Journal of Mechanical Research and Application (JMRA), Vol. 14 No.4, 1403 (2025),28-39

JMRA
Journal of Mechanical Research and Application
ISSN: 2251-7383, eISSN: 2251-7391

High-Velocity Impact Behavior of 3D Fiber Metal Laminates Incorporating Nano-Reinforced Syntactic Foam

Reza Hajizadeh Asl[1], Mehdi Yarmohammad Tooski[1], Mohsen Jabbari[1], Laleh Maleknia [1]

Abstract:

This research conducts an experimental assessment of the high-velocity impact response of three-dimensional fiber metal laminates (3D FMLs) integrated with a nano-reinforced syntactic foam core. Laminates with different nanoclay loadings (0, 3, 5, and 7 wt.%) were fabricated in both reinforced and unreinforced forms and subjected to ballistic testing. Impact experiments were carried out using a light gas gun system that launched 9 mm steel projectiles at a velocity of 235 m/s, enabling determination of the ballistic limit velocities. The dynamic behavior and failure mechanisms of the laminates were examined through field emission scanning electron microscopy (FESEM) to quantify the role of nanoparticle reinforcement on their impact resistance. The findings revealed that the addition of 5 wt.% nanoclay yielded an 18.84% reduction in residual projectile velocity and a 14.97% improvement in absorbed impact energy compared with unreinforced 3D FMLs. Morphological and macroscopic inspections demonstrated that nanoclay enhanced fiber–matrix interfacial adhesion, suppressed matrix microcracking, and mitigated interlaminar delamination. These effects were attributed to the reinforcing action of nanoclay within the polymeric phase. Conversely, nanoclay incorporation was observed to reduce adhesion at the aluminum–composite interface, which promoted more severe plastic deformation of the aluminum sheets during impact. Additionally, microstructural analysis confirmed that nanoclay particles facilitated fiber fibrillation, thereby enhancing the energy dissipation capacity of the laminate under high-velocity impact conditions.

Keywords: Fiber Metal Laminates (FMLs)، High-Velocity Impact ،Nanoclay Reinforcement، Syntactic Foam Core، Ballistic Performance

Introduction

[1] Department of Medical Engineering, South Tehran Branch, Islamic Azad University, Tehran Iran

Fiber Metal Laminates (FMLs) constitute a class of advanced hybrid composite materials, first introduced with the development of aluminum–aramid reinforced laminates (ARALL) [1]. While ARALL demonstrated superior fatigue resistance and fracture toughness, its application was limited by comparatively low compressive strength [2]. Subsequent generations, including carbon and glass fiber-reinforced aluminum laminates (CARALL and GLARE), were developed to offer enhanced mechanical performance and structural stability [3].These laminates are architected as multilayered structures, synergistically combining alternating metallic sheets and fiber-reinforced polymer (FRP) plies. This design merges the high specific stiffness and strength-to-weight ratio of composites with the ductility, toughness, and impact resistance of metals. Consequently, FMLs can withstand diverse loading conditions, including static, creep, and cyclic fatigue loads. A primary limitation, however, stems from their brittle polymeric matrices, which render them susceptible to impact-induced damage mechanisms such as matrix cracking, delamination, and fiber breakage [4]. Compared to monolithic metallic and conventional composite structures, FMLs provide superior fire resistance, enhanced fatigue performance, and improved impact resistance, all while maintaining a low specific weight [5]. These properties have led to their adoption in aerospace applications like fuselage skins and propeller blades [6], in defense for armor systems, and in the automotive industry for energy-absorbing structures [7,8]. The operational environments in aerospace and defense frequently subject structures to high-velocity impact (HVI) events from threats such as bird strike, hail, and runway debris, which can severely compromise structural integrity and service life [9]. Extensive empirical and numerical research has therefore been dedicated to characterizing the dynamic response of FMLs under ballistic impact, consistently demonstrating their superior energy absorption, controlled failure mechanisms, and enhanced perforation resistance compared to conventional materials [10–13].

