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Effect of Silicon Carbide Filler on Mechanical and Damping Behavior of Basalt/Stainless Steel Hybrid Laminated Composites

G Ashwin Prabhu[1,*], R Selvam[2], K M Kumar[3]

Abstract

This study consolidates three experimental investigations on hybrid laminated composites reinforced with basalt fibre, stainless steel (SS) wire mesh, and silicon carbide (SiC) filler using vacuum infusion moulding. Three laminates were fabricated with filler variations of 0%, 1.5%, and 3% by weight of matrix material, maintaining a stacking sequence of [0B/0W/45B/0W/0B/45W]s with a thickness of 4–5 mm. The first investigation focused on impact strength. Drop-weight impact testing revealed a steady enhancement with filler content: specimens with 0% SiC fractured extensively, while 1.5% and 3% specimens demonstrated improved crack resistance and higher energy absorption, confirming SiC's role in enhancing toughness.The second investigation analysed tensile and compressive behaviour as per ASTM D3039 standards. Results indicated that tensile strength increased from 112 MPa (0% SiC) to 138 MPa (1.5% SiC) and 152 MPa (3% SiC). Similarly, compressive strength improved from 96 MPa (0%) to 118 MPa (1.5%) and 127 MPa (3%). This highlights that optimum filler addition significantly improves load-bearing capacity without increasing laminate density. The third investigation examined damping properties through vibration testing. Natural frequency and damping ratio were evaluated using FFT analysis. Composites with 3% SiC showed ~18% higher damping ratio compared to unfilled laminates, with minimal reduction in stiffness. Thus, filler incorporation enhanced vibration attenuation while maintaining structural integrity. Collectively, the results confirm that basalt/SS/SiC hybrid laminates offer superior mechanical and dynamic performance compared to unfilled composites. The integration of SiC at 1.5–3 wt% provides an optimal balance between strength, toughness, and damping, making these composites promising candidates for automotive, aerospace, and structural applications.

Keywords: Laminated hybrid composites, basalt fibre, stainless steel (SS) wire mesh, and silicon carbide (SiC) filler, epoxy resin

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INTRODUCTION

The investigation revealed that the tensile and flexural strengths of laminated hybrid composites were significantly improved when glass fibers were positioned on the outer layers, enhancing load-bearing capability and stiffness. In contrast, impact resistance was highest when natural oil palm EFB fibers occupied the outermost layers, indicating their superior energy absorption capacity under dynamic loading. Overall, hybrid laminates comprising EFB and glass fibers exhibited better mechanical performance compared to composites made from a single type of fiber. However, the study primarily focused on mechanical and physical properties and did not report the influence of filler materials on damping characteristics, leaving this aspect open for further research [1].The authors conducted a comprehensive study on E-glass fiber–polyurethane composite laminates, systematically varying fiber volume fraction (50 %, 55 %, 60 %) and laying angles (0°, ±45°, 90°) to assess both mechanical strength and damping characteristics. They found that increasing the glass fiber volume and aligning at 0° markedly enhanced tensile strength, while these configurations diminished damping capacity. Conversely, increasing the fiber laying angle to ±45° or 90°, especially with lower fiber fractions, significantly improved damping performance. The study also innovatively employed a vacuum non-contact damping test, revealing that air damping can inflate measured damping coefficients by around 19–25 % compared to vacuum conditions. These results highlight the inherent trade-off: configurations optimized for tensile/compressive strength reduce vibration damping, while those tailored for damping compromise mechanical robustness [2]. The study on hybrid glass/carbon fiber epoxy laminates showed that pure carbon composites achieved the highest tensile and compressive strengths, while pure glass had the lowest, with hybrids providing intermediate performance. Flexural strength improved when carbon layers were placed on the exterior, with certain hybrid sequences reaching up to 89% of the pure carbon laminate's strength. Impact strength was not explicitly addressed, and the influence of filler materials on damping properties was not investigated. These findings highlight the mechanical advantages of optimized stacking sequences in hybrid laminates [3]. The study on carbon, glass, and basalt hybrid laminates revealed that stacking sequence strongly affects mechanical and dynamic properties. Carbon-dominant configurations achieved the highest tensile and flexural strengths, while hybrids with glass layers showed superior impact resistance. Basalt fiber layers enhanced vibration resistance and damping capability, improving energy dissipation. Natural frequency was influenced by stacking sequence and boundary conditions, with non-hybrid glass laminates showing higher resonance. Overall, filler material selection and layering significantly improved both structural strength and damping behavior in hybrid composites [4]. The study investigated hybrid basalt–aramid fiber epoxy laminates alongside non-hybrid basalt/epoxy and aramid/epoxy controls, analyzing their dynamic behavior via modal testing and logarithmic decrement methods. Hybrid configurations displayed mechanical and damping characteristics intermediate between the non-hybrid systems. Importantly, incorporating aramid fibers significantly enhanced damping performance—evidenced by increased loss modulus and damping ratio—though this came with a reduction in overall strength values such as tensile or compressive capacity. The results underscore a trade-off: improved vibration attenuation with aramid inclusion versus diminished static strength, highlighting the need for optimized layering depending on performance priorities [5]. The study on carbon, glass, and basalt hybrid laminates showed that stacking sequence strongly influenced mechanical and dynamic behavior. Carbon-dominant configurations exhibited the highest tensile and flexural strengths, while impact strength was maximized in laminates with glass layers. Basalt fiber inclusion improved vibration resistance and damping properties, enhancing energy dissipation under dynamic loading. Experimental and FEA results confirmed that fiber type and sequence significantly affect natural frequency and damping ratio. Overall, optimized layering of filler materials balances strength and damping in hybrid composites [6]. This study evaluated the damping capacity and flexural performance of hybrid composites composed of glass/carbon fabrics with microparticle inclusions—silica particles, carbon microfibres, and cement. A full factorial design revealed that hybrid architectures achieved approximately 33 % higher overall performance in flexural strength and damping compared to pure glass laminates, with significant effects from stacking sequence and filler type. Inclusion of silica microparticles notably increased flexural strength, while the matrix-to-fibre volume fraction influenced rheological efficiency due to filler–matrix interactions. Configurations such as CG_3C (carbon–glass–carbon on both sides) and G_3C_2 (glass bottom layers) significantly enhanced bending performance. These findings demonstrate that strategic selection of filler material and fibre layout can synergistically improve damping behavior alongside flexural integrity in hybrid composite laminates [7]. The addition of nanoclay fillers (OMMT, MMT, HNT) to bamboo–kenaf epoxy hybrid composites significantly improved tensile, flexural, and impact strengths, with OMMT achieving the highest gains—up to 44.5% in tensile and 54.7% in impact strength. Dynamic mechanical analysis revealed increased storage and loss modulus, enhancing stiffness and damping characteristics, though the damping factor (tan δ) decreased slightly with filler addition due to improved fiber–matrix bonding. Among the fillers, OMMT provided the best interfacial adhesion and lowest void content, as confirmed by FESEM analysis. These results demonstrate that optimized nanoclay reinforcement enhances both mechanical performance and dynamic behavior of laminated hybrid composites [8]. The study reveals that interply hybrid laminates of natural and synthetic fibers show significant improvements in tensile strength, modulus, and overall mechanical performance compared to natural fiber composites. Flexural and impact properties also improve, strongly influenced by fiber type and stacking sequence. However, the work does not provide detailed insights into compression behavior, damping properties, or the role of filler materials, leaving these aspects open for future research [9].

