Scientia cum Industria

PLATINUM OPEN ACCESS

eISSN 2318-5279

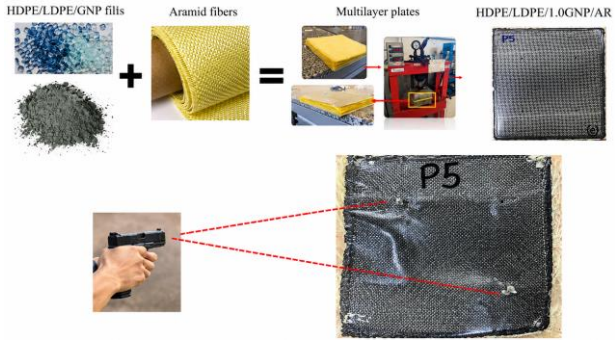
*Original Research*

# Mechanical and ballistic performance of multilayer aramid laminates with nanofiller-reinforced HDPE/LDPE films

**Danieli Dallé**[1]
**Lídia Kunz Lazzari**[1*]
**Cleide Borsoi**[2]
**Heitor Ornaghi Junior**[1]
**Lilian Vanessa Rossa Beltrami**[1]
**Ademir José Zattera**[1]

[1] Universidade de Caxias do Sul, Caxias do Sul-RS, Brazil.
[2] Universidade do Vale do Taquari, Lageado-RS, Brazil.
* Corresponding author: lidia_lazzari@yahoo.com.br

Received: January 15, 2026
Revised: October 13, 2026
Accepted: October 14, 2026
Published: November 3, 2026




**Abstract:** The increasing demand for lightweight and efficient ballistic protection systems has motivated polymer-based composites combining high impact resistance. In this study, nanostructured high-density polyethylene (HDPE) and low-density polyethylene (LDPE) films containing cellulose nanofibers (CNF), graphene nanoplatelets (GNP), or organoclay (CLAY), were produced by melt extrusion and combined with aramid fabric (AR) to manufacture multilayer composite plates through hot compression molding. The composites were characterized by Split Hopkinson Pressure Bar (SHPB) dynamic compression tests, ballistic impact tests following NIJ 0101.06 and NBR 15000 standards, backface deformation measurements, and tensile, flexural, and impact tests. Among the evaluated formulations, the composite containing 1.0 wt.% CNF exhibited the best overall mechanical performance under dynamic loading, showing higher stress, toughness, and energy absorption than the reference material. No plate was perforated and all backface deformations (22.2–29.1 mm) were below 44 mm, meeting the Level III-A criteria under the conditions adopted, although three formulations were impacted above the velocity tolerance (a more severe condition). The GNP and CLAY formulations exhibited the lowest backface deformation after ballistic impact, indicating enhanced energy dissipation. The results show that nanostructured HDPE/LDPE films reinforced with suitable nanofillers, particularly CNF, are promising for multilayer ballistic protection systems.

**Keywords:** Nanofillers, cellulose nanofibers, aramid fabric, ballistic protection, multilayer plate.

## Introduction

Lightweight ballistic protection requires composite systems that combine low areal density with efficient impact-energy dissipation. Aramid fabrics are widely used because of their high specific strength, but their cost motivates hybrid designs incorporating lower-cost thermoplastics such as high-density polyethylene (HDPE) and low-density polyethylene (LDPE) [1–9]. Multilayer architectures can distribute impact loads across the fabric and interlayer matrix. Nanofillers may further modify stress transfer and damage evolution: cellulose nanofibers (CNF) offer a renewable, high-aspect-ratio reinforcement, whereas graphene nanoplatelets (GNP) and organoclay (CLAY) provide platelet morphologies that can affect matrix deformation and energy dissipation [10–15]. Although nanofillers have been investigated in polymer composites and aramid-based armor, the use of CNF-reinforced thermoplastic films as interlayers in multilayer ballistic laminates remains insufficiently explored. This study therefore compares HDPE/LDPE films containing CNF, CLAY, or GNP, with and without a coupling agent (CA), in aramid laminates subjected to quasi-static mechanical, Split Hopkinson Pressure Bar (SHPB), and ballistic tests.