This drive for enhanced performance has led to research into material modifications, particularly through the incorporation of nanoreinforcements into the polymeric matrix to improve interfacial bonding, energy absorption, and damage tolerance [14,15]. For instance, Khurram et al. [17] demonstrated that a 2.5 wt.% CNT addition improved adhesion via nano-mechanical interlocks. Shahjouei et al. [18] observed that 0.9 wt.% GNPs increased in-plane stiffness, and Haro et al. [19] reported that nanofillers improved fiber-matrix adhesion while microfillers reduced void content. Nanoclay reinforcements have shown particular promise in enhancing ballistic performance. Behari et al. [20] reported that incorporating 3 wt.% modified nanoclay enhanced flexural strength and fracture toughness under HVI. Research has detailed key energy dissipation mechanisms, including fiber fracture, matrix cracking, and metal plastic deformation [21], and has shown that impact response is also influenced by projectile geometry [22,23]. Comparative studies, such as those by Heimbs et al. [24], have further evaluated different fiber systems for optimal performance. Recent multi-scale reinforcement strategies focus on nanofillers like nanoclay due to its high aspect ratio and ability to improve interfacial adhesion [25–27]. Studies on nanoclay-reinforced sandwich panels have demonstrated significantly higher kinetic energy absorption compared to conventional structures [28–32]. In this study, we investigate the high-velocity impact behavior of three-dimensional fiber metal laminates (3D FMLs) incorporating a syntactic foam core reinforced with nanoclay. Experimental ballistic testing was conducted using a light-gas gun with steel spherical projectiles at an impact velocity of 235 m/s. The primary objective is to quantify the influence of nanoclay concentration on the ballistic limit velocity, residual velocity, and energy absorption characteristics, thereby contributing to the development of advanced impact-resistant hybrid structures.

2. Materials and methods

2. 1. Materials

This study fabricated a three-dimensional fiber metal laminate (3D FML) comprising two 2024-T3 aluminum alloy sheets and composite laminates made from twelve layers of woven E-glass fiber in an epoxy matrix, all bonded to a syntactic foam core. The epoxy resin was modified with Cloisite 5A nanoclay to enhance mechanical properties. To optimize interfacial adhesion, the aluminum and glass fibers underwent a chemical surface treatment using NaOH, $K_2Cr_2O_7$, and H_2SO_4 to increase surface roughness and wettability. The core consisted of a syntactic foam made with ceramic microballoons (33)

Table 1 mechanical and Structural properties of ceramic microballoons

Microballoon type	Outer diameter (μm)	True density (g/cm3)	Thickness to radius ratio (%)
WM	170	0. 7	10

The architectural layout, including the ply stacking sequence and overall geometric design of the three-dimensional fiber metal laminate (3D FML) specimens, is detailed in Figures 1 and 2.

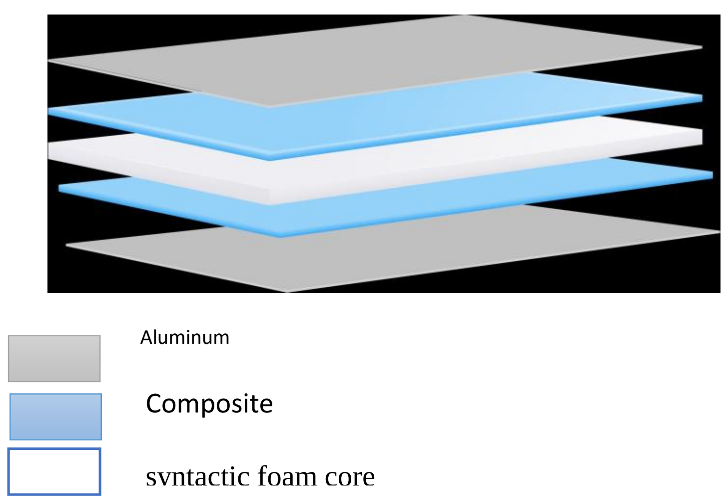

Fig. 1. Stacking sequence and geometry of the 3D fiber metal laminate (3D FML) specimens

2.2. Specimens fabrication

The fabrication process initiated with the production of syntactic foam cores. These consisted of an epoxy matrix containing a constant 20 vol% of ceramic microballoons. To study the influence of nanoclay, weight fractions of 0%, 3%, 5%, and 7% were added (35,36). The epoxy resin was first heated to 75°C for 24 hours to lower its viscosity. The nanoclay was then dispersed via high-shear mixing at 500 RPM for 30 minutes, followed by 15 minutes of ultrasonication at 60% amplitude (36). After degassing to remove microbubbles, the microballoons were manually mixed in with a wooden rod to prevent crushing, and the hardener was added. The mixture was cast into a mold and cured at room temperature for 48 hours. For the final 3D FML assembly, the cured core was cut into panels. These were sandwiched between twelve layers of E-glass fabric (six per side) using a hand lay-up technique. A pressing operation was applied after 24 hours of curing to enhance core-skin adhesion and optimize the fiber volume fraction.

