Investigations of Structural Integrity Enhancement through Single-Walled Carbon Nanotubes in Glass Fibre Reinforced Polymers Under Impact Loading Conditions

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**Abstract.** Composite materials are engineered by combining two or more distinct materials to achieve superior performance characteristics unattainable by individual constituents alone. In this study, the integration of single-walled carbon nanotubes (SWCNTs) into glass fiber-reinforced polymer (GFRP) composites is explored to enhance structural performance, targeting applications in aerospace, automotive, and marine sectors. Geometric models are developed using ANSYS ACP, and advanced computational simulations, alongside experimental validations, are employed for multi-disciplinary component optimization. The research focuses on six different GFRP variants—E GFRP, E GFRP UD O, E GFRP polyester, S GFRP, E GFRP fabric O, and GFRP W—reinforced with an epoxy resin matrix and embedded with SWCNTs. A high-impact load of 1,503,700 N is applied across all models using ANSYS Structural to assess mechanical behavior. Comparative evaluations are conducted to determine the influence of nanotube-enhanced fillers. Results demonstrated that SWCNT-reinforced GFRP composites outperformed their base material counterparts in both numerical simulations and experimental tests, confirming the effectiveness of SWCNTs in improving the durability and strength of fiber-reinforced nanocomposites.

# INTRODUCTION

Carbon Nanotubes (CNTs) are nanoscale carbon structures with dimensions in the range of a few nanometers, offering exceptional properties that make them ideal for enhancing composite materials. In this study, composites are developed to improve mechanical performance, utilizing CNTs within a matrix composed of 60% carbon fiber and 40% epoxy resin mixed with a hardener. Among the critical evaluations in material engineering is the impact test, which assesses a material’s ability to absorb energy and provides insights into its ductility, brittleness, and resistance to sudden forces. Standardized specimens are subjected to high-velocity impact loads to determine these properties. The synergy between the reinforcement, matrix, and filler components plays a crucial role in defining the performance of nanocomposites. Among these, the reinforcement’s orientation—unidirectional, bidirectional, or multidirectional—is key to tuning structural properties. Modifications in the matrix focus on enhancing interfacial bonding, reducing delamination, and optimizing the influence of fillers. The core composition of materials significantly affects mechanical property estimations [1].

To improve the durability and functionality of composites, optimal matrix materials often include ceramics, nanoparticles, and fluoropolymers like deflons. In evaluating the mechanical behavior of Single-Walled Carbon Nanotubes (SWCNTs), this study incorporates various glass fiber-based reinforcements, highlighting their pivotal role in load transfer within composites [2]. Fibers made from materials such as carbon, glass, and boron offer varying mechanical strengths and durability levels, directly impacting the performance of the resulting laminates. A strong chemical bond between the fibers and matrix enhances thermal, electrical, and mechanical characteristics, underscoring the importance of choosing a compatible matrix material [3, 4]. Among available matrices, epoxy resin stands out due to its superior compatibility, bonding capability, and reliability with diverse fiber types. As a result, it is widely employed as the primary matrix in composite development [5].

Finite Element Analysis (FEA) has been applied to study CNT-reinforced polymer composites, with detailed validation of material models, mesh configurations, mechanical properties, and elemental definitions [6]. The analysis explores the effectiveness of CNTs in reinforcing the polymer matrix, load transfer mechanisms, and the challenges associated with producing uniform nanocomposites. Critical factors such as CNT weight percentage, processing methods, matrix types, and environmental influences are evaluated to determine the best practices for performance optimization. The review consolidates data on ideal filler loadings, advanced manufacturing methods, and matrix selection criteria for producing high-performance nanocomposites [7]. In addition, the study investigates the agglomeration phenomena of CNTs in reinforced composites, offering insights into their structural characteristics and the adverse effects of poor dispersion on both the matrix and reinforcement phases [8].

# IMPOSED Methodology

The development of the nanocomposite in this study is carried out using ANSYS ACP (Ansys Composite PrepPost), a specialized numerical tool for composite analysis. Prior research has played a crucial role in defining the essential material properties of carbon nanotubes, such as Young’s modulus, Poisson’s ratio, and density [9–12]. The process begins with the conceptual design of the test specimen, followed by finite element modeling (FEM) to simulate its structural response. Structural analysis techniques are employed to assess the behavior of the composite under applied loads, with specific attention given to the assignment of boundary conditions and the application of control equations in the FEA framework. Accurate mesh generation is also performed to ensure computational precision and convergence. Regardless of the variations in computational modeling approaches, it is imperative to adhere to validated simulation protocols to ensure reliable and reproducible results [13–16].

**Computational model**

The geometric model used for this analysis is developed using ANSYS ACP, a powerful tool tailored for composite material simulations. Through this modeling approach, key material properties such as Young’s modulus, Poisson’s ratio, and density of carbon nanotubes are defined based on previous studies. The meshing process is executed using the ANSYS meshing utility, where the selection of appropriate element types is critical solid elements are chosen for 3D bulk structures, while shell elements are employed for thin-walled components. Material definitions, including elastic modulus, Poisson’s ratio, and density, are assigned to the components. Boundary conditions such as fixed supports or prescribed displacements are applied to simulate realistic constraints. Loads are introduced in the form of forces or pressure, depending on the test scenario, using ANSYS’s integrated loading tools. The simulation is then carried out within the ANSYS environment, with careful monitoring of convergence criteria, warnings, and errors to ensure the accuracy and reliability of results [17-19]. Figure 1 displays the computational model constructed using standard 3D modeling parameters, which forms the foundation for the structural evaluation [31-35].

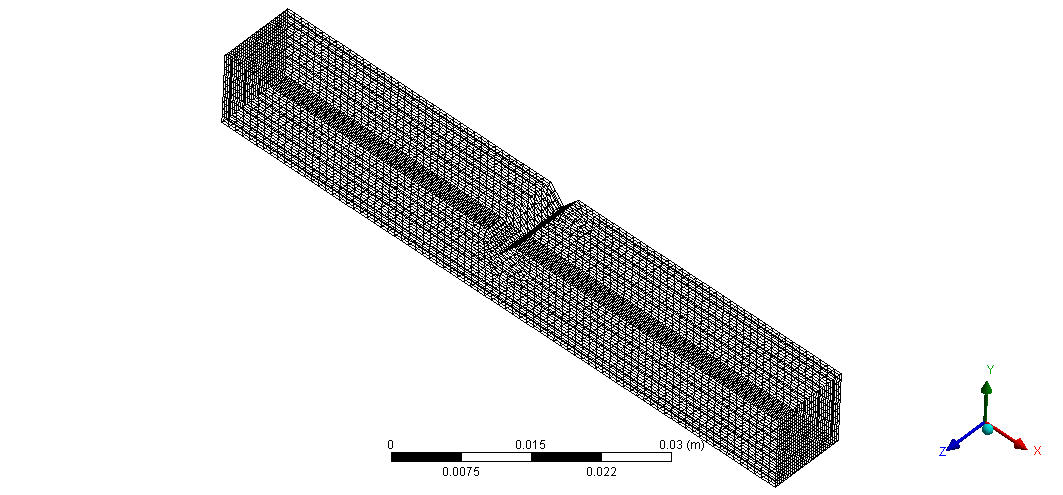
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1. Computational model for the Impact test analysis