## Experimental Section

### Materials

The increasing demand for lightweight and efficient ballistic protection systems has motivated polymer-based composites combining high impact resistance, low weight, and lower cost. In this study, nanostructured high-density polyethylene (HDPE) and low-density polyethylene (LDPE) films containing cellulose nanofibers (CNF), graphene nanoplatelets (GNP), or organoclay (CLAY), were produced by melt extrusion and combined with aramid fabric (AR) to manufacture multilayer composite plates through hot compression molding. The composites were characterized by Split Hopkinson Pressure Bar (SHPB) dynamic

© The author(s) 2026. This is an open access article published under the terms and conditions of the *Creative Commons Attribution International License*, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author(s) and source are credited. The author(s) granted the publication rights to *Scientia cum Industria*.

compression tests, ballistic impact tests following NIJ 0101.06 and NBR 15000 standards, backface deformation measurements, and tensile, flexural, and impact tests. Among the evaluated formulations, the composite containing 1.0 wt.% CNF exhibited the best overall mechanical performance under dynamic loading, showing higher stress, toughness, and energy absorption than the reference material. No plate was perforated and all backface deformations (22.2–29.1 mm) were below 44 mm, meeting the Level III-A criteria under the conditions adopted, although three formulations were impacted above the velocity tolerance (a more severe condition). The GNP and CLAY formulations exhibited the lowest backface deformation after ballistic impact, indicating enhanced energy dissipation. The results show that nanostructured HDPE/LDPE films reinforced with suitable nanofillers, particularly CNF, are promising for multilayer ballistic protection systems.

### Methods

The production of the nanostructured polymeric films and multilayer composite plates consisted of four sequential stages: (i) production of cellulose nanofibers, (ii) preparation of the LDPE/CNF masterbatch, (iii) extrusion of nanostructured HDPE/LDPE films, and (iv) manufacture of multilayer composite plates by hot compression molding. All steps are described in the supplementary material, as are the characterizations performed. Table 1 presents the nomenclature and composition of the samples.

**Table 1.** Nomenclature and composition of the polymeric films and multilayer plates.

| | Polymeric films | | | | | | Multilayer plates | |
|---|---|---|---|---|---|---|---|---|
| **Sample** | CNF % (m/m) | CLAY % (m/m) | GNP % (m/m) | CA % (m/m) | LDPE % (m/m) | HDPE % (m/m) | No. layers of aramid fabric | N° layers of film |
| HDPE / LDPE | - | - | - | - | 14.0 | 86.0 | - | - |
| HDPE / LDPE / 0.5CNF | 0.5 | - | - | - | 13.5 | 86.0 | - | - |
| HDPE / LDPE / 1.0CNF | 1.0 | - | - | - | 13.0 | 86.0 | - | - |
| HDPE / LDPE / 1.5CNF | 1.5 | - | - | - | 12.5 | 86.0 | - | - |
| HDPE / LDPE / AR | - | - | - | - | 14.0 | 86.0 | 20 | 21 (interspersed 0/90°) |
| HDPE / LDPE / CA/AR | - | - | - | 2.0 | 14.0 | 84.0 | | |
| HDPE / LDPE /0.5CNF / AR | 0.5 | - | - | - | 13.5 | 86.0 | | |
| HDPE / LDPE / 1.0CNF / AR | 1.0 | - | - | - | 13.0 | 86.0 | | |
| HDPE / LDPE / 1.0CNF / CA / AR | 1.0 | - | - | 2.0 | 13.0 | 84.0 | | |
| HDPE / LDPE / 1.5CNF / AR | 1.5 | - | - | - | 12.5 | 86.0 | | |
| HDPE / LDPE / 1.0CLAY / CA / AR | - | 1.0 | - | 2.0 | 13.0 | 84.0 | | |
| HDPE / LDPE / 1.0GNP / AR | - | - | 1.0 | - | 13.0 | 86.0 | | |

## Results and Discussion

### Multilayer plates with HDPE/LDPE/CNF films

Figure 1a–d shows the true stress–strain curves obtained from the SHPB tests for the multilayer composites with different CNF contents. All laminates exhibited a similar mechanical response under dynamic compression, characterized by an initial elastic region followed by progressive strain hardening until reaching the maximum compressive stress. After the peak stress, strain softening was observed for all formulations, indicating the onset of damage accumulation and progressive degradation of the laminate structure during high strain-rate loading.

Among the evaluated formulations, the laminate containing 1.0 wt.% CNF exhibited the highest maximum compressive stress, while also sustaining higher strain levels before the onset of failure compared with the other CNF concentrations. In contrast, the laminate containing 0.5 wt.% CNF showed a lower peak stress than the reference HDPE/LDPE/AR laminate (35.70 vs. 49.04 MPa, Table 3), whereas increasing the CNF content to 1.5 wt.% did not result in additional gains in dynamic mechanical performance (48.04 MPa). These results suggest the existence of an optimum nanofiller concentration capable of maximizing the reinforcing effect under high strain-rate loading.