2. 4 Impact testing procedure

High-velocity impact tests were conducted using a gas gun system to propel spherical 316 stainless steel projectiles (9 mm diameter, 3 g mass) at a target velocity of 235 m/s. The projectiles were heat-treated to a hardness of 52 HRC to ensure consistent penetration. The 4-meter-long barrel had an internal diameter of 10 mm, with projectile release controlled by a high-speed solenoid valve and a pressure vessel rated to 60 bar. The 3D FML specimens were rigidly clamped in a fixture, exposing a 100 mm x 100 mm target area. The ballistic limit velocity, defined as the minimum velocity for complete perforation, was determined using a standard empirical relation (Equation 1) (37,38).

$$V_{BL} = \sqrt{{V_i}^2 - {V_r}^2} \quad \text{for } V_r > 0 \quad (1)$$

The energy absorption capacity of the 3D FML specimens under high-velocity impact was quantified using Equation (2), which calculates the total energy dissipated by the laminate during the impact event.

$$E_k = \frac{1}{2} m_p {V_{BL}}^2 \ (2)$$

where m_p, Vi، Vo، Ek, V_{BL} and were the impactor mass, initial velocity, residual velocity, absorbed energy, and limiting velocity, respectively. (18)

2. 5 Microstructural Characterization

3. he fracture morphology of the constituent aluminum and composite core layers was characterized via field emission scanning electron microscopy (FESEM) using a VEGA TESCAN-LMU system. This analysis also served to evaluate the quality of nanoclay dispersion in the epoxy matrix.

4. Results

3. 1. Impact behavior

The impact test results, detailed in Table 2 and Figures 2–3, demonstrate that nanoclay reinforcement significantly enhances the ballistic performance of 3D fiber metal laminates (FMLs). The unreinforced specimen (0 wt.% nanoclay) exhibited the highest residual velocity (138 m/s), indicating minimal energy absorption. Performance improved with nanoclay addition: 3 wt.% reduced residual velocity by 7% to 129 m/s, while 5 wt.% yielded an 18.8% reduction to 112 m/s—the optimal result. This enhancement is attributed to improved stress transfer, matrix toughening, and mechanisms like crack deflection and fiber bridging. However, 7 wt.% nanoclay increased residual velocity to 121 m/s due to nanoparticle agglomeration, which causes stress concentrations and reduces energy dissipation efficiency. Ballistic limit velocity followed a similar trend, rising from 190.5 m/s (0 wt.%) to 206.6 m/s (5 wt.%) before declining to 201.7 m/s (7 wt.%). Absorbed energy data corroborated these findings, with the 5 wt.% sample showing a 17.2% increase over the baseline, while the 7 wt.% specimen improved by only 6.05%. The results confirm that 5 wt.% nanoclay optimally enhances energy absorption through improved interfacial adhesion and nanomechanical interlocks, whereas higher concentrations induce agglomeration and matrix embrittlement. These findings underscore the potential of nanoclay-reinforced FMLs for aerospace and defense applications requiring superior impact resistance.

Table 2 Results obtained from the high-velocity impact test of 3D FMLs.

Nanoclay content (wt. %)	Residual velocity (m/s)	Limit velocity (m/s)	Absorbed energy (J)	Specific absorbed energy (J/kg)
0	138	190. 5	97. 1	971
3	129	196. 2	103. 3	1033
5	112	206. 6	114. 2	1142
7	121	201. 7	108. 7	1087