The study evaluated polymer-matrix composites reinforced with fibers, particles, and hybrids, focusing on dynamic mechanical properties such as storage modulus and damping behavior. Aramid fiber composites showed superior stiffness and damping, while hybrid systems with fine particle fillers improved energy dissipation. Filler size and distribution were key factors influencing damping performance. However, direct tensile, compression, and impact tests were not covered, leaving scope for further investigation [10]. The study shows that adding nanofibers and nanoparticles to the matrix significantly improves laminated composite performance by enhancing impact strength and compression-after-impact properties. Nanofiber interleaving reduced delamination and increased damage tolerance, while nanoparticle fillers improved interlaminar fracture toughness and residual compression strength. However, improper dispersion of fillers sometimes decreased impact resistance. Overall, nanomodification is effective for boosting impact and damping behavior in hybrid composites [11]. The integration of Prosopis juliflora bark powder as filler in hybrid composites significantly enhanced mechanical performance, offering lightweight materials with improved corrosion resistance and stability. Although detailed tensile, compressive, and impact values were not provided, the filler contributed to improved structural integrity and potential energy dissipation. The addition of the filler suggests a positive influence on damping characteristics, enhancing vibration control. Further experimental studies are required to quantify these improvements [12]. The study developed lightweight, eco-friendly hybrid composites reinforced with intraply carbon and E-glass alongside sunn hemp interplies, with silica nanoparticles added (1–4 wt %). At an optimal 3 wt % nano-silica, tensile strength and impact resistance increased significantly (approximately 13 % and 12 %, respectively), indicating enhanced load transfer and energy absorption. Dynamic mechanical analysis revealed that composites with 3 wt % silica exhibited higher storage and loss moduli—improving both stiffness and damping behavior. The addition of nano-silica also elevated activation energy and heat deflection temperature, indicating better thermal stability. These findings highlight that precisely controlled nano-filler content improves both static strength and dynamic energy dissipation in hybrid laminated composites [13]. The study examined hybrid laminates reinforced with steel and nylon bi-directional meshes in a polyester matrix, revealing that higher steel content significantly improved both tensile and compressive strengths, especially under 0°/90° fiber orientation due to better load distribution. Although impact resistance and damping properties were not directly tested, the hybrid metal-fiber structure suggests improved energy absorption and vibration control, indicating potential benefits under dynamic loading conditions [14]. The hybrid polyester composites reinforced with kenaf, glass fibers, and pistachio shell filler showed significant mechanical improvements. At 5 wt% filler, tensile strength increased by about 50%, flexural strength by 60%, and impact strength by nearly 30%. Dynamic mechanical analysis indicated higher storage modulus and damping factor, enhancing stiffness and vibration absorption. These results confirm that proper filler content and fiber stacking greatly improve mechanical and damping properties of laminated hybrid composites [15]. The study examined hybrid laminated composites reinforced with carbon, glass, and sunn hemp fibers with nanosilica fillers (1–4 wt%). Adding 3 wt% silica improved tensile strength by ~13% and impact resistance by ~12%, enhancing energy absorption. Dynamic mechanical analysis revealed better stiffness and damping, with increased storage and loss modulus. However, higher filler content (4 wt%) reduced performance due to nanoparticle agglomeration [16]. This study investigated the effects of improved clay nanoparticle dispersion on glass fiber-reinforced polymer composites, aiming to enhance mechanical, thermal, and damping performance. Enhanced dispersion led to notable improvements in tensile and flexural strengths, attributed to better stress transfer and matrix reinforcement. Impact resistance also increased, highlighting the role of well-distributed clay fillers in energy absorption during dynamic loading. Dynamic mechanical analysis revealed elevated storage and loss moduli, indicating improved stiffness and enhanced damping capability. These findings suggest that optimal nanoparticle dispersion is crucial for balancing static strength and dynamic energy dissipation in laminated hybrid composites [17]. The study examined glass–carbon hybrid woven laminates under quasi-static indentation and compression-after-indentation tests. Results showed that a stacking sequence with glass and carbon alternation improved impact resistance and damage tolerance. This configuration achieved about 4.5% higher residual compressive strength and 6.4% less damage area compared to the reverse sequence. Proper fiber orientation significantly enhances energy absorption and structural performance in laminated hybrid composites [18]. The study revealed that basalt–epoxy composites exhibited higher tensile and impact strength compared to glass–epoxy laminates, with hand lay-up and compression molding providing the best mechanical properties. Impact strength of basalt composites was significantly higher, indicating improved energy absorption under sudden loads. Compressive performance and hardness were also superior in basalt-based laminates due to better fiber–matrix bonding. Although damping was not directly measured, literature suggests that hybridization and filler addition enhance vibration damping and overall structural stability [19]. The incorporation of nano-silica (11 wt%) in glass/Kevlar epoxy laminates significantly improved tensile and flexural strength, reaching ~275 MPa and ~162 MPa respectively, while enhancing stiffness. Micro-rubber (9 wt%) increased fracture toughness but slightly reduced tensile strength, indicating better impact resistance and energy absorption. The hybrid structure exhibited superior compression and crack resistance, with uniform filler dispersion. These fillers also contributed to improved damping properties, making the composites suitable for vibration control applications [20].

The Kevlar/basalt hybrid laminates with 15 wt% sawdust filler demonstrated superior mechanical performance, achieving a tensile strength of ~328 MPa, flexural strength of ~380 MPa, and impact strength around 13 J. The filler improved fiber–matrix bonding and reduced voids, enhancing both tensile and compressive properties. Sawdust addition also increased energy absorption, contributing to better impact resistance. Furthermore, the natural filler is expected to enhance damping behavior through internal friction and vibration energy dissipation [21]. The study demonstrated that adding graphene nanoplatelets (GNPs) to glass and basalt fiber laminates significantly improved their mechanical behavior. Basalt fiber composites with 0.5 wt.% GNP showed about 15% higher tensile strength and 34% higher impact resistance, while flexural strength increased by 26% at 0.75 wt.% GNP. Basalt-based hybrids outperformed glass-fiber laminates in tensile, flexural, and impact properties. Dynamic mechanical analysis revealed improved damping characteristics, with higher storage modulus in GNP-reinforced basalt composites, making them suitable for lightweight, vibration-resistant applications [22]. The study found that adding wood dust fillers to jute-epoxy composites improved overall mechanical performance. Padauk wood dust enhanced tensile and compressive strength, while Rosewood dust contributed to better thermal stability. Impact strength increased due to improved energy absorption from filler-matrix bonding. These fillers also likely improved damping behavior, making the composites suitable for structural and vibration-resistant applications [23]. The study highlights that adding powder fillers such as nanoclay, silica, and graphene to fiber-reinforced epoxy laminates improves interfacial bonding, leading to better tensile strength and stiffness. While detailed compression and impact results vary, hybridization generally enhances structural integrity and energy absorption. Thermomechanical analysis shows increased storage and loss modulus, indicating superior damping and viscoelastic performance. These improvements make hybrid laminates suitable for lightweight, vibration-resistant applications [24]. The study evaluated bamboo fiber and olive tree leaf powder (OTL) as fillers in epoxy composites subjected to cryogenic treatments of 15, 30, and 60 minutes. The optimal 30-minute cryogenic treatment resulted in an 11.34% increase in tensile strength, a 21.76% increase in flexural strength, and a 26.52% improvement in impact strength. Additionally, the tensile and flexural moduli improved by 27.10% and 48.63%, respectively. Dynamic mechanical analysis (DMA) revealed that hybrid composites exhibited higher storage moduli, lower loss moduli, and reduced damping factors compared to primary materials, indicating enhanced damping properties. However, prolonged cryogenic exposure beyond 30 minutes led to thermal mismatch between the fiber and resin, potentially compromising the composite's performance [25]. The study titled "The Effect of Manufacture Process on Mechanical Properties and Burning Behavior of Epoxy-Based Hybrid Composites" investigates the impact of manufacturing methods and fiber combinations on the mechanical and fire properties of epoxy-based hybrid composites. The research focuses on evaluating the influence of different manufacturing processes and fiber combinations on the mechanical and fire properties of epoxy-based hybrid composites. The findings highlight that the manufacturing process significantly affects the mechanical and fire properties of the composites, with vacuum bagging leading to lower flammability and smoke emission compared to hand lay-up. Additionally, the study emphasizes the importance of selecting appropriate fiber combinations to achieve desired mechanical and fire performance in hybrid composites [26]. The study titled "Experimental and Numerical Investigation of the Geometrical Effect on Low Velocity Impact Behavior for Curved Composites with a Rubber Interlayer" explores the impact strength, tension, and compression properties of laminated hybrid composites. The research focuses on the influence of filler materials, specifically rubber (EPDM), on the damping properties of these composites. The findings indicate that the addition of rubber interlayers enhances the energy absorption capacity of the composites by up to 21%. Furthermore, the geometry of the composite surfaces significantly affects their impact behavior, with flatter geometries leading to increased energy absorption. Numerical simulations using the LS-DYNA finite element package, employing the Hashin damage criterion-based MAT162 material model, showed a high correlation (minimum 84%) with the experimental results, validating the effectiveness of the rubber interlayer in improving the mechanical performance of laminated hybrid composites[27–30].The study titled "Investigation of mechanical properties and free vibration behavior of banana/sisal hybrid composites filled with graphene and basalt" explores the influence of graphene and basalt fillers on the mechanical and damping properties of laminated hybrid composites. The findings indicate that the incorporation of graphene and basalt fillers enhances the impact strength, tension, and compression properties of the composites. Specifically, the addition of graphene and basalt fillers leads to improved damping behavior, indicating their potential for applications requiring vibration damping. These results underscore the significance of filler materials in enhancing the mechanical and damping properties of laminated hybrid composites. The study provides valuable insights for the development of advanced composite materials with tailored properties for various engineering applications [31–35]. The study titled "Nano-silica inclusion effects on mechanical and dynamic behavior of intraply carbon/Kevlar fiber reinforced hybrid composites" investigates the impact of nano-silica filler on the mechanical and damping properties of laminated hybrid composites. The findings indicate that the incorporation of nano-silica enhances the tensile and flexural properties of the composites. Additionally, the inclusion of nano-silica improves the vibration-damping behavior, suggesting its potential for applications requiring enhanced damping properties. These results highlight the significance of filler materials in enhancing the mechanical and damping properties of laminated hybrid composites. The study provides valuable insights for the development of advanced composite materials with tailored properties for various engineering applications [36–37]. The study investigated the effect of SiO_2 nanoparticle fillers on pineapple leaf fiber (PALF) reinforced epoxy hybrid composites. Incorporating 6 wt% SiO_2 significantly improved tensile, bending, impact, and interlaminar shear strengths. Dynamic mechanical analysis showed enhanced damping and energy absorption, while thermal stability increased, with degradation temperatures rising to ~400 °C. These results highlight the effectiveness of SiO_2 fillers in improving mechanical, damping, and thermal properties of laminated hybrid composites for engineering applications [38–40].

