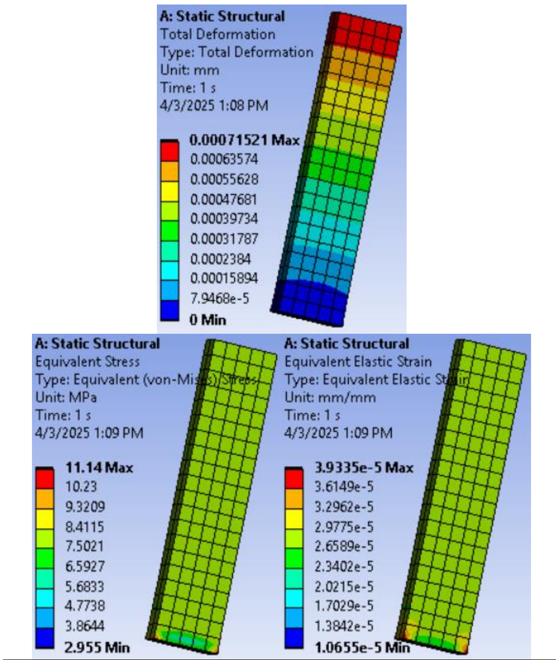
10.912	5.7492e-5	0.0010683

Figure 3 The results of the tensile strength for model: 60% epoxy and 40% graphene by volume.



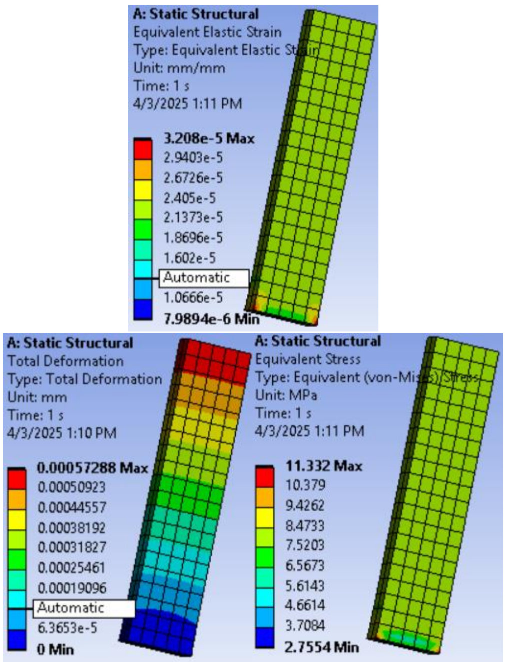
11.023	4.661e-5	0.0008569

Figure 4 The results of the tensile strength for model: 50% epoxy and 50% graphene by volume.



11.14	3.9335e-5	0.00071521

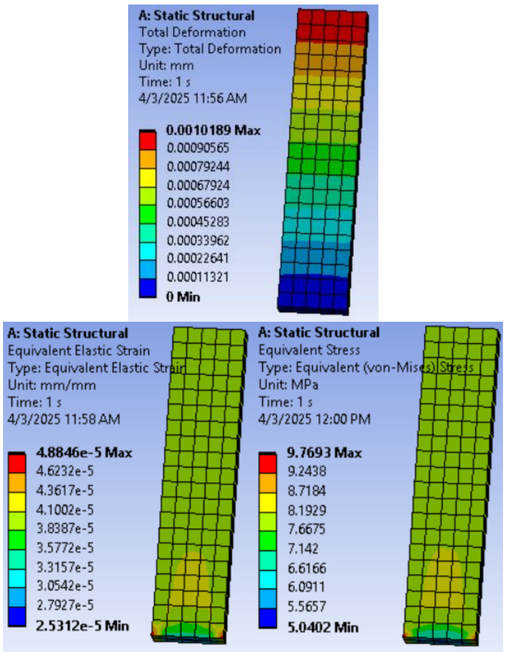
Figure 5 The results of the tensile strength for model: 40% epoxy and 60% graphene by volume.