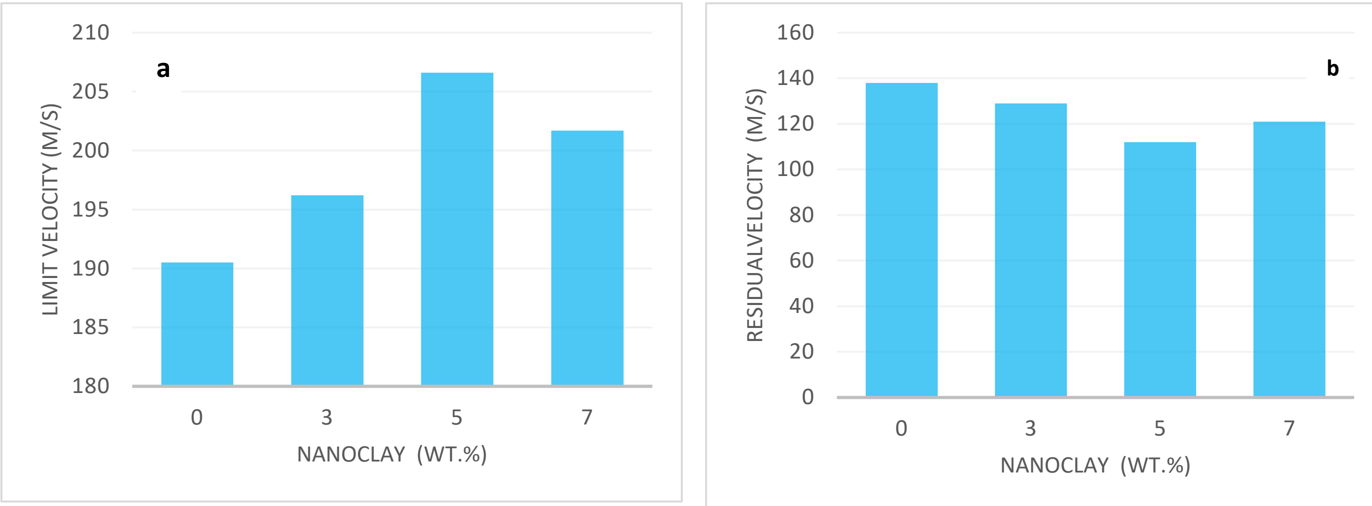

Fig. 2 *High-velocity impact results for reinforced and unreinforced FMLs: (a) ballistic limit velocity, (b) residual velocity.*

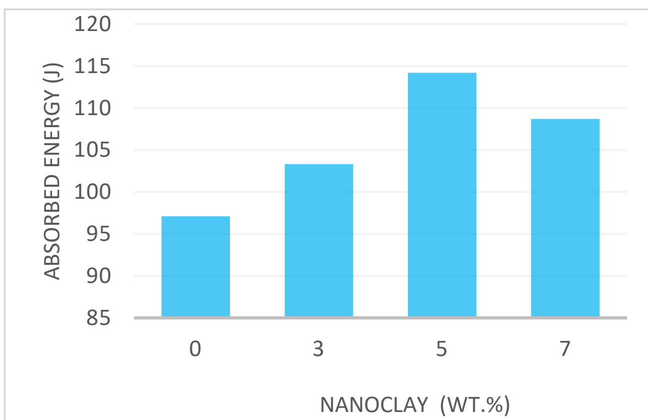

Fig. 3*. High-velocity impact absorbed energy results for reinforced and unreinforced FMLs*

3. 2 Microscopic Analysis

Figure 4 shows nanoclay dispersion in the resin matrix at 0, 3, 5, and 7 wt.%. A uniform distribution is observed at 3 wt.% and 5 wt.%, while agglomeration and inhomogeneity become evident at the higher 7 wt.% concentration.

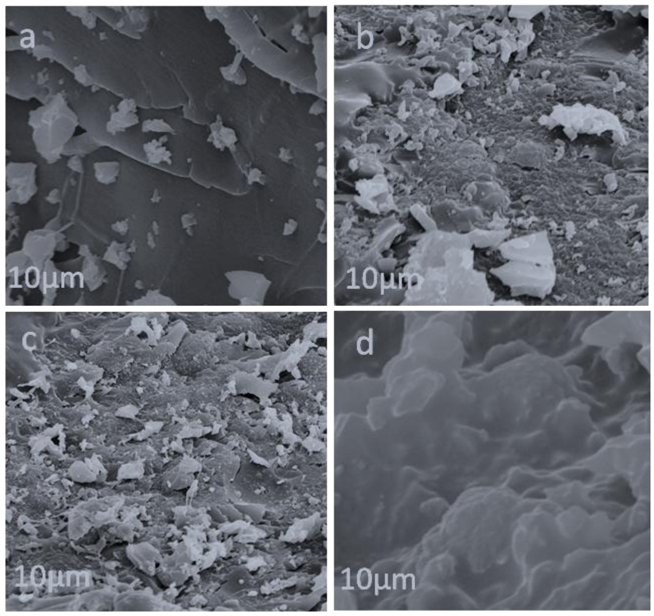

Fig.4. *FESEM analysis of nanoclay distribution in the composite matrix: (a) 0 wt.%, (b) 3 wt.%, (c) 5*

Figure 5 presents FESEM analysis of the nanoclay-reinforced 3D FML cores. The 0 wt.% sample (Fig. 8a) shows poor epoxy-fiber adhesion, indicated by residual resin on the fiber surfaces, which weakens load transfer. Incorporation of 3 wt.% nanoclay (Fig. 8b) improves interfacial bonding, while 5 wt.% (Fig. 8c) significantly enhances matrix-fiber cohesion. However, at 7 wt.% (Fig. 8d), severe nanoclay agglomeration occurs, creating stress concentrations that promote crack initiation and growth. This agglomeration at higher concentrations detrimentally compromises the mechanical properties, underscoring the importance of optimal nanoclay dispersion for maximizing laminate performance.