The non-monotonic response suggests an optimum CNF content. At 1.0 wt.% CNF, the laminate combined higher compressive stress and toughness; higher loading did not provide further gains. Possible effects of dispersion and agglomeration are interpretations, as no microstructural characterization was performed [11,14].

The 1.0 wt.% CNF laminate also showed the largest area under the stress–strain curve, indicating greater energy absorption under dynamic compression.

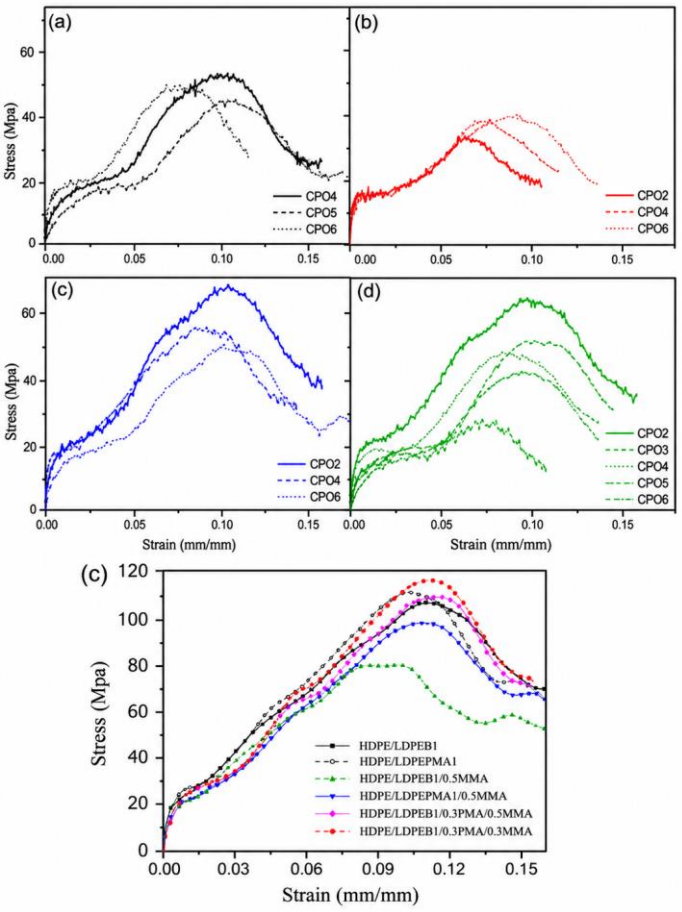
These SHPB results support selecting 1.0 wt.% CNF for comparison with CLAY and GNP, although the distinct test conditions used for the two series preclude direct comparison of their absolute stress values.

Table 2 summarizes the average SHPB properties (total deformation, toughness, maximum compressive stress, and strain at maximum stress) and the quasi-static tensile, flexural, and Charpy impact properties of the CNF-series laminates.

The incorporation of cellulose nanofibers influenced the dynamic mechanical response of the multilayer laminates, with different behaviors depending on the CNF content. Among the evaluated formulations, the laminate containing 1.0 wt. % CNF presented the highest average values of total deformation, toughness, and maximum compressive stress (6.67%, 41.04%, and 22.43% higher than the reference, respectively), whereas the laminate containing 0.5 wt. % CNF exhibited the lowest average

values for these properties. The laminate containing 1.5 wt. % CNF showed intermediate behavior, with average values lower than those obtained for the 1.0 wt.% CNF laminate. As no statistical test was applied to the SHPB data, these differences are discussed in terms of mean values, considering the larger scatter of the 1.0 and 1.5 wt.% CNF laminates.

**Figure 1.** True stress–strain curves of multilayer plates made with HDPE/LDPE/CNF films and aramid fabric in the SHPB test (a) HDPE/LDPE/AR, (b) HDPE/LDPE/0.5CNF/AR, (c) HDPE/LDPE/1.0CNF/AR, (d) HDPE/LDPE/1.5CNF/AR, and (e) multilayer plates made with nanostructured HDPE/LDPE films (CNF, CLAY and GNP) with and without coupling agent and aramid fabric in the SHPB test. Specimen diameter: 14 mm (a–d) and 12 mm (e).