11.332	3.208e-5	0.00057288

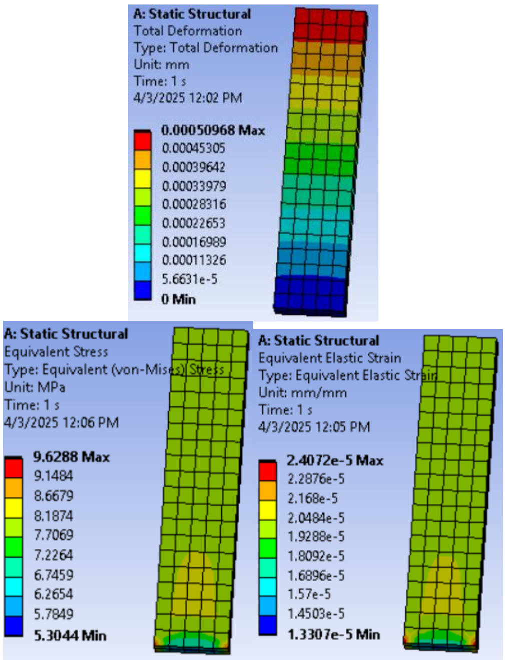
Figure 6 The results of the tensile strength for model: 25% epoxy and 75% graphene by volume.

Also, the calculation of the tensile strength of polyurethane under an applied tensile force of 98.1N:



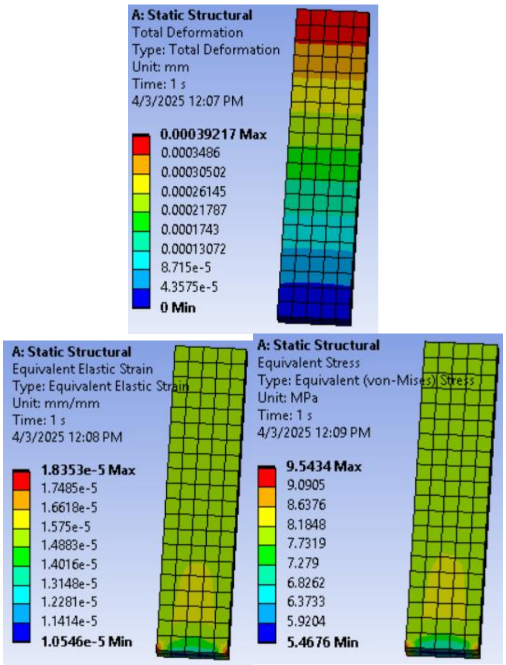
9.7693	4.8846e-5	0.0010189

Figure 7 The results of the tensile strength for polyurethane 100% model



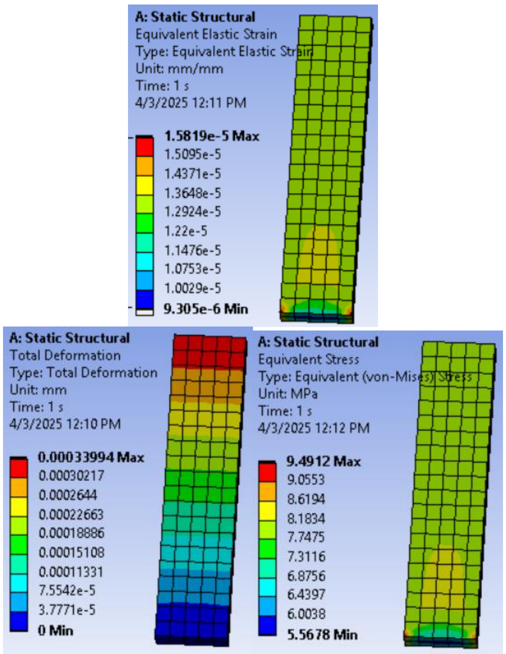
9.6288	2.4072e-5	0.00050968

Figure 8 The results of the tensile strength for model: 75% polyurethane and 25% graphene nanotubes by volume.



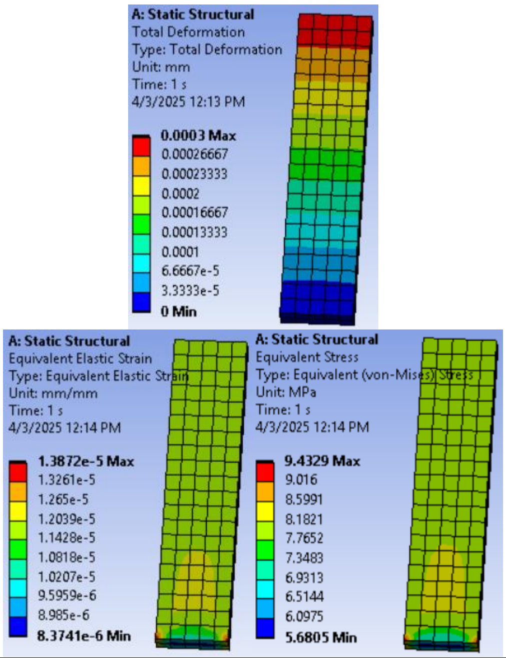
9.5434	1.8353e-5	0.00039217

Figure 9 The results of the tensile strength for model: 60% polyurethane and 40% graphene nanotubes by volume.