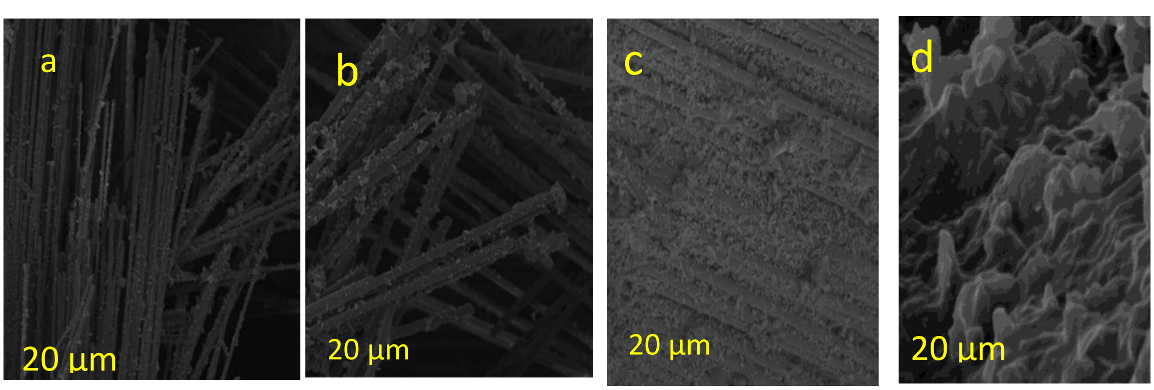

Fig. 5. *FESEM images of the fracture surface of FMLs containing nanoclay after high-velocity impact: (a) 0 wt.%, (b) 3 wt.%, (c) 5 wt.%, and (d) 7 wt.%*

Research confirms that crack propagation in composites initiates at matrix weak points, such as nanoclay agglomerations, where poor resin wetting creates stress concentrations that degrade mechanical properties. While 5 wt.% nanoclay can reduce epoxy-glass fiber adhesion (20,37), it generally enhances matrix load transfer and restricts crack growth. However, microcracks often propagate along fiber-matrix interfaces, leading to fibrillation under high strain. In 3D FMLs, aluminum-composite interfacial adhesion is critical. Nanoclay incorporation strengthens this bond, shifting failure from the interface into the epoxy matrix itself, thereby improving impact resistance. This is evidenced by higher absorbed energy and ballistic limit velocities. The mechanism transitions from simple adhesive bonding to enhanced nanocomposite mechanical interlocking, which significantly improves load transfer and structural cohesion under dynamic loads (37). Optimizing nanoclay content is thus essential for maximizing the ballistic performance of 3D FMLs.

3. 3. Ballistic limit velocity

Ballistic testing on thirty-six 3D FML panels evaluated failure mechanisms and ballistic limits. All specimens exhibited projectile-diameter plugging and core-skin debonding. Nanoclay modification reduced crack length but increased microcrack density, enhancing energy dissipation—most effectively at 5 wt.%. However, 7 wt.% nanoclay decreased compressive strength and perforation resistance due to particle agglomeration and embrittlement. Results indicate a critical trade-off between nanoclay-induced toughening and structural integrity loss at higher concentrations.

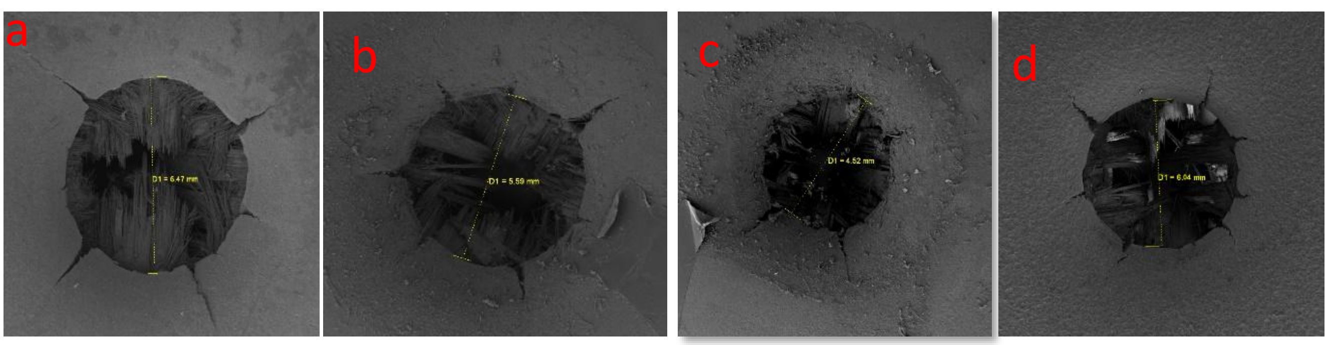

Fig. 6. *FESEM analysis of the projectile impact on the plate: (a) 0 wt.%, (b) 3 wt.%, (c) 5 wt.%, and (d) 7 wt.%.*