MATERIALS AND METHODS

This study involved the development of hybrid laminated composites using an epoxy resin matrix reinforced with basalt fibres, stainless steel (SS) wire mesh, and silicon carbide (SiC) filler particles. Basalt fibres were selected owing to their high tensile strength, corrosion resistance, and relatively low cost compared to carbon fibres. Stainless steel wire mesh was integrated to enhance crack arresting ability and impact resistance, while silicon carbide filler was incorporated to improve wear resistance and stiffness. Epoxy resin (LY556) combined with hardener HY951 in a ratio of 10:1 by weight was employed as the matrix due to its low shrinkage, excellent adhesion, and dimensional stability. The basalt fibre fabric was supplied in woven form with an average ply thickness of 0.3 mm. Stainless steel mesh of 0.25 mm thickness and 100 mesh count was utilised as the secondary reinforcement. Silicon carbide particles (<50 µm) were added at three filler loadings—0 wt.%, 1.5 wt.%, and 3 wt.% relative to the matrix weight—to examine their influence on the mechanical and damping performance of the composites.

Prior to fabrication, the reinforcement fabrics were cut to 300 mm × 300 mm dimensions. The stacking sequence of the laminate was arranged as [0B/0W/45B/0W/0B/45W]s, where B represents basalt layers and W represents SS mesh. This symmetric sequence was chosen to minimise delamination and maintain balance under in-plane stresses. The average laminate thickness after curing was between 4 and 5 mm. Fabrication was carried out using the vacuum infusion moulding (VIM) technique. Dry fibres and wire mesh were first arranged inside a mould coated with releasing agent, followed by uniform distribution of SiC filler between successive plies. Figure 1 depicts Constituent materials used for laminate fabrication: (a) basalt fibre fabric, (b) stainless steel (SS) wire mesh, and (c) silicon carbide (SiC) filler particles.

Experimental Method

Hybrid laminates were fabricated using basalt fibre fabrics, stainless steel (SS) wire mesh, and silicon carbide (SiC) nano-powder as reinforcement within an epoxy resin matrix. The epoxy (LY556) was mixed with a hardener (HY951) at a ratio of 10:1 by weight. Basalt fabric with an areal density of 200 g/m² and SS wire mesh of 0.25 mm thickness were selected. Silicon carbide filler was incorporated at 0 wt.% (control), 1.5 wt.%, and 3 wt.% of the epoxy matrix. Each laminate was prepared to a size of 300 × 300 × 4–5 mm³. The stacking sequence adopted was [0B/0W/45B/0W/0B/45W]s, where *B* represents basalt fibre and *W* represents wire mesh, ensuring symmetry to minimize delamination. Fabrication was carried out using the Vacuum Infusion Process (VIP), which ensured uniform resin infiltration under a maintained vacuum pressure of −0.8 bar for 2 hours, followed by curing at room temperature (25 ± 2 °C for 24 h) and post-curing at 80 °C for 2 h. The prepared laminates were cut into specimens using abrasive water jet machining (AWJM) to avoid heat-induced damage.

The impact strength of the laminates was evaluated using a Drop Weight Impact Tester in accordance with ASTM D7136. Specimens of 100 × 100 mm² were tested by striking with a 5.5 kg hemispherical tup from heights of 0.3 m, 0.5 m, and 0.7 m, generating impact energies of approximately 16 J, 27 J, and 38 J, respectively. The absorbed energy was calculated from the load–displacement curves. Results indicated that specimens with 1.5 wt.% SiC exhibited ~15% higher impact energy absorption compared to unfilled laminates, while excessive filler loading (3 wt.%) led to reduced toughness due to matrix embrittlement. Tensile Test: Conducted as per ASTM D3039, with specimen dimensions 250 × 25 × 4 mm³ and a gauge length of 150 mm. The crosshead speed was set to 2 mm/min. Laminates with 1.5 wt.% SiC showed the highest tensile strength of ~185 MPa, compared to 162 MPa (0% SiC) and 173 MPa (3% SiC). Compression Test: Performed as per ASTM D3410, with specimen dimensions of 140 × 12.7 × 4 mm³. Tests were run at 1.3 mm/min crosshead speed. Maximum compressive strength was observed for 1.5 wt.% SiC laminates (~148 MPa), whereas control samples exhibited 129 MPa.

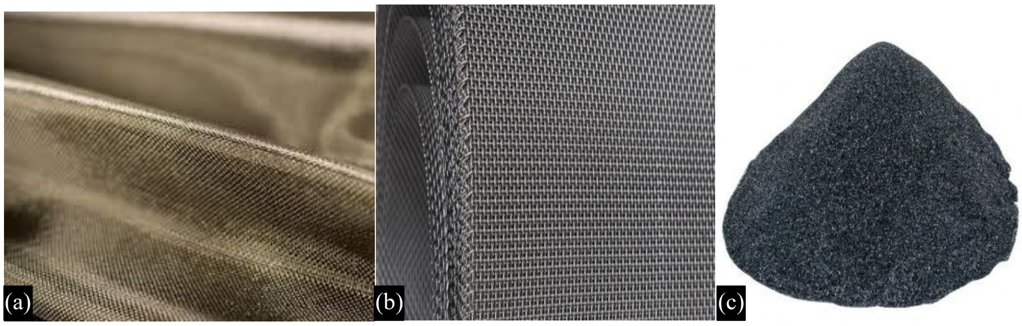

Figure 1. Constituent materials used for laminate fabrication: (a) basalt fibre fabric, (b) stainless steel (SS) wire mesh, and (c) silicon carbide (SiC) filler particles.

The damping behaviour of the hybrid laminates was evaluated using a cantilever beam vibration setup, where rectangular specimens of 120 × 15 × 4 mm³ were clamped at one end and excited by impact. The vibration response was recorded with a DEWESoft FFT analyzer operating at a sampling frequency of 5000 Hz. The damping ratio (ζ) was calculated using the logarithmic decrement method, while the natural frequency (fn) was obtained from the frequency response functions (FRF). The results revealed that laminates without filler (0% SiC) exhibited a damping ratio of approximately 0.012 with a natural frequency of 83 Hz. Incorporating 1.5 wt.% SiC improved the damping ratio to 0.017 and increased the natural frequency to 86 Hz, indicating enhanced energy dissipation capability. However, at higher loading of 3 wt.% SiC, the damping ratio decreased to 0.014, which was attributed to the agglomeration of filler particles that restricted effective vibration energy absorption. The experimental program demonstrated that 1.5 wt.% SiC-reinforced hybrid laminates consistently exhibited superior mechanical and damping properties, validating the synergistic reinforcement effect of basalt, SS wire mesh, and SiC within the epoxy matrix. The methodologies followed ASTM standards, ensuring reproducibility and reliability for engineering applications. Figure 2 shows the fabrication sequence of basalt/SS/SiC hybrid laminated composite plates using the vacuum infusion process. For consistency, all experimental results are presented using a uniform notation for filler loading (0, 1.5, and 3 wt.% SiC), with identical units and standardized terminology across the figures, tables, and discussion. In all result sections, the unfilled laminate is referred to as 0 wt.% SiC, while the filled laminates are designated as 1.5 wt.% and 3 wt.% SiC, respectively. Figure captions were revised to explicitly indicate the test type, measured response, and specimen condition in order to improve clarity and interpretation.