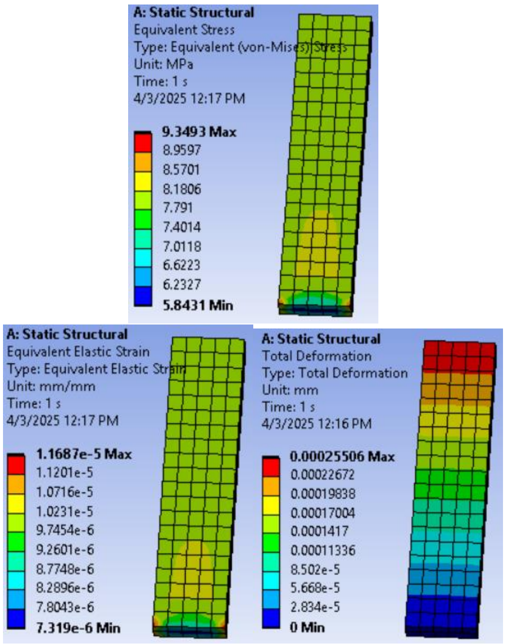
9.4912	1.5819e-5	0.00033994

Figure 10 The results of the tensile strength for model: 50% polyurethane and 50% graphene nanotubes by volume.



9.4329	1.3872e-5	0.0003

Figure 11 The results of tensile strength of model: 40% polyurethane and 60% graphene nanotubes by volume.



9.3493	1.1687e-5	0.00025506

Figure 12 The results of the tensile strength for model: 25% polyurethane and 75% graphene nanotubes by volume.

Results and Discussion

The study showed that in polyurethane-based composites, raising the graphene percentage in epoxy and polyurethane composites enhances stiffness, with the modulus of elasticity going from 59.526 MPa at 25% graphene to 59.980 MPa at 75% graphene as shown in Figure 1-6. Additionally, the deformation values decreased as the graphene content increased, suggesting improved load resistance. However, ductility was reduced at higher graphene levels, which would affect flexibility and impact resistance.

Validation:

This validates the prediction of the bending behaviour of the graphene-reinforced composites by the finite element model's correctness and dependability.
When the bending moment was 177 N.mm, the epoxy-based composites with graphene nanotubes showed a gradual decrease in deformation as the concentration of graphene increased as shown in appendix A. For example, the strain went from 0.024769 at 25% graphene to 0.0087059 at 75% graphene, but the modulus stayed almost the same (about 59.4–59.5 MPa). This behaviour shows that graphene makes things stiffer and less likely to bend when moments are applied. Similarly, the strain of epoxy reinforced with graphene nanotubes significantly reduced from 0.01161 at 25% nanotube content to 0.0034939 at 75 percent. The modulus increased slightly to 59.915 MPa, indicating that the material was capable of high volume holding. All these values were located only when the moment was 177 N.mm, which makes the FEA model more credible and allows using high contents of graphene. The results show good consistency, and the ultimate tensile strength and the elastic modulus showed a difference of less than five percent among the samples as shown in figure (7-12). This indicates the mechanical behavior of the composite graphene-reinforced SMA polymer composites.

Parametric Study:

The parametric methods have been used to examine the effect of various levels of graphene on the mechanical behavior of epoxy and polyurethane composites. The experiment involved the investigation of the influences of different graphene volume per cent (25, 40, 50, 60 and 75 percent) on modulus of elasticity and tensile strain responses. In both epoxy and polyurethane composite, the content of graphene was also rising exponentially with the modulus of elasticity. The modulus of elasticity for the epoxy-graphene composites, for instance, varied from 59.526 MPa at 25% graphene to 59.413 MPa at 75% graphene. The modulus for polyurethane-graphene composites, likewise, ranged from 59.817 MPa at 25% graphene to 59.980 MPa at 75% graphene. Adding Shape Memory Alloys to the composite systems made the structure noticeably more stable when it was bent. Adding SMA improved the recovery behaviour and lowered permanent deformation, especially in models with more graphene. This combination of SMA and graphene made it easier to control strain and made the composite matrix stronger overall.