**Discretization**

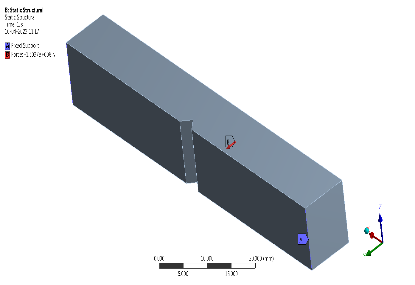
For accurate simulation of an impact test in ANSYS, precise definition of material properties and boundary conditions is essential. The model must undergo proper discretization using effective meshing techniques to ensure reliable and consistent results [32–36]. The selection of an appropriate mesh type plays a pivotal role in achieving accuracy, making high mesh quality a critical requirement. In regions experiencing significant deformation, adaptive meshing is recommended to refine the mesh locally and enhance result fidelity. Figure 2 illustrates the standard discretized configuration of the impact test specimen [37-40]. Finite element models are developed from this discretized geometry, enabling structural assessment under loading conditions. The use of structured mesh layouts simplifies the discretization process and contributes to dependable results within shorter computation times. For this study, medium-level settings are adopted for both nodes and elements to balance accuracy and efficiency. While unstructured meshes can improve output uniformity, they often require more time to construct and lead to longer simulation runtimes. To streamline analysis and maintain precision, the ANSYS meshing tool is used to generate structured meshes for the test specimen, modeled as a rectangular bar [20-22].



1. Discretized model of the Impact test analysis

**Boundary conditions**

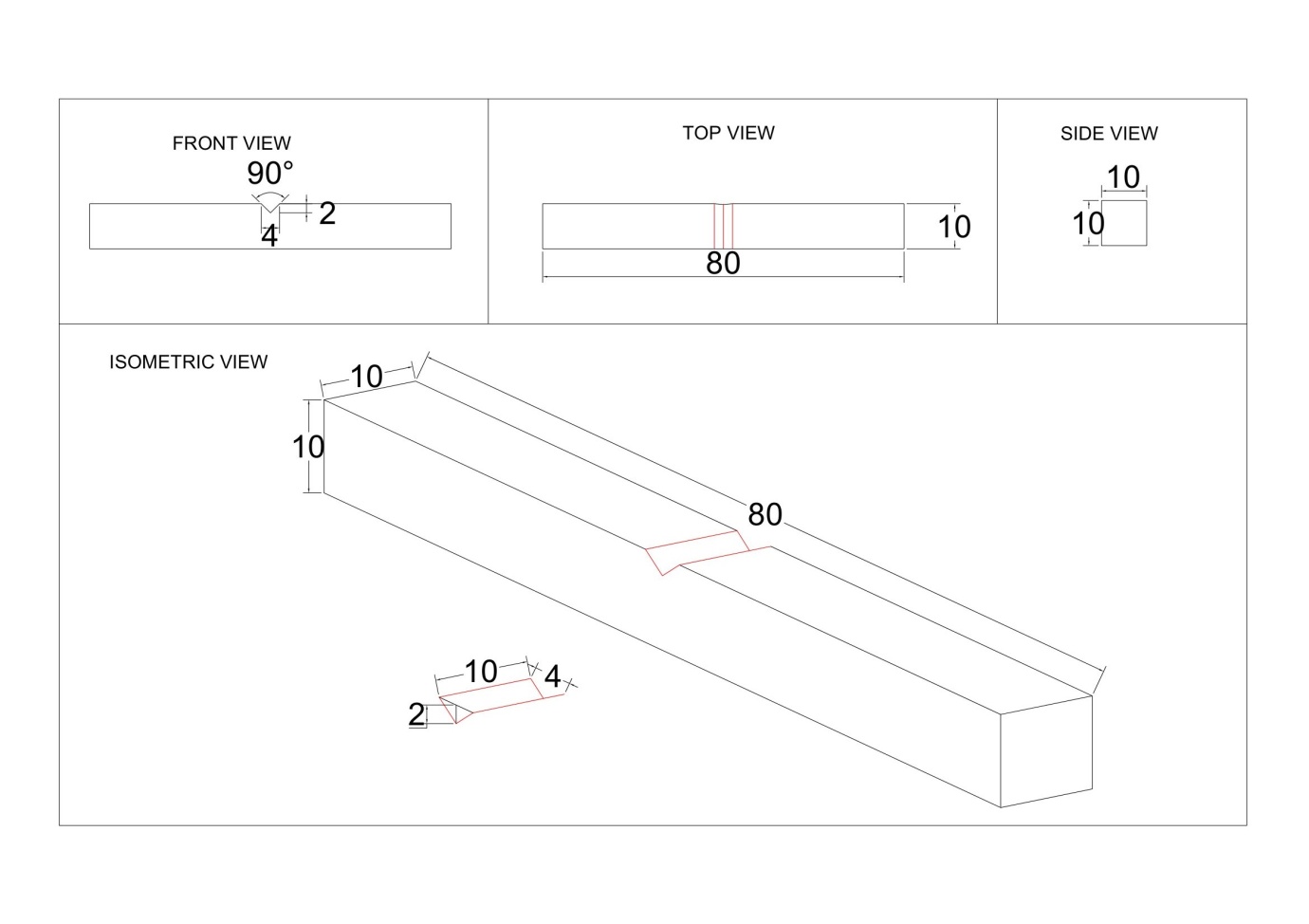
In ANSYS simulations, the impact test specimens are commonly constrained at both ends, with a concentrated load applied at the midpoint. Boundary conditions are defined using fixed support and impact loading parameters, along with accurately assigned material properties to reflect real-world behavior [23 -27]. An efficiently generated mesh is essential to capture the specimen’s structural response accurately while maintaining computational efficiency. In this analysis, both ends of the specimen are fixed, and a central impact load of 1,503,700 N is applied. Figure 3 illustrates the typical computational model used for simulating this loading scenario [28-30].