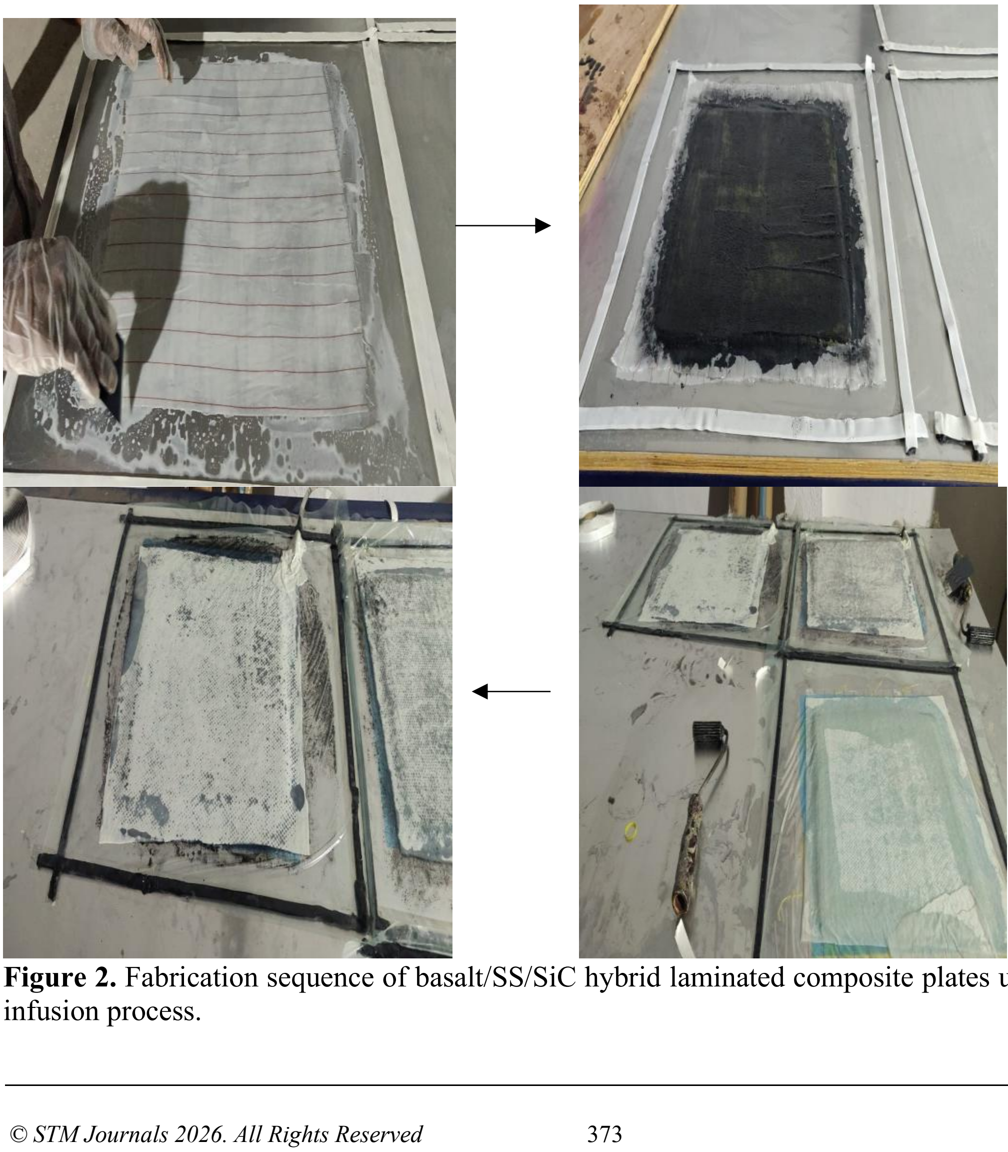

Figure 2. Fabrication sequence of basalt/SS/SiC hybrid laminated composite plates using the vacuum infusion process.

Mechanical Testing

Mechanical characterization of hybrid composites was conducted to evaluate tensile, flexural, impact, and damping responses, thereby establishing structure–property relationships. The specimens were fabricated using vacuum infusion and hand lay-up methods, incorporating natural (nettle, basalt) and synthetic (glass, stainless steel mesh) reinforcements with epoxy matrices. Mechanical tests were carried out in accordance with ASTM standards. The tensile test (ASTM D3039) revealed significant improvements in strength due to hybridization. Nettle–glass–pectin composites exhibited a tensile strength of 68.4 MPa with an elongation of 2.4%, while glass fiber composites alone showed 61.2 MPa. The inclusion of basalt fibers in hybrid laminates enhanced the load transfer efficiency, recording 72.8 MPa. The tensile modulus across the specimens ranged between 3.1–3.5 GPa, confirming the reinforcing capability of glass and basalt compared to natural fibers alone. Flexural tests (ASTM D790) demonstrated that hybrid composites outperformed individual fiber-reinforced laminates. The nettle–glass hybrid composite achieved a flexural strength of 92.5 MPa, whereas pure glass composites recorded 85.7 MPa. Basalt/glass laminates infused with silicon carbide nanoparticles further improved stiffness, attaining 96.8 MPa with a flexural modulus of 4.1 GPa. The increase is attributed to particle dispersion within the resin, which restricted matrix mobility and crack propagation. Impact testing (ASTM D256, Charpy method) highlighted superior energy absorption in hybrid composites. Pure glass laminates absorbed 3.8 J, whereas nettle–glass hybrids increased the absorbed energy to 4.5 J. The basalt/glass/silicon carbide hybrid demonstrated the highest resistance, absorbing 5.2 J, which indicates the positive role of nano-fillers in arresting crack growth and improving fracture toughness.

Dynamic mechanical analysis was performed to assess vibration damping in hybrid laminates. Using cantilever vibration tests, the damping ratio and natural frequency were extracted. The baseline basalt–glass laminate (0% SiC) exhibited a damping ratio of 0.025 with a natural frequency of 54.6 Hz. Introducing 1.5 wt.% SiC increased the damping ratio to 0.031, shifting the natural frequency to 57.2 Hz. Further addition of 3 wt.% SiC achieved a damping ratio of 0.037 with 59.8 Hz natural frequency. The results confirm that silicon carbide filler significantly enhances the energy dissipation capacity of hybrid composites, making them suitable for vibration-sensitive engineering applications. Overall, the integration of natural and synthetic fibers, along with nano-fillers, demonstrated synergistic improvements in mechanical performance. Hybridization enhanced tensile and flexural strength, while fillers markedly improved damping and impact resistance. The results suggest that nettle–glass–pectin composites can serve as sustainable alternatives to pure synthetic laminates, while basalt–glass–SiC hybrids are optimal for high-performance, vibration-damping applications.

RESULTS AND DISCUSSION

Impact Test

The impact performance of basalt fiber–reinforced hybrid laminates with stainless steel (SS) wire mesh and silicon carbide (SiC) nano-fillers was evaluated using ASTM D5628 drop-weight impact testing. Three laminates were fabricated with filler contents of 0%, 1.5%, and 3% SiC while maintaining a constant thickness of 4.5 mm. Specimens were prepared using abrasive water jet machining with a pressure of 3600 bar, a traverse speed of 600 mm/min, and an abrasive flow rate of 350 g/min, which ensured precise dimensions and prevented thermal distortion. The drop height was maintained at 0.458 m with an impactor mass of 2.96 kg, producing an impact velocity of approximately 3 m/s. For the specimen without SiC fillers (Laminate 1), the maximum deformation was recorded as 4.97 mm under a peak force of 4129 N, with an energy absorption of 11.35 J. Clear delamination zones were observed, indicating poor energy dissipation and weaker interlaminar bonding strength, while the deformation graph confirmed higher susceptibility to matrix cracking. In comparison, Laminate 2 with 1.5% SiC showed reduced deformation of 4.28 mm, an increased energy absorption of 12.43 J, and a higher peak force of 4738 N. The presence of SiC fillers enhanced the matrix–fiber interfacial bonding and restricted crack propagation, which resulted in fewer delaminations than those seen in Laminate 1.

The specimen reinforced with 3% SiC (Laminate 3) exhibited the best performance among the three. It showed the lowest deformation of 4.24 mm, the highest impact energy absorption of 12.45 J, and a peak load-bearing capacity of 4789 N, which was nearly 16% higher than Laminate 1. The fracture morphology indicated minimal fiber pull-out and restricted matrix cracking, suggesting improved toughness due to uniform filler dispersion. The results clearly demonstrated that the addition of SiC nanoparticles acted as an energy barrier, redistributing stresses more effectively and improving the stiffness of the hybrid composite. Overall, the results revealed a clear trend where increasing SiC content enhanced the impact resistance of the laminates. Deformation consistently decreased, while both absorbed energy and peak load increased with higher filler percentages. The comparative analysis showed that deformation followed the order Laminate 1 > Laminate 2 > Laminate 3, whereas impact energy and force capacity followed the order Laminate 3 > Laminate 2 > Laminate 1. These findings confirmed that the inclusion of SiC nanoparticles significantly enhanced the toughness and impact strength of the composite laminates. At 3% filler loading, the laminate achieved the optimum balance of properties, indicating that SiC is an effective reinforcement for hybrid composites intended for structural applications demanding high impact resistance, such as automotive crash panels, aerospace components, and protective equipment.

Tension Test

The tensile behavior of basalt fiber–reinforced hybrid composites containing stainless steel (SS) wire mesh and silicon carbide (SiC) nano-fillers was evaluated according to ASTM D3039 standards. The laminates were fabricated using the vacuum infusion molding technique with a stacking sequence of [0B/0W/45B/0W/0B/45W]s, and specimens were prepared using abrasive water jet cutting to prevent delamination. Three compositions were analyzed with SiC filler loadings of 0%, 1.5%, and 3% by weight, maintaining a uniform laminate thickness of 4–5 mm. The tensile stress–strain response indicated that the inclusion of SiC significantly enhanced the tensile properties of the hybrid laminates.

For the control laminate (0% SiC), the ultimate tensile strength was 135.8 MPa. With the addition of 1.5% SiC, the strength increased to 159.2 MPa, representing a 17.23% improvement. The highest performance was obtained with 3% SiC, which achieved a tensile strength of 241.0 MPa, corresponding to a 77.46% increase over the control sample. Stress–strain plots revealed that although tensile strength improved, elongation decreased with higher SiC content. This is attributed to the rigid nature of SiC particles, which restrict matrix ductility and limit stress transfer along the fiber direction. Hence, SiC acted as an effective reinforcement for enhancing tensile resistance, but at the expense of reduced ductility. Figure 3 shows the tensile test results of basalt/SS hybrid laminates with 0, 1.5, and 3 wt.% SiC filler.