Figure 7 analyzes post-impact crack propagation in the aluminum layer, demonstrating nanoclay's role in altering fracture behavior. The unreinforced (0 wt.%) sample exhibited a maximum crack length of 3.09 mm with six radial cracks. Incorporation of 3 wt.% nanoclay reduced maximum crack length to 1.72 mm and increased crack count to seven, indicating improved stress distribution and interfacial adhesion. Optimal performance occurred at 5 wt.%, with crack length further reduced to 1.60 mm, demonstrating effective crack suppression and enhanced delamination resistance through improved nanoparticle-matrix interaction. This was aided by chemical etching of the aluminum surface, which created micro-cavities for resin infiltration, forming nanocomposite mechanical interlocks.

However, at 7 wt.%, agglomeration caused stress concentration, increasing crack length to 1.90 mm. This confirms that excessive nanoclay content compromises structural homogeneity. The 5 wt.% concentration produced the most favorable crack network—dense but short—maximizing energy dissipation and impact resistance. These findings emphasize that optimizing nanoclay dispersion is critical for enhancing FML performance without inducing embrittlement or reducing compressive strength.

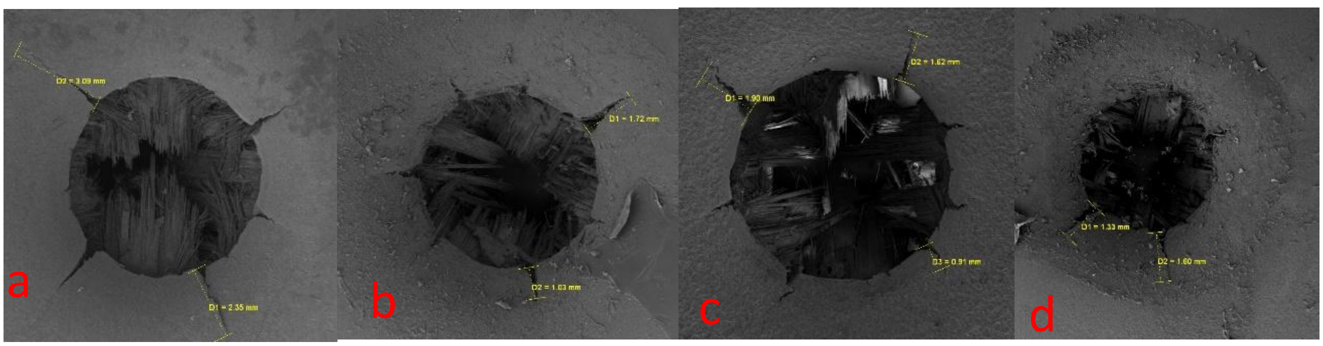

Fig. 7. FESEM analysis of cracks formed on the plate: (a) 0 wt.%, (b) 3 wt.%, (c) 5 wt.%, and (d) 7 wt.%.

5. Conclusion

This study systematically evaluated the effect of nanoclay reinforcement on the high-velocity impact behavior of three-dimensional fiber metal laminates (3D FMLs). The optimal performance was achieved with 5 wt.% nanoclay, which significantly improved ballistic resistance, energy absorption, and damage tolerance. At this concentration, residual velocity decreased by 18.84% to 112 m/s, ballistic limit velocity increased to 206.6 m/s, and absorbed energy rose by 17.2%, indicating enhanced stress transfer and crack deflection. Microstructural analysis via FESEM confirmed uniform nanoclay dispersion at 3–5 wt.%, improving resin-fiber adhesion and inhibiting crack propagation. Conversely, 7 wt.% nanoclay led to agglomeration, causing stress concentration, matrix embrittlement, and reduced performance. Fractography highlighted the role of nanoclay in promoting nanomechanical interlocking at the fiber-metal interface, shifting failure from adhesive to cohesive modes. In conclusion, nanoclay-reinforced FMLs demonstrate superior impact resistance within an optimal concentration range. The 5 wt.% formulation offers the best balance of properties, making it highly suitable for aerospace, defense, and automotive applications where lightweighting and impact protection are critical. Future efforts should focus on optimizing dispersion techniques to prevent agglomeration and further improve mechanical performance.

References

1. Serubibi A, Hazell PJ, Escobedo JP, Wang H, Oromiehie E, Prusty GB, et al. Fibre-metal laminate structures: High-velocity impact, penetration, and blast loading – A review. Compos Part A Appl Sci Manuf. 2023 Oct 1;173:107674.