1. Fixed support applied in the model

# EXPERIMENTAL VALIDATION-IMPACT LOAD

For impact tests, the specimen is fabricated using GFRP, Epoxy resin mixed with SWCNTs, and it is done by hand laying process. And once the material is cured, the technician can then cut out the required shape for the impact test specimen [41-49].



1. A typical view of impact test specimen – design draft

Figure 4 depicts the dimensional view of the impact test specimen which is designed and used for the analysis.

|  |  |
| --- | --- |
|  | A metal object with a black metal bar  Description automatically generated with medium confidence |
| 1. Impact test specimen in test apparatus | 1. Impact test specimen in test apparatus |

Figure 5 displays the Charpy impact testing apparatus used for experimental validation, where the impact load was applied. Figure 6 illustrates the test specimen positioned within the apparatus during the analysis.

|  |  |
| --- | --- |
|  |  |
| 1. Test specimen after testing | 1. Impact test result |

Figure 7 represents the broken specimen which after the impact load is applied and Figure 8 depicts the digital instrument that is used to obtain the result from the apparatus after the load is applied.

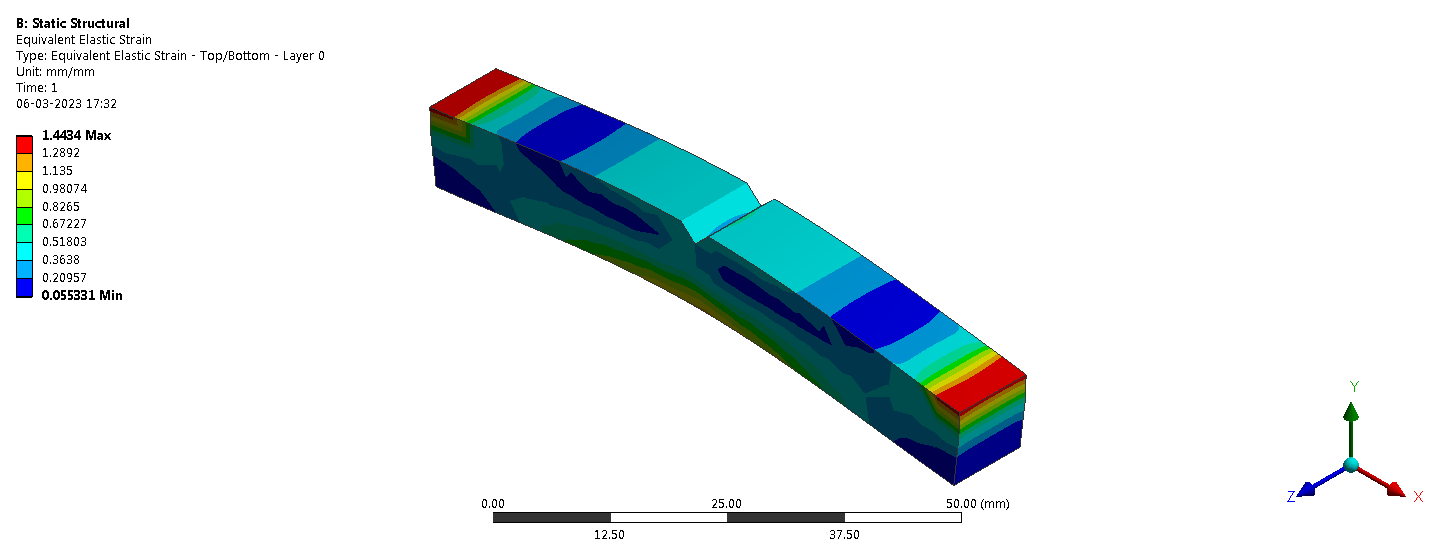
# RESULTS AND DISCUSSION

The impact test specimen is designed and analyzed computationally, and the subsequent results are illustrated in this section. Figures 9 to 11 represents the total deformation, Equivalent stress, Equivalent elastic strain of GFRP base material [50-59].

A rainbow colored rectangular object

Description automatically generated

1. S-GFRP Deformation-Base material



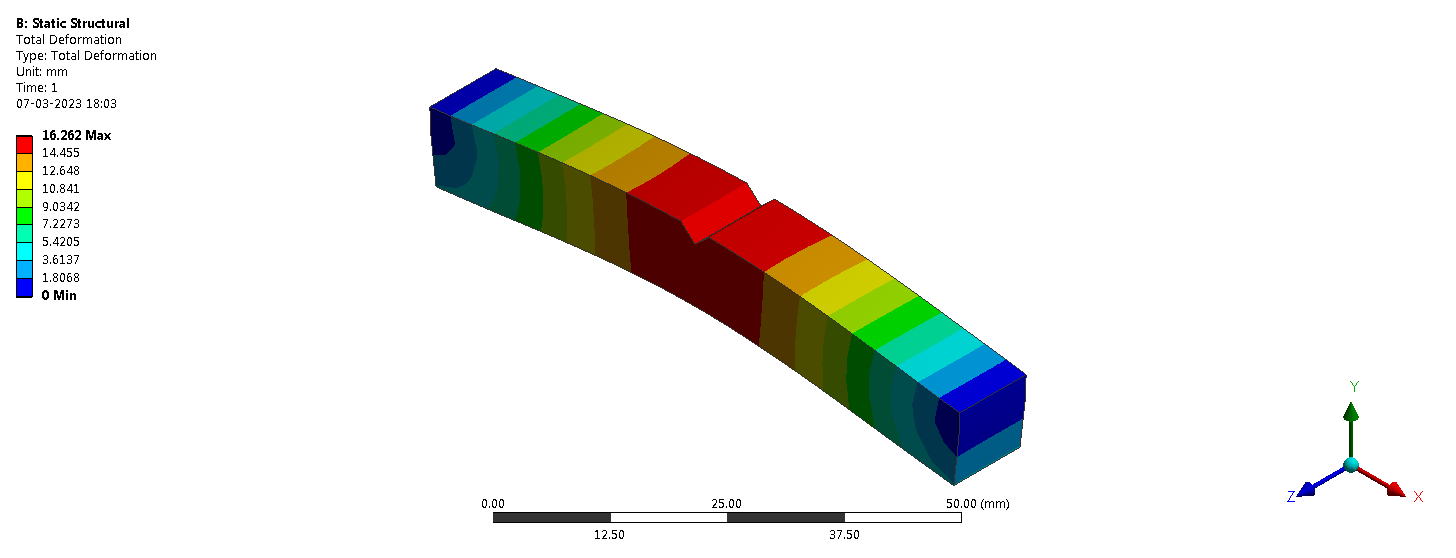
1. S-GFRP material Equivalent Elastic Strain-Base material