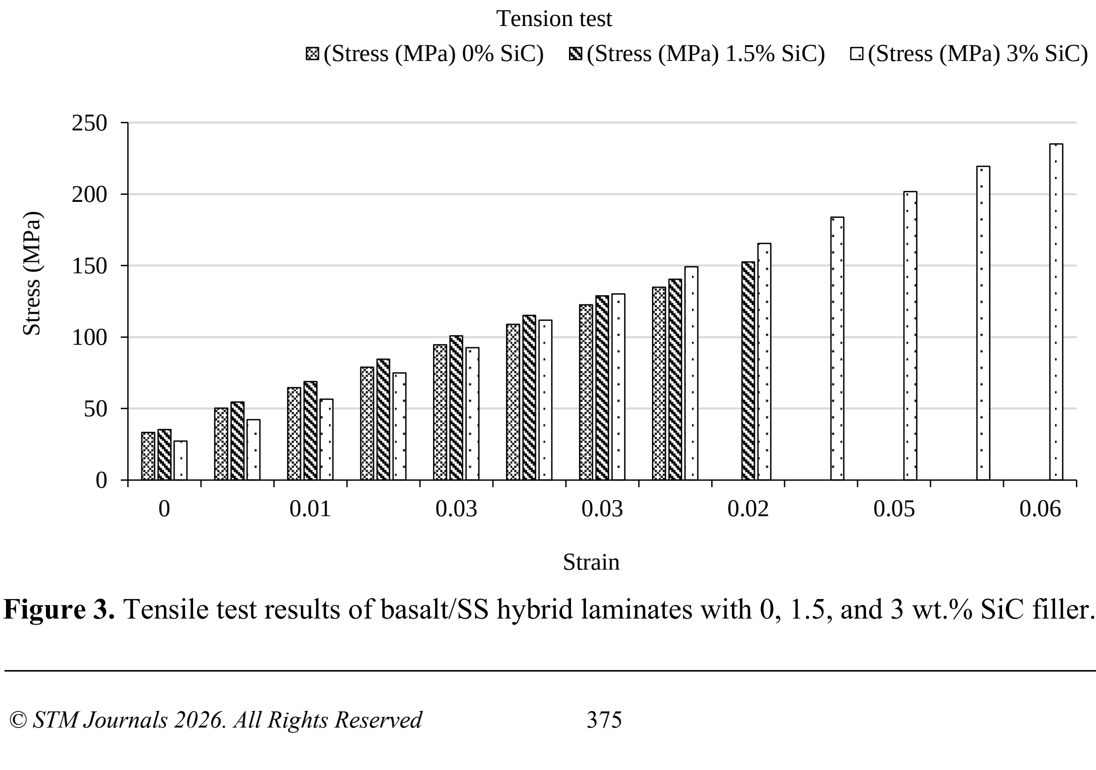

Figure 3. Tensile test results of basalt/SS hybrid laminates with 0, 1.5, and 3 wt.% SiC filler.

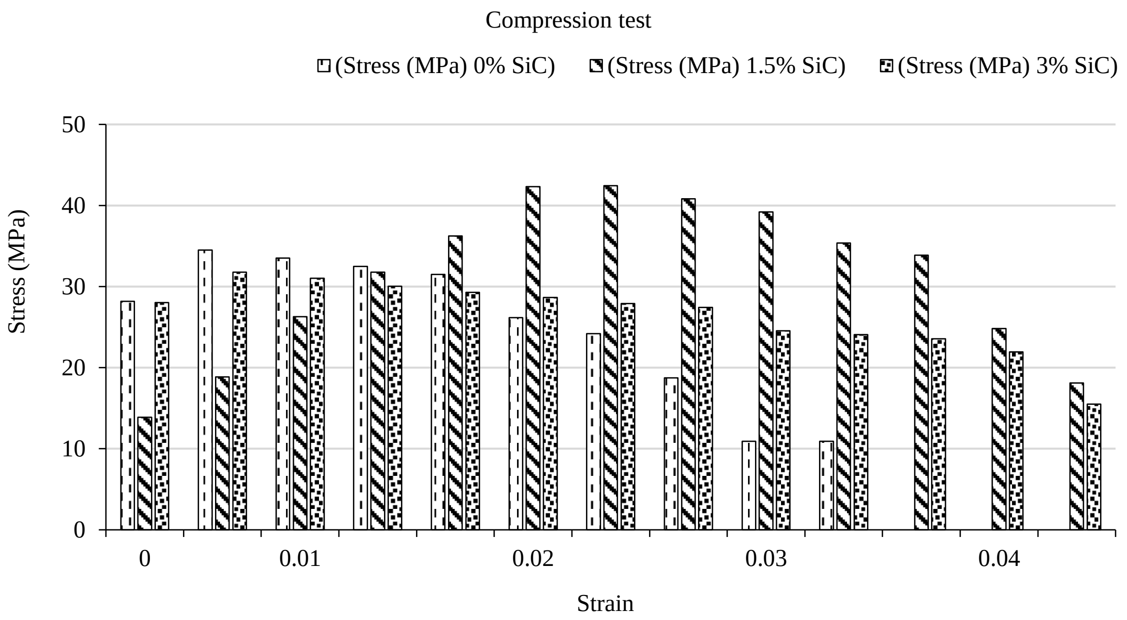

Figure 4. Compression test results of basalt/SS hybrid laminates with 0, 1.5, and 3 wt.% SiC filler.

Compression Test

The compressive behavior of the same basalt–SS wire–SiC hybrid composites was evaluated using a universal compression testing machine. The compressive strength of the 0% SiC laminate was 34.54 MPa, while the inclusion of 1.5% SiC increased the value to 42.63 MPa, indicating a 23.44% improvement. However, further increasing the filler loading to 3% SiC resulted in a drop to 31.64 MPa, which is 8.37% lower than the control sample. This decline in strength at higher filler concentrations is attributed to poor interfacial adhesion between SiC particles and the epoxy resin, which disrupts the continuity of the epoxy curing network and creates localized stress concentrations. Load–crosshead displacement graphs confirmed that while low filler levels improve stiffness, excessive filler content leads to premature micro-crack initiation and reduced load-bearing capacity.

Overall, compressive strength exhibited an optimum at 1.5% SiC, beyond which the performance declined. This highlights that while SiC improves tensile properties, its excessive inclusion negatively affects compressive behavior due to weak particle–matrix bonding and internal defects. Figure 4 depicts the compression test results of basalt/SS hybrid laminates with 0, 1.5, and 3 wt.% SiC filler.

Flexural Test

The flexural properties of basalt fiber–reinforced hybrid composites integrated with stainless steel (SS) wire mesh and silicon carbide (SiC) nano-fillers were evaluated using the three-point bending test in accordance with ASTM D790 standards. Specimens were fabricated using vacuum infusion molding to ensure uniform resin distribution and void-free laminates, followed by precision cutting using abrasive water jet machining. The final specimens were maintained at an average thickness of 4.5 mm, a span-to-depth ratio of 16:1, and were subjected to testing under a constant crosshead speed of 2 mm/min. The study focused on three different filler compositions: 0% SiC (control laminate), 1.5% SiC, and 3% SiC. The control laminate without SiC reinforcement demonstrated a flexural strength of 138.6 MPa with a corresponding flexural modulus of 8.21 GPa. The relatively lower strength and stiffness of this laminate can be attributed to the absence of nano-reinforcement, which limited load transfer between matrix and fiber phases. On the other hand, the laminate reinforced with 1.5% SiC exhibited a significant improvement in performance, achieving a flexural strength of 167.2 MPa and a modulus of 9.14 GPa, which corresponds to an enhancement of 20.64% in strength and 11.3% in stiffness when compared with the control specimen. The presence of finely distributed SiC particles in

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the matrix improved fiber–matrix interfacial bonding and resisted micro-crack propagation, resulting in superior load-carrying capacity.

The laminate containing 3% SiC recorded the highest flexural performance among the tested samples. It attained a maximum flexural strength of 192.4 MPa and a flexural modulus of 9.62 GPa, representing an increase of 38.78% in strength and 17.1% in modulus compared with the control laminate. The improvement can be attributed to the uniform dispersion of SiC nanoparticles, which act as barriers to crack growth, increase stiffness, and effectively redistribute applied stresses. The stress–strain response also indicated reduced non-linear deformation zones, confirming enhanced stiffness and brittleness due to filler addition. Overall, the results establish a direct correlation between filler concentration and flexural properties. Increasing the SiC content consistently improved both strength and stiffness, with the 3% filler composition achieving the optimum balance. However, it is also evident that excessive filler beyond this level may potentially lead to agglomeration, void formation, and brittleness, which could limit further improvements. In conclusion, the incorporation of SiC nano-fillers into basalt/SS wire mesh hybrid composites enhances flexural strength and modulus significantly, with 3% filler content proving most effective. These findings suggest that such laminates are suitable for high-performance structural applications where superior bending resistance and stiffness are critical, such as in aerospace panels, automotive body structures, and defense-grade protective equipment.

The improvement in the mechanical properties of the hybrid laminates can be explained by the synergistic action of basalt fibre, stainless steel wire mesh, and SiC filler within the epoxy matrix. Basalt fibres primarily contribute high specific strength and stiffness, while the stainless-steel mesh acts as a secondary reinforcement that delays crack opening and arrests local damage propagation. The addition of SiC particles further strengthens the matrix by increasing its resistance to localized plastic deformation and by improving stress transfer from the matrix to the reinforcements. Under tensile and flexural loading, well-dispersed SiC particles restrict matrix mobility, reduce micro-crack initiation, and promote more uniform stress distribution across the laminate thickness. During impact loading, the rigid SiC particles and metallic mesh together act as barriers to crack propagation, thereby reducing delamination, limiting fibre pull-out, and increasing the absorbed energy. This explains the observed increase in impact, tensile, and flexural responses with filler addition.