Conclusion

This research shows that the bending characteristics of SMA polymer composites are greatly enhanced by graphene nanotubes reinforcement. Though stiffness and strength are improved, the decrease in ductility calls for selective graphene concentration based on application demands. Future studies should concentrate on improving computational models including using advanced material models that include nonlinear behavior and combining Multiphysics simulations. Beyond simply the bending behaviour, this will allow for more precise forecasts of the material's behaviour under several operating circumstances. The study shows that graphene-reinforced composites, especially those with more graphene, had less deformation and better stiffness when they were bent at a constant moment of 177 N.mm. The data show that these materials can be used in load-bearing situations where bending resistance is very important. This makes it even more likely that graphene and polymers can be used together in structures that need to be very strong and not bend too much. Adding Shape Memory Alloys to the polymer–graphene composites worked well to improve the recovery of deformation and lower the residual strain when flexural loads were applied. Their smart behaviour, along with graphene's ability to make things stronger, gives them two benefits: they become stiffer and can recover on their own. This makes these composites good candidates for use in biomedical or aerospace parts that need both strength and flexibility.

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References

[1] A. Kausar, ‘Polyurethane Composite Foams in High-Performance Applications: A Review’, Polym. Plast. Technol. Eng., vol. 57, no. 4, pp. 346–369, Mar. 2018, doi: 10.1080/03602559.2017.1329433.
[2] R. F. Gibson, ‘A review of recent research on mechanics of multifunctional composite materials and structures’, Compos. Struct., vol. 92, no. 12, pp. 2793–2810, Nov. 2010, doi: 10.1016/J.COMPSTRUCT.2010.05.003.
[3] T. F. Alhamada, M. A. Azmah Hanim, D. W. Jung, A. A. Nuraini, and W. Z. W. Hasan, ‘A Brief Review of the Role of 2D Mxene Nanosheets toward Solar Cells Efficiency Improvement’, Nanomaterials, vol. 11, no. 10, p. 2732, Oct. 2021, doi: 10.3390/nano11102732.
[4] A. Kausar and I. Ahmad, ‘Versatile shape memory nanocomposites: technological platform for biomedical applications’, in Shape Memory Polymer-Derived Nanocomposites, Elsevier, 2024, pp. 237–254. doi: 10.1016/B978-0-443-18504-5.00011-7.
[5] Y. Hong, I. Azcune, A. Rekondo, and E. Saiz, ‘The effect of graphene properties on the extrusion of a shape memory epoxy vitrimer’, Mater. Des., vol. 246, p. 113344, Oct. 2024, doi: 10.1016/j.matdes.2024.113344.
[6] T. F. Alhamada et al., ‘MXene-based novel nanocomposites doped SnO2 for boosting the performance of perovskite solar cells’, Sci. Rep., vol. 14, no. 1, pp. 1–11, Dec. 2024, doi: 10.1038/S41598-024-64632-1;SUBJMETA.
[7] T. F. Alhamada, M. A. Azmah Hanim, R. Saidur, A. Nuraini, W. Z. Wan Hasan, and D. W. Jung, ‘Recent advances in polymer and perovskite based third-generation solar cell devices’, Mater. Today Proc., vol. 74, pp. 533–539, Jan. 2023, doi: 10.1016/J.MATPR.2022.12.158.
[8] ‘Polyurethane Shape Memory Polymers - W.M. Huang, Bin Yang, Yong Qing Fu - كتب Google’. https://books.google.iq/books?hl=ar&lr=&id=mHrlc8oAxWQC&oi=fnd&pg=PP1&dq=nanomaterial+composites+polymer+polyurethane+shape+memory+alloys+(SMA)+&ots=rduyEUS5EH&sig=JQBF6GKJUFZ3_byw4eI2fLDZBQk&redir_esc=y#v=onepage&q=nanomaterial composites polymer polyurethane shape memory alloys (SMA)&f=false (accessed Sep. 29, 2025).
[9] M. C. Biswas, S. Chakraborty, A. Bhattacharjee, and Z. Mohammed, ‘4D Printing of Shape Memory Materials for Textiles: Mechanism, Mathematical Modeling, and Challenges’, Adv. Funct. Mater., vol. 31, no. 19, p. 2100257, May 2021, doi: 10.1002/ADFM.202100257.
[10] M. Song, J. Yang, and S. Kitipornchai, ‘Bending and buckling analyses of functionally graded polymer composite plates reinforced with graphene nanoplatelets’, Compos. Part B Eng., vol. 134, pp. 106–113, Feb. 2018, doi: 10.1016/J.COMPOSITESB.2017.09.043.
[11] C. H. Thai, A. J. M. Ferreira, T. D. Tran, and P. Phung-Van, ‘Free vibration, buckling and bending analyses of multilayer functionally graded graphene nanoplatelets reinforced composite plates using the NURBS formulation’, Compos. Struct., vol. 220, pp. 749–759, Jul. 2019, doi: 10.1016/j.compstruct.2019.03.100.
[12] A. Wang, H. Chen, Y. Hao, and W. Zhang, ‘Vibration and bending behavior of functionally graded nanocomposite doubly-curved shallow shells reinforced by graphene nanoplatelets’, Results Phys., vol. 9, pp. 550–559, Jun. 2018, doi: 10.1016/j.rinp.2018.02.062.
[13] J. Yang, D. Chen, and S. Kitipornchai, ‘Buckling and free vibration analyses of functionally graded graphene reinforced porous nanocomposite plates based on Chebyshev-Ritz method’, Compos. Struct., vol. 193, pp. 281–294, Jun. 2018, doi: 10.1016/j.compstruct.2018.03.090.
[14] D. Chen, J. Yang, and S. Kitipornchai, ‘Nonlinear vibration and postbuckling of functionally graded graphene reinforced porous nanocomposite beams’, Compos. Sci. Technol., vol. 142, pp. 235–245, Apr. 2017, doi: 10.1016/j.compscitech.2017.02.008.
[15] B. Xu et al., ‘Progress in phase field modeling of functional properties and fracture behavior of shape memory alloys’, Prog. Mater. Sci., vol.