A multicolored object with a scale

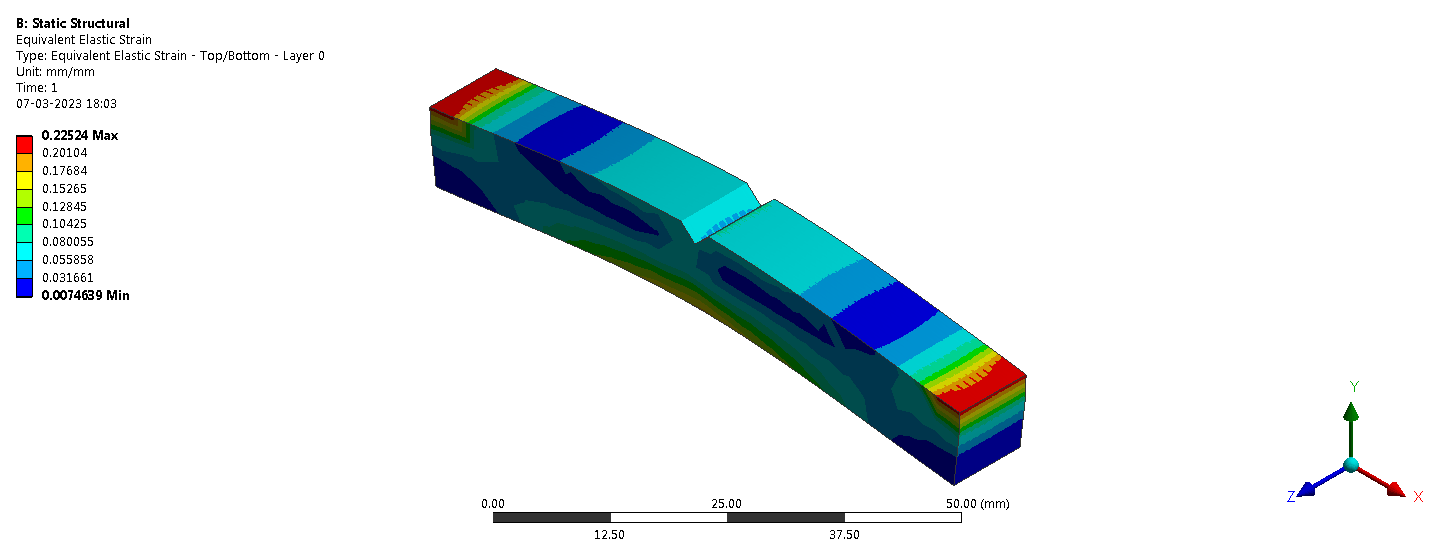
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1. S-GFRP material Equivalent Stress-Base material

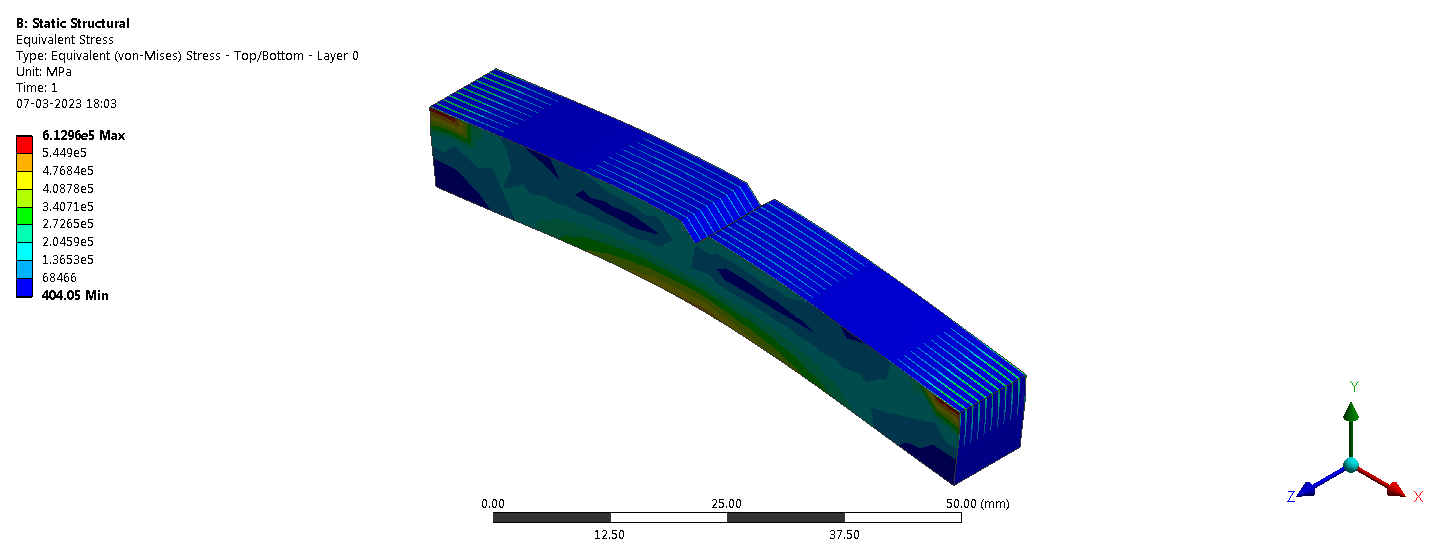
The impact test specimen [60-65] was designed and analyzed through computational methods, and the resulting data are presented in Figures 12 to 14, which illustrate the total deformation, equivalent stress, and equivalent elastic strain of the base GFRP material.