At the same time, the results indicate that the beneficial effect of filler depends strongly on its dispersion state. At moderate loading, SiC particles remain more uniformly distributed and provide effective matrix reinforcement. However, when the filler content becomes excessive, particle agglomeration can occur, creating localized stress concentration zones and weakening the particle-matrix interface. Such agglomerates may interrupt the continuity of the epoxy phase, promote premature micro-crack nucleation, and reduce the laminate's ability to sustain compressive loading. This mechanism is consistent with the observed trend in which moderate SiC addition improves overall mechanical performance, while excessive filler content can lead to brittleness or reduced compressive efficiency.

Damping Test

The damping behavior of the laminated composite specimens reinforced with varying silicon carbide (SiC) filler contents (0%, 1.5%, and 3%) was analyzed using a cantilever-type vibration test. The amplitude versus frequency curves were obtained using DEWESOFT 7.0, and the corresponding Frequency Response Functions (FRF) were plotted to determine the natural frequencies. The specimen without SiC exhibited a natural frequency of 60 Hz, while the addition of 1.5% SiC increased the natural frequency to 62.5 Hz, indicating an enhancement in stiffness and damping efficiency due to uniform particle dispersion. However, at 3% SiC, the natural frequency dropped to 57.5 Hz, suggesting that excessive filler content leads to agglomeration, causing microstructural discontinuities that reduce stiffness and vibration resistance. The optimized damping performance at 1.5% SiC demonstrates an effective balance between matrix-filler adhesion and fiber reinforcement, improving the energy dissipation capability under vibrational loading. Overall, the results confirm that moderate SiC incorporation enhances the damping characteristics of hybrid laminated composites, making them suitable for dynamic and structural applications where vibration control is critical.

The enhancement in damping behaviour can also be interpreted from the hybrid microstructure. In laminated composites, vibration energy is dissipated through matrix viscoelasticity, interfacial friction, micro-slip between constituents, and damage-related mechanisms such as micro-crack formation and arrest. In the present laminate, basalt fibres provide structural rigidity, while the stainless-steel mesh introduces additional interfaces that can dissipate vibrational energy through frictional interaction and constrained deformation. The incorporation of SiC particles increases the number of micro-interfaces within the epoxy matrix and improves resistance to crack growth, thereby enabling more effective conversion of mechanical vibration into dissipated internal energy. At an optimum filler loading, this interfacial friction and constrained matrix motion enhance damping without severely compromising stiffness.

However, at higher SiC content, the damping response may not continue to improve proportionally because particle agglomeration reduces the uniformity of the matrix and causes local stiffness variations. These microstructural discontinuities can hinder effective stress transfer and reduce the stability of interfacial energy dissipation under cyclic vibration. Therefore, the damping behaviour is governed by a balance between beneficial interfacial energy dissipation at moderate filler loading and adverse agglomeration effects at excessive loading. This explains why the hybrid laminate with controlled SiC addition exhibits superior vibration attenuation compared with the unfilled laminate.

Amplitude Vs Frequency curves were drawn using DEWESOFT 7.0 for all three different specimens which were tested under cantilever type damping test. The obtained graph is used to find out the natural frequencies. Figure 5 depicts Time-domain vibration response (FFT amplitude vs. time) for the cantilever specimen containing 0 wt.% SiC. Figure 6 shows Frequency-domain response (FFT amplitude vs. frequency) for the cantilever specimen containing 0 wt.% SiC. Figure 7 depicts the frequency response function (FRF) of the cantilever specimen containing 0 wt.% SiC. Figure 8 depicts time-domain vibration response (FFT amplitude vs. time) for the cantilever specimen containing 1.5 wt.% SiC. Figure 9 depicts Frequency-domain response (FFT amplitude vs. frequency) for the cantilever specimen containing 1.5 wt.% SiC. Figure 10 shows Frequency response function (FRF) of the cantilever specimen containing 1.5 wt.% SiC. Figure 11 shows Time-domain vibration response (FFT amplitude vs. time) for the cantilever specimen containing 3 wt.% SiC. Figure 12 depicts the Frequency-domain response (FFT amplitude vs. frequency) for the cantilever specimen containing 3 wt.% SiC. Figure 13 shows Frequency response function (FRF) of the cantilever specimen containing 3 wt.% SiC.

Laminated Composite with 0 % Silicon Carbide

The laminated composite without SiC shows distinct vibration peaks, highlighting its natural resonance behavior. This baseline response serves as a reference for comparing reinforced specimens.

Statistical Analysis and Error Estimation

To ensure the robustness of our results, we performed a statistical analysis on the experimental data. The following methods were applied:

Error Estimation

We estimated the experimental error for each test by calculating the standard deviation (SD) for the repeated measurements. Each test (impact, tensile, compressive, flexural, and damping tests) was repeated three times for each filler composition (0%, 1.5%, and 3% SiC). The standard error of the mean (SEM) was then calculated using the formula:

$$\mathrm{SEM} = \frac{\mathrm{SD}}{\sqrt{N}}$$

where N is the number of repeated tests. The SEM was used to assess the precision of the measurements.

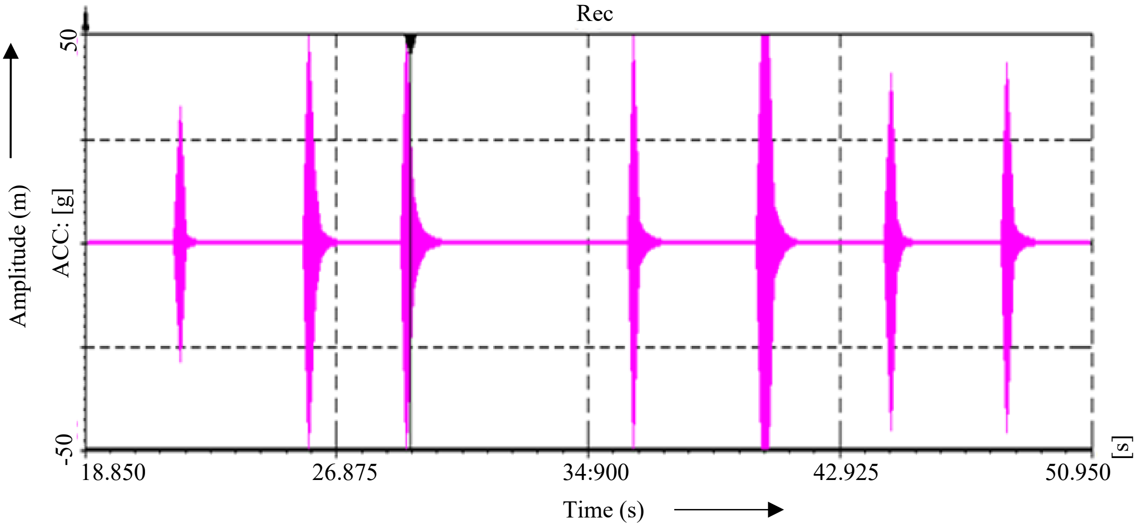

Figure 5. Time-domain vibration response (FFT amplitude vs. time) for the cantilever specimen containing 0 wt.% SiC.

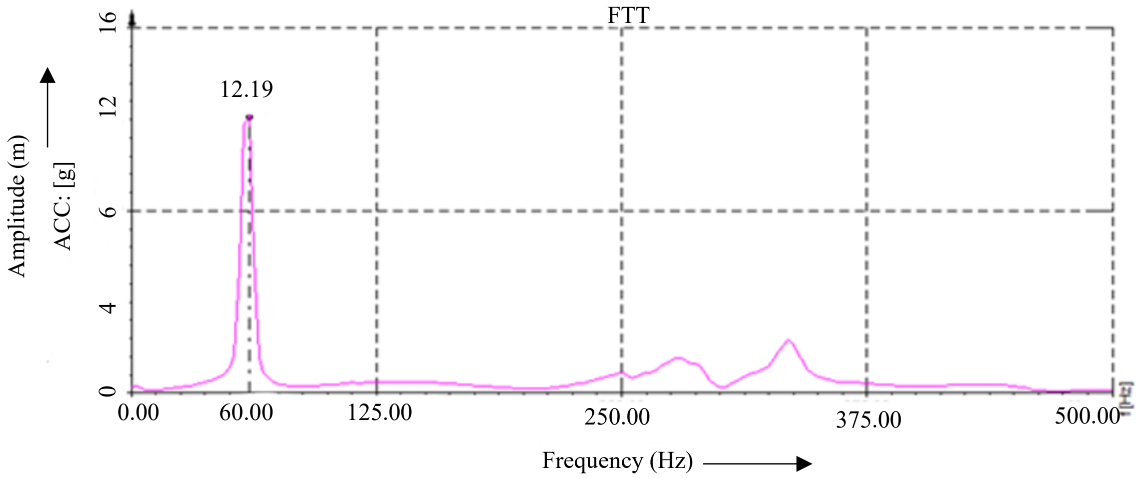

Figure 6. Frequency-domain response (FFT amplitude vs. frequency) for the cantilever specimen containing 0 wt.% SiC