2. Heimbs S, Wagner T, Viana Lozoya JT, Hoenisch B FF. Comparison of impact behaviour of glass, carbon and Dyneema composites. Proc Inst Mech Eng Part C J Mech Eng Sci. 2019;233(3):951–66.

3. Yang C, Chen Z, Yao S, Xu P, Li S, Alqahtani MS. Parametric study on the crushing performance of a polyurethane foam-filled CFRP/Al composite sandwich structure. Polym Test. 2022 Apr 1;108:107515.

4. Kamaloo A, Jabbari M, Tooski MY, Javadi M. Nonlinear Free Vibrations Analysis of Delaminated Composite Conical Shells. Int J Struct Stab Dyn. 2019;

5. Zhu X, Chen W, Liu L, Xu K, Luo G, Zhao Z. Experimental investigation on high-velocity impact damage and compression after impact behavior of 2D and 3D textile composites. Compos Struct. 2023 Jan 1;303:116256.

6. Praveen R, Koteswara Rao S, Damodaram R SKS. Numerical and experimental investigations on the effect of target thickness and solution treatment on the ballistic behaviour of AA7075 thick plates. Proc Inst Mech Eng Part C J Mech Eng Sci. 2022;236(7):3530–45.

7. Önder A, Robinson M. Investigating the feasibility of a new testing method for GFRP/polymer foam sandwich composites used in railway passenger vehicles. Compos Struct. 2020 Feb 1;233:111576.

8. Alavi Nia A, Mokari S, Zakizadeh M, Kazemi M. Experimental and numerical investigations of the effect of cellular wired core on the ballistic resistance of sandwich structures. Aerosp Sci Technol. 2017 Nov 1;70:445–52.

9. Sahoo CK, Bhatia GS, Balaganesan G, Arockiarajan A. Post repair high velocity impact behaviour of carbon-glass hybrid composite: Experimental and numerical study. Int J Impact Eng. 2022 Oct 1;168:104305.

10. Serubibi A, Hazell PJ, Escobedo JP, Wang H, Oromiehie E, Prusty GB, et al. Fibre-metal laminate structures: High-velocity impact, penetration, and blast loading – A review. Compos Part A Appl Sci Manuf [Internet]. 2023;173(March):107674. Available from: https://doi.org/10.1016/j.compositesa.2023.107674

11. Morinière FD, Alderliesten RC, Sadighi M, Benedictus R. An integrated study on the low-velocity impact response of the GLARE fibre-metal laminate. Compos Struct. 2013;100:89–103.

12. Asaee Z, Shadlou S, Taheri F. Low-velocity impact response of fiberglass/magnesium FMLs with a new 3D fiberglass fabric. Compos Struct [Internet]. 2015;122:155–65. Available from: http://dx.doi.org/10.1016/j.compstruct.2014.11.038

13. Khoramishad H, Alikhani H, Dariushi S. An experimental study on the effect of adding multi-walled carbon nanotubes on high-velocity impact behavior of fiber metal laminates. Compos Struct. 2018 Oct 1;201:561–9.

14. Wang A, Xia D, Xian G, Li H. Effect of nanoclay grafting onto flax fibers on the interfacial shear strength and mechanical properties of flax/epoxy composites. Polym Compos. 2019;40(9):3482–92.

15. Cheng X, Liu L, Feng X, Shen L, Wu Z. Low Temperature-Based Flexural Properties of Carbon Fiber/Epoxy Composite Laminates Incorporated with Carbon Nanotube Sheets. Macromol Mater Eng. 2019;304(10):1–10.

`

16. Amirbeygi H, Khosravi H, Tohidlou E. Reinforcing effects of aminosilane-functionalized graphene on the tribological and mechanical behaviors of epoxy nanocomposites. J Appl Polym Sci. 2019;136(18):1–8.

17. Khurram AA, Hussain R, Afzal H, Akram A, Subhanni T. Carbon nanotubes for enhanced interface of fiber metal laminate. Int J Adhes Adhes [Internet]. 2018;86:29–34. Available from: https://doi.org/10.1016/j.ijadhadh.2018.08.008

18. Shahjouei S, Barati MR, Tooski MY. High Velocity Impact Response and Damage Mechanism of an Aluminium/Glass-Carbon Fiber/Epoxy Composite Plate Reinforced with Graphene Nano-plates. Fibers Polym. 2021;22(2):480–8.