1. S-GFRP material Deformation-With SWCNTs

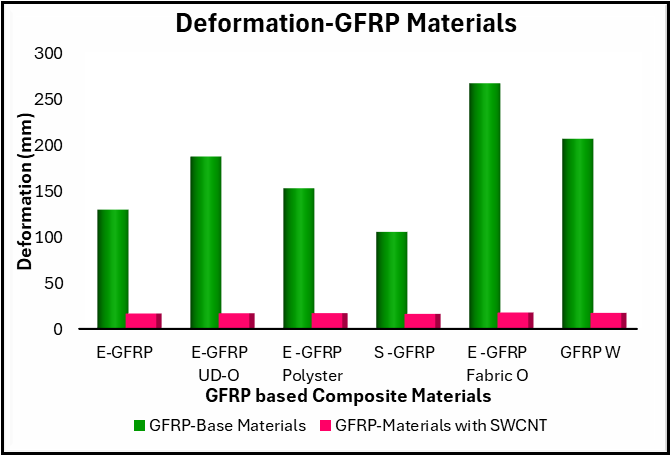


1. S-GFRP material Equivalent Elastic Strain-With SWCNTs

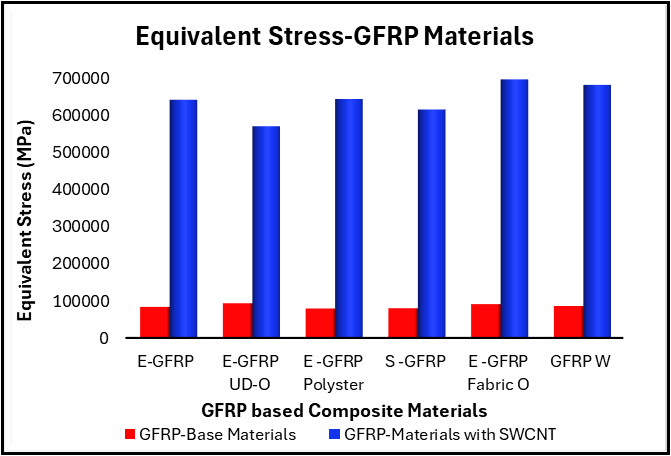


1. S-GFRP material Equivalent stress – with SWCNTs

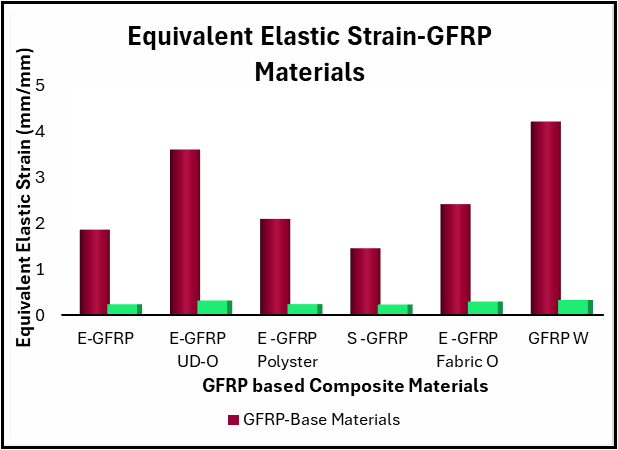
Figures 15 to 17 present the computational analysis results, showcasing the graphical representations of total deformation, equivalent stress, and equivalent elastic strain for the proposed GFRP material, both with and without SWCNT reinforcement [66-70].



1. Comprehensive report of Total Deformation of various GFRP Base material composites and with SWCNT composite material.



1. Comprehensive report of Equivalent Stress and Equivalent of various GFRP base material and with SWCNT nanocomposites.



1. Comprehensive report of Equivalent Elastic strain of various GFRP base material and with SWCNT nanocomposites.

The comprehensive analysis reveals that the total deformation in the GFRP composite reinforced with SWCNTs is significantly lower than that of the base material. While the stress levels in the SWCNT-reinforced composite are comparatively higher, the corresponding strain values remain lower. This indicates the material's enhanced ability to endure applied loads without compromising structural integrity, highlighting the effectiveness of SWCNT reinforcement in improving the load-bearing capacity of GFRP composites.

# CONCLUSION

The pre-processing for simulation was carried out using ANSYS software. Validation confirms that the advanced one-way coupled approach employed in this study is both effective and reliable for analyzing composite materials. Structurally, composites reinforced with SWCNTs demonstrated superior performance compared to the base materials.

In evaluating the characteristics of advanced nanocomposites, impact testing was conducted under identical loading conditions for all cases. The computational outcomes closely align with the experimental findings, reinforcing their validity. As illustrated in Figures 15 to 17, glass fiber composites infused with SWCNTs exhibit significantly reduced deformation and strain. Although stress levels were comparatively higher, the strain remained low—indicating that the structural integrity of the material was well preserved.

Among the various glass fiber composites tested, S-GFRP reinforced with SWCNTs delivered the most notable performance under impact loading, showing an 83% reduction in deformation and a 98% decrease in elastic strain compared to the unreinforced GFRP baseline. This enhanced performance is attributed to the effective reinforcement provided by the SWCNTs. E-GFRP composites also displayed improved behavior under the same conditions. Overall, these results highlight the substantial improvement in impact resistance and structural stability achieved through the incorporation of SWCNTs into glass fiber-reinforced composites.