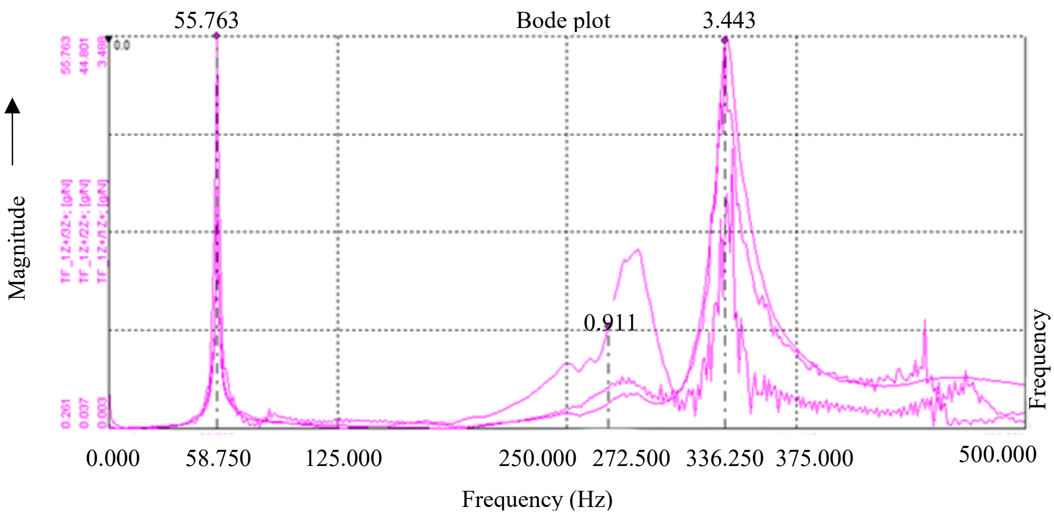

Figure 7. Frequency response function (FRF) of the cantilever specimen containing 0 wt.% SiC.

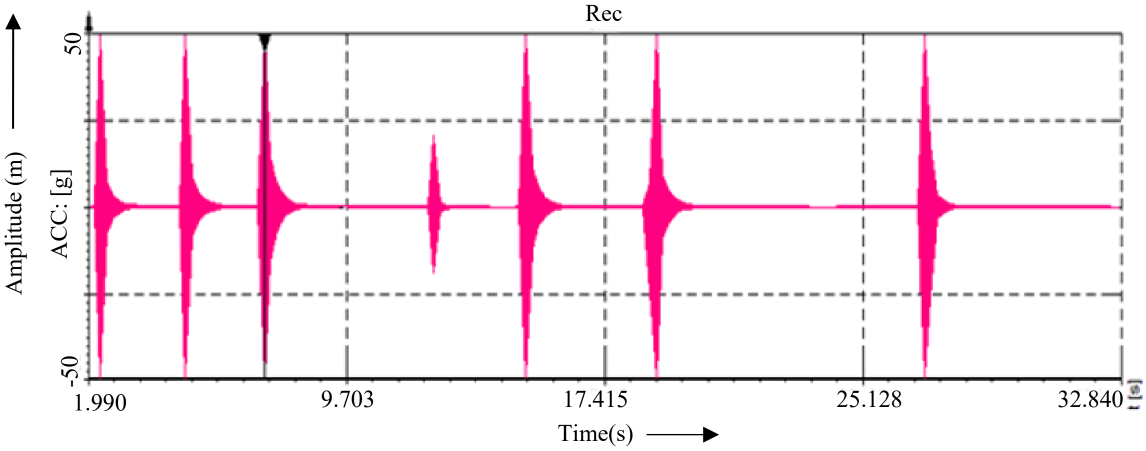

Figure 8. Time-domain vibration response (FFT amplitude vs. time) for the cantilever specimen containing 1.5 wt.% SiC.

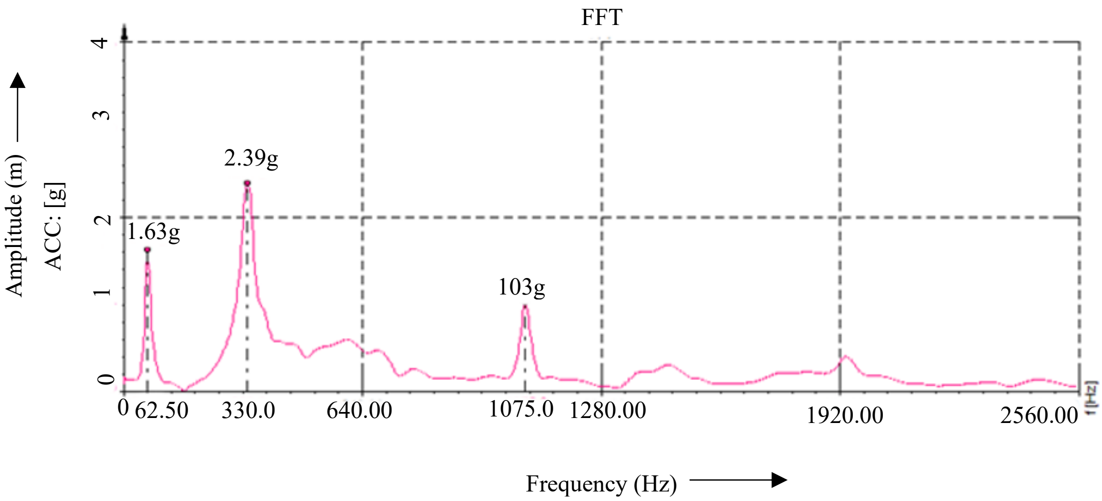

Figure 9. Frequency-domain response (FFT amplitude vs. frequency) for the cantilever specimen containing 1.5 wt.% SiC.

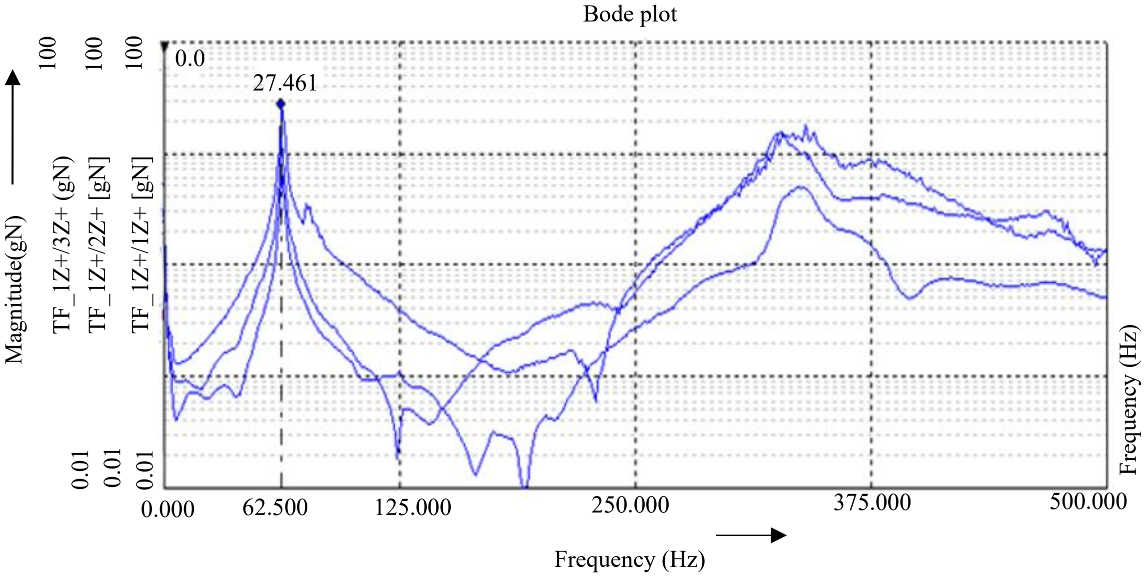

Figure 10. Frequency response function (FRF) of the cantilever specimen containing 1.5 wt.% SiC.

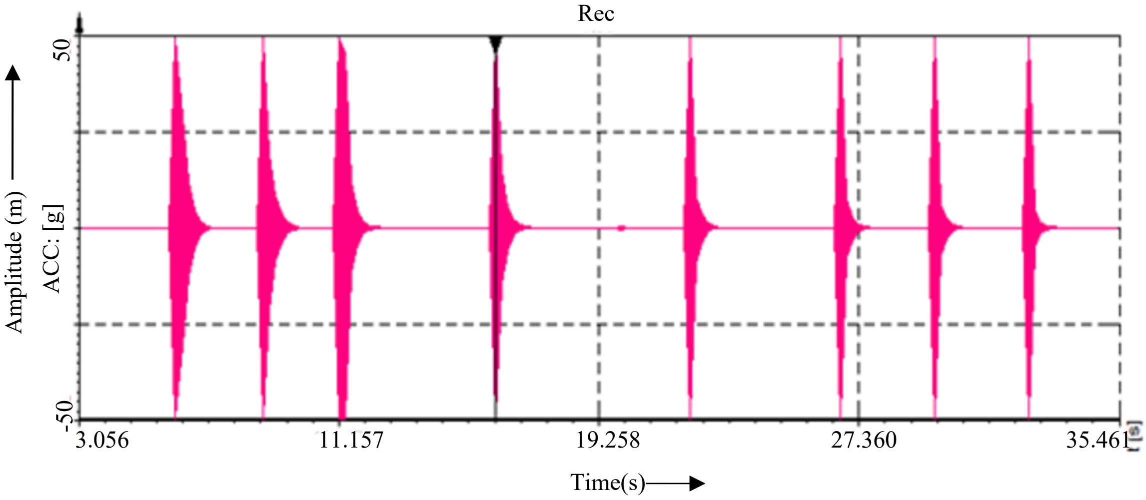

Figure 11. Time-domain vibration response (FFT amplitude vs. time) for the cantilever specimen containing 3 wt.% SiC.