19. Haro EE, Odeshi AG, Szpunar JA. The energy absorption behavior of hybrid composite laminates containing nano-fillers under ballistic impact. Int J Impact Eng [Internet]. 2016;96:11–22. Available from: http://dx.doi.org/10.1016/j.ijimpeng.2016.05.012

20. Bahari-Sambran F, Eslami-Farsani R, Arbab Chirani S. The flexural and impact behavior of the laminated aluminum-epoxy/basalt fibers composites containing nanoclay: An experimental investigation. J Sandw Struct Mater. 2020;22(6):1931–51.

21. Fan J, Cantwell WJ, Guan ZW. The low-velocity impact response of fiber-metal laminates. J Reinf Plast Compos. 2011;30(1):26–35.

22. Abdullah MR, Cantwell WJ. The impact resistance of polypropylene-based fibre-metal laminates. Compos Sci Technol. 2006;66(11–12):1682–93.

23. Magarajan U SKS. Effect of ceramic particles reinforcement on the ballistic resistance of friction stir processed thick AA6061 surface composite targets. Proc Inst Mech Eng Part C J Mech Eng. 2021;235(15):2782–94.

24. Heimbs S, Wagner T, Viana Lozoya JT, Hoenisch B, Franke F. Comparison of impact behaviour of glass, carbon and Dyneema composites. Proc Inst Mech Eng Part C J Mech Eng Sci. 2019;233(3):951–66.

25. Koricho EG, Khomenko A, Haq M, Drzal LT, Belingardi G, Martorana B. Effect of hybrid (micro- and nano-) fillers on impact response of GFRP composite. Compos Struct [Internet]. 2015;134:789–98. Available from: http://dx.doi.org/10.1016/j.compstruct.2015.08.106

26. Ávila AF, Carvalho MGR, Dias EC, da Cruz DTL. Nano-structured sandwich composites response to low-velocity impact. Compos Struct [Internet]. 2010;92(3):745–51. Available from: http://dx.doi.org/10.1016/j.compstruct.2009.09.010

27. Ahmadi H, Liaghat G, Charandabi SC. High velocity impact on composite sandwich panels with nano-reinforced syntactic foam core. Thin-Walled Struct. 2020 Mar 1;148.

28. Uddin MF, Mahfuz H, Zainuddin S, Jeelani S. Improving Ballistic Performance of Polyurethane Foam by Nanoparticle Reinforcement. J Nanotechnol. 2009;2009:1–8.

29. Zhang H, Gn SW, An J, Xiang Y, Yang JL. Impact Behaviour of GLAREs with MWCNT Modified Epoxy Resins. Exp Mech. 2014;54(1):83–93.

30. Taherzadeh-Fard A, Khodadadi A, Liaghat G, Yao XF, Mehrizi MAZ. Mechanical properties and energy absorption capacity of chopped fiber reinforced natural rubber. Compos Part C Open Access. 2022 Mar 1;7:100237.

31. Mahmood H, Tripathi M, Pugno N, Pegoretti A. Enhancement of interfacial adhesion in glass fiber/epoxy composites by electrophoretic deposition of graphene oxide on glass fibers. Compos Sci Technol. 2016 Apr 1;126:149–57.

32. Kawashima S, Wang K, Ferron RD, Kim JH, Tregger N, Shah S. A review of the effect of nanoclays on the fresh and

hardened properties of cement-based materials. Cem Concr Res. 2021 Sep 1;147:106502.

33. M S, TK K, S BL, R R, S Raj S. Behavior of epoxy reinforced banana glass fiber hybrid composite with nanoclay interference. Proc Inst Mech Eng Part C J Mech Eng Sci [Internet]. 2021 Aug 2;236(6):2995–3003. Available from: https://doi.org/10.1177/09544062211035796

34. Gupta N, Priya S, Islam R, Ricci W. Characterization of mechanical and electrical properties of epoxy-glass microballoon syntactic composites. Ferroelectrics. 2006;345(1):1–12.

35. Gupta N, Ye R, Porfiri M. Comparison of tensile and compressive characteristics of vinyl ester/glass microballoon syntactic foams. Compos Part B Eng. 2010;41(3):236–45.

36. Ahmadi H, Liaghat G, Charandabi SC. High velocity impact on composite sandwich panels with nano-reinforced syntactic foam core. Thin-Walled Struct. 2020;148:106599.

37. Ebrahimnezhad-Khaljiri H, Eslami-Farsani R, Talebi S. Investigating the High Velocity Impact Behavior of the Laminated Composites of Aluminum/Jute Fibers- Epoxy Containing Nanoclay Particles. Fibers Polym. 2020;21(11):2607–13.

38. Nasirzadeh R, Sabet AR. Study of foam density variations in composite sandwich panels under high velocity impact loading. Int J Impact Eng. 2014 Jan 1;63:129–39.