# References

1. Raj Kumar. G, Senthil Kumar. M, K. Raja Sekar, Mohamed Bak. K &Varun. S, The Mechanical Characterization of Carbon Fiber Reinforced Epoxy with Carbon Nanotubes, International Journal of Mechanical and Production Engineering Research and Development, ISSN(E): 2249-8001 Vol. 9, Special Issue 1, 243-255, Jan 2019.
2. Vala et al., (2024). Investigation of varying tip clearance gap and operating conditions on the fulfilment of low-speed axial flow fan. International Journal of Turbo & Jet-Engines, (0). https://doi.org/10.1515/tjj-2024-0067
3. Raj Kumar G, P. Jagadeeshwaran, Vijayakumar Mathaiyan, Ramesh M, and Dong Won Jung, Comparative Numerical Analyses of Different Carbon Nanotubes Added with Carbon Fiber–Reinforced Polymer Composite, Nanomaterials and Nanocomposites: Characterization, Processing, and Applications, Chapter – 9, pp. 139 – 165, ISBN 9780367483890, DOI: 10.1201/9781003160946-12, 2021.
4. K. Venkatesan, S. Geetha, G. Raj Kumar, P. Jagadeeshwaran, R. Raj Kumar; Advanced structural analysis of various composite materials with carbon nano-tubes for property enhancement. AIP Conf. Proc. 2 November 2020; 2270 (1): 030005. https://doi.org/10.1063/5.0019367
5. S.I. Yengejeh, S.A. Kazemi, and A. Öchsner, “Carbon nanotubes as reinforcement in composites: A review of the analytical, numerical and experimental approaches,” Computational Materials Science 136, 85–101 (2017)
6. Vinodh et al., (2024). Experimental analysis on surface hardness of AA5083 with SiC/eggshell powder reinforced novel metal matrix composite. In International Conference on Medical Imaging, Electronic Imaging, Information Technologies, and Sensors (MIEITS 2024) (Vol. 13188, pp. 368-377). SPIE. https://doi.org/10.1117/12.3030842
7. A K Guptaa, S.P. Harsha, “Analysis of Mechanical Properties of Carbon Nanotube Reinforced Polymer Composites Using Continuum Mechanics Approach”,Procedia Materials Science, Volume 6, 2014, Pages 18-25
8. J. Du, J. Bai, and H. Cheng, “The present status and key problems of carbon nanotube based polymer composites,” eXPRESS Polymer Letters 1(5), 253–273 (2007).
9. R.I. Rubel, Md.H. Ali, Md.A. Jafor, and Md.M. Alam, “Carbon nanotubes agglomeration in reinforced composites: A review,” AIMS Materials Science 6(5), 756–780 (2019).
10. Venkatesan K, Ramesh M, Raj Kumar G, Senthil Kumar M, Optimization of Orientation Of Carbon Fiber Reinforced Polymer Based on Structural Analysis, International Journal of Scientific & Technology Research, ISSN 2277-8616, Volume 8 - Issue 11, 3020 – 3029, November 2019.
11. Mehta et al., (2024). Twisted tape inserts in parabolic trough solar collectors: Assessment of Energy, Exergy, and Environmental impacts. Applied Thermal Engineering, 250, 123566.
12. S. Bhagavathiyappan, M. Balamurugan, M. Rajamanickam, G. Raj Kumar, M. Senthil Kumar; Comparative computational impact analysis of multi-layer composite materials. AIP Conf. Proc. 2 November 2020; 2270 (1): 040007. https://doi.org/10.1063/5.0019380
13. M. Ramesh. P. Jagadeeshwaran, K. Deviparameswari, S. Meenakshi, Prisha K. Asher R. Vaidegi, B. Feonsa Antonitta, Impact behavioral studies on various composite materials using Fluid-Structure interaction (FSI), Materials Today: Proceedings, Volume 51, Part 1, 2022, Pages 1134-1140. https://doi.org/10.1016/j.matpr.2021.07.112.
14. Aslam et al., (2024). Smart Multiphase Power Converter in the Fault-Tolerant Machine Development for Aerospace Applications. In 2024 Ninth International Conference on Science Technology Engineering and Mathematics (ICONSTEM) (pp. 1-5). IEEE. https://doi.org/10.1109/ICONSTEM60960.2024.10568598
15. Vinayagam, G., Thaiyan Rajendran, R., Mohan, M.S. et al. Multi-perspective Investigations of Aerosol’s Non-linear Impact on Unmanned Aerial Vehicle for Air Pollution Control Applications Under Various Aerosol Working Environments. Aerosol Sci Eng 8, 213–240 (2024). https://doi.org/10.1007/s41810-024-00219-7
16. Gnanasekaran RK, Shanmugam B, Raja V, Al-Bonsrulah HAZ, Rajendran P, Radhakrishnan J, Eldin SM and Narayanan V (2023), Comprehensive computational investigations on various aerospace materials under complicated loading conditions through conventional and advanced analyses: a verified examination. Front. Mater. 10:1147310. doi: 10.3389/fmats.2023.1147310.
17. Naveen Kumar K, Bruce Ralphin Rose J, Swathi V, Narmatha R, Venkatesan. K, Research on Structural behavior of Composite Materials on different Cantilever Structures using FSI, International Journal of Engineering and Advanced Technology, ISSN: 2249 – 8958, Volume-8, Issue-6S3, pp: 1075-1086, September 2019, DOI: 10.35940/ijeat.F1178.0986S319.
18. Raj Kumar, G., Arul Prakash, R., Senthil Kumar, M., Indira Prasanth, S., Kesavan, K. and Balasubramanian, S. 2022. Optimizations on various lightweight composite materials under complex load using advanced computational simulation. In: Kumar, K. and Babu, B. ed. Hybrid Composites: Processing, Characterization, and Applications. Berlin, Boston: De Gruyter, pp. 81-102. https://doi.org/10.1515/9783110724684-005.
19. Chaudhary et al., (2024). AI-Driven Digital Mirror Technology for Securing IoT-Enabled Smart Infrastructures. In 2024 International Conference on Integrated Intelligence and Communication Systems (ICIICS) (pp. 01-08). IEEE. https://doi.org/10.1109/ICIICS63763.2024.10859436
20. Aswin Kumar. V, Sivaguru. M, Rohini Janaki. B, Sumanth Eswar. K. S, Kiran. P, Structural Optimization of Frame of the Multi-Rotor Unmanned Aerial Vehicle through Computational Structural Analysis, IOP Journal of Physics: Conference Series, 1849 012004, 2021, https://doi.org/10.1088/1742-6596/1849/1/012004
21. G Raj Kumar, et al., Comparative Investigations on the Main Elements of Carbon Fiber Based Composites Using Computational Structural Simulations, Journal of Physics: Conference Series, 1504 012003, pp. 1 - 11, 2020, https://iopscience.iop.org/article/10.1088/1742-6596/1504/1/012003.
22. Indira Prasanth S, Kesavan K, Kiran P, Sivaguru M, Sudharsan R, Raj Kumar G, Fiber Oriental Optimization on Glass Fiber Reinforced Polymer Composite in Multi Objective Perspective based on Computational Structural Analysis, IOP Journal of Physics: Conference Series, 1849 012005, 2021, https://doi.org/10.1088/1742-6596/1849/1/012005.
23. G Raj Kumar, M Senthil Kumar, S Sathish Kumar, 2nd International Conference on Condensed Matter and Applied Physics (ICC 2017), Experimental testing and numerical simulation on natural composite for aerospace applications, AIP Conf. Proc. 1953, 090045-1–090045-5; https://doi.org/10.1063/1.5032892, 978-0-7354-1648-2.