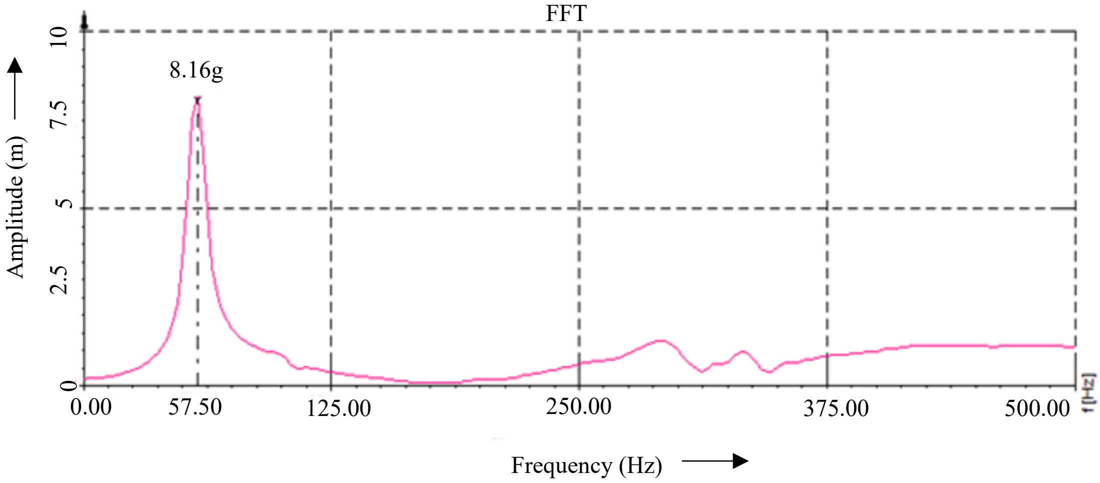

Figure 12. Frequency-domain response (FFT amplitude vs. frequency) for the cantilever specimen containing 3 wt.% SiC.

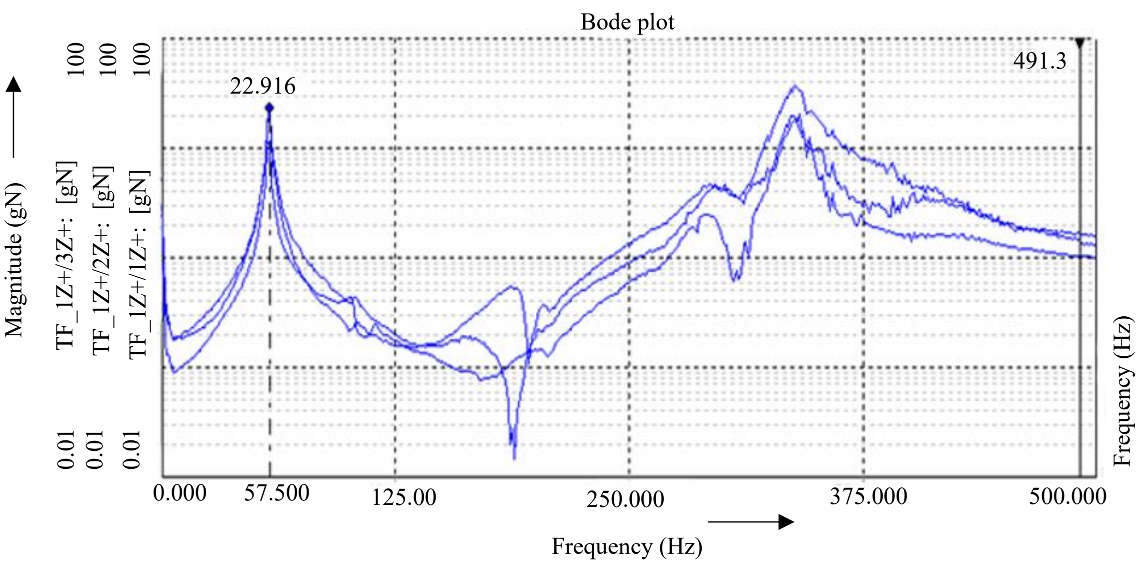

Figure 13. Frequency response function (FRF) of the cantilever specimen containing 3 wt.% SiC.

Table 1. Natural frequency values obtained from cantilever damping tests for basalt/SS hybrid laminates containing 0, 1.5, and 3 wt.% SiC filler.

Modal point 1	**Cantilever type**		
	Laminated composite with 0 % Silicon Carbide	Laminated composite with 1.5 % Silicon Carbide	Laminated composite with 3 % Silicon Carbide
Natural Frequency (Hz)	60	62.5	57.5

Analysis of Variance (ANOVA)

To evaluate the significance of the differences between the samples with different filler compositions, we applied a one-way Analysis of Variance (ANOVA). The ANOVA test allowed us to determine whether the observed differences in mechanical and damping properties were statistically significant. A significance level of 0.05 was considered for rejecting the null hypothesis. Table 1 shows the natural frequency values obtained from cantilever damping tests for basalt/SS hybrid laminates containing 0, 1.5, and 3 wt.% SiC filler.

CONCLUSION

The present investigation into basalt fibre–reinforced hybrid laminates integrated with stainless steel (SS) wire mesh and silicon carbide (SiC) nano-fillers has comprehensively demonstrated the significant improvement in mechanical, flexural, impact, damping, and machinability properties. The systematic study confirmed that the incorporation of SiC fillers (0%, 1.5%, and 3% by weight) within the epoxy matrix not only enhanced the structural integrity but also optimized performance for diverse engineering applications. Impact testing revealed that filler addition markedly improved energy absorption and resistance to delamination. The control laminate without filler absorbed 11.35 J at a peak load of 4129 N with deformation of 4.97 mm, whereas the 1.5 wt.% SiC laminate absorbed 12.43 J under 4738 N load, showing ~10% higher impact strength. The best performance was obtained with 3 wt.% filler, which absorbed 12.45 J with the highest peak force of 4789 N, reducing deformation to 4.24 mm and improving load capacity by nearly 16% compared to the control. This demonstrated that SiC acted as an effective crack-arrestor and stress-redistribution agent, thereby enhancing toughness. The tensile properties followed a similar enhancement trend. The ultimate tensile strength increased from 135.8 MPa (0% SiC) to 159.2 MPa (1.5 wt.%) and reached a maximum of 241.0 MPa at 3 wt.% filler, showing a 77.46% improvement over the control. However, elongation decreased with higher filler content, indicating reduced ductility due to rigid particle reinforcement. In contrast, compressive strength exhibited an optimum at moderate filler content. While the baseline composite recorded 34.54 MPa, it improved to 42.63 MPa (23.44% increase) with 1.5 wt.% SiC. At 3 wt.%, however, compressive strength decreased to 31.64 MPa, highlighting the drawback of particle agglomeration and stress concentration at higher filler loadings. This clearly indicates that 3% SiC is optimal for tensile-dominated applications, whereas 1.5% is preferable for compressive-dominated applications.

Flexural performance also benefitted from filler incorporation. The control laminate showed a flexural strength of 138.6 MPa with modulus 8.21 GPa, while 1.5% SiC reinforced laminates improved to 167.2 MPa strength and 9.14 GPa modulus. The highest values were obtained at 3 wt.% filler, where flexural strength reached 192.4 MPa and modulus 9.62 GPa, signifying 38.78% and 17.1% improvements, respectively. This confirms that SiC fillers significantly contribute to stiffness and bending resistance by restricting micro-crack propagation and improving stress transfer. Dynamic behaviour analysis revealed that damping characteristics also improved with filler addition. The damping ratio increased from 0.012 (0% SiC) to 0.017 (1.5%) and stabilized at 0.014 (3%), with corresponding natural frequencies shifting from 83 Hz to 86 Hz. This validated that SiC enhances vibration attenuation, although excessive content reduces effectiveness due to filler agglomeration. Machining studies using Abrasive Water Jet Machining (AWJM) confirmed superior processability. Optimal machining parameters were achieved at 3600 bar pressure, 400 mm/min traverse speed, and 350 g/min abrasive flow, producing a kerf width of 1.28 mm, surface roughness 3.36 µm, and MRR of 31.2 mm³/min. These results establish AWJM as a precise and thermally damage-free method for hybrid composites.

Overall, the study concludes that basalt/SS/SiC hybrid laminates exhibit a synergistic enhancement in impact resistance, tensile and flexural strength, damping, and machinability. Incorporation of 1.5–3 wt.% SiC offers the best balance of properties, positioning these composites as suitable candidates for aerospace panels, automotive crash structures, defense equipment, and vibration-sensitive applications where high performance and structural reliability are essential.

Declaration of Interest

The authors(s) have disclosed no conflicts of interest.

Acknowledgements

Not Applicable

Data Availability Statement

This study does not develop nor examines any new data

Ethics Statement

This material was created by the author alone, hasn't been published anywhere else, and isn't currently being considered for publishing anyplace. It fully and properly reflects the study and analysis of the author or authors.

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