148, p. 101364, Feb. 2025, doi: 10.1016/J.PMATSCI.2024.101364.

[16] X. Xie, B. Xu, C. Yu, Q. Kan, and G. Kang, 'Phase field study on the temperature dependence of the shape memory effect and superelasticity of NiTi alloys with different grain sizes', Eur. J. Mech. A/Solids, vol. 112, Jul. 2025, doi: 10.1016/j.euromechsol.2025.105656.

[17] B. Ahmed et al., 'Shape Memory Graphene Nanocomposites—Fundamentals, Properties, and Significance', Process. 2023, Vol. 11, Page 1171, vol. 11, no. 4, p. 1171, Apr. 2023, doi: 10.3390/PR11041171.

[18] S. K. Sahu and P. S. Rama Sreekanth, 'Multiscale RVE modeling for assessing effective elastic modulus of HDPE based polymer matrix nanocomposite reinforced with nanodiamond', Int. J. Interact. Des. Manuf., vol. 18, no. 9, pp. 6371–6380, Nov. 2024, doi: 10.1007/S12008-022-01080-Z/METRICS.

[19] E. K. Njim et al., 'Mechanical Properties of Sandwiched Construction with Composite and Hybrid Core Structure', Adv. Polym. Technol., vol. 2024, no. 1, p. 3803199, Jan. 2024, doi: 10.1155/2024/3803199.

[20] A. Moradi, R. Ansari, and M. K. Hassanzadeh-Aghdam, 'Synergistic effect of carbon nanotube/graphene nanoplatelet hybrids on the elastic and viscoelastic properties of polymer nanocomposites: finite element micromechanical modeling', Acta Mech., vol. 235, no. 4, pp. 1887–1909, Apr. 2024, doi: 10.1007/S00707-023-03782-1/METRICS.

[21] 1.126Q1SJR Q1; 1.126NAABS NANAABDC NAApplied Mathematical ModellingA Anjomshoa, A. Shahidi, … B. H.-A. M., and undefined 2014, 'Finite element buckling analysis of multi-layered graphene sheets on elastic substrate based on nonlocal elasticity theory', Elsevier, Accessed: Jul. 26, 2025. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0307904X14001395

[22] 0.782Q1SJR Q1; 0.782NAABS NANAABDC NAComputational Materials ScienceS Kilikevičius, S. Kvietkaitė, … K. Ž.-C. M., and undefined 2020, 'Numerical investigation of the mechanical properties of a novel hybrid polymer composite reinforced with graphene and MXene nanosheets', Elsevier, Accessed: Jul. 26, 2025. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0927025619307967

[23] H. Raad, E. K. Njim, M. J. Jweeg, M. Al-Waily, L. Hadji, and R. Madan, 'Vibration Analysis of Sandwich Plates with Hybrid Composite Cores Combining Porous Polymer and Foam Structures', J. Comput. Appl. Mech., vol. 55, no. 3, pp. 485–499, Jun. 2024, doi: 10.22059/JCAMECH.2024.377658.1121.

[24] A. K. Mekala, S. Panda, and V. Sarnaik, 'Dynamic performance of sandwich beams with uniform and axially graded carbon black reinforced viscoelastic nanocomposite cores', Mech. Based Des. Struct. Mach., pp. 1–28, Aug. 2025, doi: 10.1080/15397734.2025.2541251.