24. Vijayalakshmi, Selvaramanan, Sekar, Aravindha Vasan, Hassan, Ahmed Mohamed, et al., "Multi-perspective structural integrity-based computational investigations on airframe of Gyrodyne-configured multi-rotor UAV through coupled CFD and FEA approaches for various lightweight sandwich composites and alloys" REVIEWS ON ADVANCED MATERIALS SCIENCE, vol. 62, no. 1, 2023, pp. 20230147. https://doi.org/10.1515/rams-2023-0147
25. K. Mohamed Bak, Raj Kumar G, Ramasamy N, Experimental and Numerical Studies on The Mechanical Characterization of Epdm/S-Sbr Nano Clay Composites, IOP Conference Series: Materials Science and Engineering, 912, 052016, 2020, pp. 1-11, doi:10.1088/1757-899X/912/5/052016
26. P. Mirrudula, P. Kaviya Priya, M. Malavika, G. Raj Kumar, M. Senthil Kumar; Comparative structural analysis of the sandwich composite using advanced numerical simulation. AIP Conf. Proc. 2 November 2020; 2270 (1): 040005. https://doi.org/10.1063/5.0019370
27. S. Indira Prasanth, K. Kesavan, P. Kiran, M. Sivaguru, R. Sudharsan, Advanced structural analysis on e-glass fiber reinforced with polymer for enhancing the mechanical properties by optimizing the orientation of fiber. AIP Conf. Proc. 2 November 2020; 2270 (1): 040006. https://doi.org/10.1063/5.0019378
28. M. Sivaguru, R. Sudharsan, S. Indira Prasanth, K. Kesavan, P. Kiran, G. Raj Kumar, "Structural optimization of advanced carbon fiber reinforced polymers under flexural load through finite element analysis", AIP Conference Proceedings 2446, 030003 (2022) https://doi.org/10.1063/5.0108159
29. Laxana Sourirajan, Balamurali Baskaran, Rajkumar Rajapandi, et al., Design, Aerodynamic, and Structural Integrity Investigations of the Advanced Three Bladed Propeller for High Payload based Unmanned Aerial Vehicles, Results in Engineering, 2025, 104573, ISSN 2590-1230,
30. Jayakumar, S.S., Subramaniam, I.P., Stanislaus Arputharaj, B. et al. Design, control, aerodynamic performances, and structural integrity investigations of compact ducted drone with co-axial propeller for high altitude surveillance. Sci Rep 14, 6330 (2024). <https://doi.org/10.1038/s41598-024-54174-x>
31. Manzoore Elahi M. Soudagar, Ravindra Pratap Singh, Nagabhooshanam Nagarajan. et al. Featuring of in-situ carbon capturing and functional performance study of hydrogen from aquaculture wastewater algae biomass via supercritical steam gasification route, Chemical Engineering Science 313 (2025) 121704. <https://doi.org/10.1016/j.ces.2025.121704>
32. Jothi Arunachalam et al. Integration of nanographene and action of fiber sequences on functional behaviour of composite laminates" International Polymer Processing, 2025. <https://doi.org/10.1515/ipp-2024-0149>
33. Manzoore Elahi M. Soudagar, et al. Enrichment of Solar Heat Exchanger Thermal Performance by the Integration of Beeswax and Hybrid Nanofluid (ZnO/MgO). ASME. J. Thermal Sci. Eng. Appl. (2025) <https://doi.org/10.1115/1.4067929>
34. Padhy et al., (2024). Enhancing IoT-Enabled Healthcare with Genetic-based Encryption and Authentication for Secure and Efficient wireless Data Transmission. In 2024 International Conference on Inventive Computation Technologies (ICICT) (pp. 1873-1878). IEEE. https://doi.org/10.1109/ICICT60155.2024.10544722
35. Rafi et al., (2024). Improving Prostate Cancer Diagnosis with Weakly Supervised Learning and Radiology-Confirmed Negative MRI Data. In 2024 International Conference on Inventive Computation Technologies (ICICT) (pp. 1183-1188). IEEE. https://doi.org/10.1109/ICICT60155.2024.10544551
36. Kelagadi et al., (2024). An Analysis on the Integration of Machine Learning and Advanced Imaging Technologies for Predicting the Liver Cancer. In 2024 4th International Conference on Pervasive Computing and Social Networking (ICPCSN) (pp. 1082-1086). IEEE. <https://doi.org/10.1109/ICPCSN62568.2024.00180>
37. Singh et al., (2024). Enhancing Mobile Robot Speed Control: PID Controller Optimization with Bio-Inspired Algorithms. In 2024 International Conference on Expert Clouds and Applications (ICOECA) (pp. 365-370). IEEE. https://doi.org/10.1109/ICOECA62351.2024.00071
38. M. Aruna et al. Integration of Magnesium Fluoride and Nano Alumina–Silicon Carbide Actions on Properties of AZ91 Alloy Hybrid Nanocomposites. Inter Metalcast (2025). <https://doi.org/10.1007/s40962-025-01617-4>
39. N. Nagarajan et al. Hybrid Stir Cast Featured with Wettability Agent and Ultrasonic Action of Magnesium Alloy Composite Composed with Nanofiller: Study Characteristics. Inter Metalcast (2025). <https://doi.org/10.1007/s40962-025-01603-w>
40. A. Sharma et al. Structural Modification and Enhancement of Optoelectronic Behaviour of ZnO Nanofilms Featuring Cu and Ti Particles. J. Electron. Mater. (2025). <https://doi.org/10.1007/s11664-025-11951-2>
41. V. Mohanavel et al. Tribological characteristics and optimization of ZrB2 configured magnesium alloy composite via squeeze casting technique. J Mech Sci Technol. 39(5), 2025. <https://doi.org/10.1007/s12206-025-0425-9>
42. Manzoore Elahi M. Soudagar et al. Higher performance solar air dryer functioned with palmitic acid phase change material and hybrid nanofluid: Thermal performance evaluation, Applied Thermal Engineering (2025). Volume 272, 2025,126413, <https://doi.org/10.1016/j.applthermaleng.2025.126413>
43. P. K. Singh et al. Enhancement of silicon nitride layer performance by Gallium–Copper–Zinc tri-layer thin films structure via plasma featured chemical vapour deposition route. J Mater Sci: Mater Electron 36, 243 (2025). <https://doi.org/10.1007/s10854-025-14326-9>
44. Lakshmaiya, N. (2024). High ionic permeability of Piper ION membrane boosts efficiency in CO2 electrolysis cells. In International Conference on Medical Imaging, Electronic Imaging, Information Technologies, and Sensors (MIEITS 2024) (Vol. 13188, pp. 172-180). SPIE. <https://doi.org/10.1117/12.3030841>
45. Kaushal et al., (2024). Evaluation of Deep Learning Approaches for Air Quality Analysis using an Image Dataset. In 2024 Second International Conference on Intelligent Cyber Physical Systems and Internet of Things (ICoICI) (pp. 1378-1383). IEEE. https://doi.org/[10.1109/ICoICI62503.2024.10696429](https://doi.org/10.1109/ICoICI62503.2024.10696429)
46. Anitha, Cuddapah, Naveena Kumar RR, Swapnil Uttamrao Deokar, Harshal Shah, and Praful V. Nandankar. Optimal Scheduling of Microgrid with Electric Vehicle Integration in Smart Grid using Progressive Graph Convolutional Network. In 2025 5th International Conference on Trends in Material Science and Inventive Materials (ICTMIM), pp. 375-380. IEEE, 2025.
47. Saadh M J et al., (2024). Recent progress and the emerging role of lncRNAs in cancer drug resistance; focusing on signaling pathways. Pathology-Research and Practice, 253, 154999. <https://doi.org/10.1016/j.prp.2023.154999>
48. Socrates, S., Bharathi, G. B., & Aluvala, S. (2024). A Framework for Automated Diagnosis and Management of Autoimmune Disorders with Neural Networks. In 2024 International Conference on Advancements in Smart, Secure and Intelligent Computing (ASSIC) (pp. 1-6). IEEE. https://doi.org/[10.1109/ASSIC60049.2024.10507903](https://doi.org/10.1109/ASSIC60049.2024.10507903)
49. Kalam, S. A., Sheela, S., Paramasivam, P., & Shanmugam, K. (2024). Bio-synthesis of nano-zero-valent iron using barberry leaf extract: classification and utilization in the processing of methylene blue-polluted water. Discover Applied Sciences, 6(12), 1-15. https://doi.org/10.1007/s42452-024-06327-w
50. Chakrapani et al., (2024). Optimizing sample length for fault diagnosis of clutch systems using deep learning and vibration analysis. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 09544089241272791. https://doi.org/10.1177/095440892412727
51. Ali, H. M., Mothilal, T., & Reddy, V. (2024). Evaluation of Lightweight Cotton Textiles for Durable and Comfortable Automotive Interior Applications (No. 2024-01-5015). SAE Technical Paper. DOI: https://doi.org/10.4271/2024-01-5015
52. Selvan et al., (2024). Investigation of the Use of Renewable Energy in Microgrid Applications. In 2024 Ninth International Conference on Science Technology Engineering and Mathematics (ICONSTEM) (pp. 1-5). IEEE . https://doi.org/10.1109/ICONSTEM60960.2024.10568631
53. N. Nagabhooshanam et al. Influences of Potassium Fluoride and Ultrasonic Vibration on Functional Performance of AZ91 Alloy Hybrid Nanocomposite with Nano-SiC/TiO2. Inter Metalcast (2025). <https://doi.org/10.1007/s40962-025-01552-4>
54. M. Aruna et al. Vacuum Die Casting Process and Microstructure/Mechanical Characteristics Study of Magnesium Alloy Composite Hybridize with Zirconium Dioxide and Silicon Nitride. Inter Metalcast (2025). <https://doi.org/10.1007/s40962-025-01550-6>
55. Soudagar, M. Manzoore Elahi et al. Effect of electron transport layer thickness and characteristics behaviour of hybrid copper indium gallium selenide thin film solar cells, Journal of Power Sources (2025). Volume 639, 2025,236657, <https://doi.org/10.1016/j.jpowsour.2025.236657>
56. A. Sharma et al. Hybrid Reinforcement Actions on Microstructural, Physical and Mechanical Properties of Magnesium Alloy Composite by Two-Step Stir Casting Process. Inter Metalcast (2025). <https://doi.org/10.1007/s40962-024-01537-9>
57. Babu et al., (2024). Enhancing Security with Machine Learning-based Finger-Vein Biometric Authentication System. In 2024 5th International Conference on Mobile Computing and Sustainable Informatics (ICMCSI)(pp. 797-802). IEEE. https://doi.org/[10.1109/ICMCSI61536.2024.00123](https://doi.org/10.1109/ICMCSI61536.2024.00123)
58. P. K. Singh et al. Integration of phase change material for enriching the solar collector featured with dryer configuration enhanced via alumina/titanium dioxide nanoparticle: performance study. J Therm Anal Calorim (2025). <https://doi.org/10.1007/s10973-025-14302-9>
59. V.V. Upadhyay et al. Trapezoidal fin featured heat exchanger performance enriched by using alumina/GNP hybrid nanofluid: thermal characteristics study. J Therm Anal Calorim (2025). <https://doi.org/10.1007/s10973-025-13997-0>
60. N. Nagarajan. et al. Thermal performance assessment of dish collector-integrated cooking application using TiO2/SiO2 hybrid nano-enhanced coated receiver. J Braz. Soc. Mech. Sci. Eng. 47, 148 (2025). <https://doi.org/10.1007/s40430-025-05454-8>
61. P. P. Singh et al. Hybrid Thin Film Coating Performance and Functional Characteristics of Silicon Nitride (SiNx) Layer for Solar Cell Application. J. Electron. Mater. (2025). <https://doi.org/10.1007/s11664-025-11888-6>
62. R, Rajarajan et al. (2025). Improving Tribological Performance and Structural Analysis of Aluminium Hybrid Nanocomposites with Nano ZrO2/SiC Reinforcement via Stir Casting Assisted with Ultrasonic Vibration. International Journal of Cast Metals Research, February, 1–14. <https://doi.org/10.1080/13640461.2025.2467611>
63. P. Sharma et al. Effect of paraffin with salt hydrates PCM and hybrid Al2O3/Tio2 nanofluid on thermal and energy storage characteristics of solar thermal heat exchanger. J Therm Anal Calorim (2025). <https://doi.org/10.1007/s10973-025-14224-6>
64. I. Hossain et al. (2025). Enriching performance of Al-Mg composites by incorporating nano-alumina and SiC via semi-solid stir processing. International Journal of Cast Metals Research, 1–11. <https://doi.org/10.1080/13640461.2025.2476826>
65. Ahmad et al., (2024). IoT-Enabled Smart E-Healthcare System with Predictive Prescription Algorithm for Automatic Patient Monitoring and Treatment. In 2024 4th International Conference on Pervasive Computing and Social Networking (ICPCSN) (pp. 1076-1081). IEEE. https://doi.org/[10.1109/ICPCSN62568.2024.00179](https://doi.org/10.1109/ICPCSN62568.2024.00179)
66. Lakshmaiya, N. (2024). Detection and impact of stochastic anomalies in investigations of urban pollution. In International Conference on Medical Imaging, Electronic Imaging, Information Technologies, and Sensors (MIEITS 2024) (Vol. 13188, pp. 269-277). SPIE. <https://doi.org/10.1117/12.3030839>
67. Lakshmaiya, N. (2024). Influence of small non-capillary washing activity on flow boiling essential heat transfer. In International Conference on Medical Imaging, Electronic Imaging, Information Technologies, and Sensors (MIEITS 2024) (Vol. 13188, pp. 224-231). SPIE.  https://doi.org/10.1117/12.3030838
68. Agrawal et al., (2024). Deep Learning Methods for Detecting ImageBased Defects in Manufacturing Processes. In 2024 Ninth International Conference on Science Technology Engineering and Mathematics (ICONSTEM) (pp. 1-5). IEEE. https://doi.org/10.1109/ICONSTEM60960.2024.10568644
69. Vinodh, D et al., (2024). Experimental investigation on tensile strength of novel metal matrix composite of aluminium alloy 5083 with SiC and eggshell powder reinforcement. In International Conference on Medical Imaging, Electronic Imaging, Information Technologies, and Sensors (MIEITS 2024) (Vol. 13188, pp. 297-306). SPIE.  https://doi.org/10.1117/12.3030843
70. Deepthi et al., (2024). Deep Learning-Enabled Human Resource Analytics in Predicting Employee Performance. In 2024 Ninth International Conference on Science Technology Engineering and Mathematics (ICONSTEM) (pp. 1-5). EEE. https://doi.org/10.1109/ICONSTEM60960.2024.10568716