The strain at maximum stress of the 1.0 wt.% CNF laminate (≈ 0.097) was similar to that of the reference (≈ 0.095), whereas the 0.5 wt.% CNF laminate showed a lower value (≈ 0.071), indicating that the incorporation of 1.0 wt. % CNF did not reduce the deformation capacity of the composite while increasing the average maximum stress and toughness. Overall, these results indicate that the incorporation of 1.0 wt. % CNF provided the most balanced average dynamic mechanical response among the formulations evaluated under the conditions adopted in this study [14]. Table 3 presents the impact velocity, backface deformation (DP), and penetration results of all multilayer plates.

**Table 2.** Average SHPB, quasi-static mechanical, and impact properties of the multilayer plates with HDPE/LDPE/CNF films (mean ± standard deviation; SHPB: six specimens tested per formulation; tensile, flexural, and Charpy: n = 5). Sample names abbreviated: all plates are HDPE/LDPE/…/AR.

| Property | AR (reference) | 0.5CNF/ AR | 1.0CNF/ AR | 1.5CNF/ AR |
|---|---|---|---|---|
| SHPB total deformation (mm/mm) | 0.15 ± 0.03 | 0.11 ± 0.02 | 0.16 ± 0.03 | 0.13 ± 0.02 |
| SHPB toughness (MJ/m³) | 4.41 ± 0.67 | 2.69 ± 0.59 | 6.22 ± 0.78 | 4.30 ± 1.71 |
| SHPB max. compressive stress (MPa) | 49.04 ± 3.57 | 35.70 ± 3.30 | 60.04 ± 9.57 | 48.04 ± 13.28 |
| SHPB strain at max. stress (mm/mm) | 0.095 ± 0.012 | 0.071 ± 0.011 | 0.097 ± 0.009 | 0.087 ± 0.011 |
| Tensile strength (MPa) | 79 ± 5 | 83 ± 10 | 66 ± 3 | 73 ± 15 |
| Flexural strength (MPa) | 19.9 ± 1.5 | 19.7 ± 1.5 | 23.0 ± 1.8 | 22.5 ± 1.7 |
| Maximum flexural strain (%) | 5.52 ± 0.40 | 5.66 ± 0.42 | 5.29 ± 0.40 | 5.59 ± 0.45 |
| Flexural modulus (MPa) | 2590 ± 470 | 1650 ± 400 | 2690 ± 690 | 2460 ± 810 |
| Charpy impact strength (kJ/m²) | 66.0 ± 1.0 | 68.3 ± 1.0 | 72.1 ± 4.0 | 78.7 ± 2.5 |

**Table 3.** Impact velocity, backface deformation (DP), penetration result, and Level III-A assessment of the multilayer plates.

| Sample | Impact velocity (m/s) | DP (mm) | Result / Level III-A criteria |
|---|---|---|---|
| HDPE/LDPE/AR | 436.28 ± 3.13 | 25.50 ± 1.88 | PP – criteria met |
| HDPE/LDPE/CA/AR | 466.52 ± 3.22* | 25.78 | |
| HDPE/LDPE/0.5CNF /AR | 435.01 ± 3.09 | 25.50 ± 2.28 | |
| HDPE/LDPE/1.0CNF /CA/AR | 418.17 ± 4.08 | 29.07 | |
| HDPE/LDPE/1.0CNF /AR | 437.78 ± 2.60 | 26.15 ± 1.24 | |
| HDPE/LDPE/1.5CNF /AR | 440.88 ± 1.56 | 25.90 ± 0.87 | |
| HDPE/LDPE/1.0CLAY/CA/AR | 480.20 ± 1.65* | 22.54 | |
| HDPE/LDPE/1.0GNP /AR | 481.31 ± 5.28* | 22.19 | |

* Impact velocity above the upper tolerance of NBR 15000-2 Level III-A (426 ± 15 m/s, i.e., 411–441 m/s); for the 8.0 g projectile, these shots correspond to kinetic energies of 871–927 J, i.e., ≈ 20–28% higher than the nominal 726 J. Velocities are means ± SD of the valid shots, each measured by two optical barriers 1 m apart; the velocity is set by the propellant charge of the ammunition and cannot be adjusted shot by shot. PP = partial penetration (no perforation). Level III-A criteria: no complete perforation and DP ≤ 44 mm [24]. DP values reported without SD correspond to a single valid DP measurement.

As shown in Table 3, five formulations (HDPE/LDPE/AR, HDPE/LDPE/0.5CNF/AR, HDPE/LDPE/1.0CNF/AR, HDPE/LDPE/1.5CNF/AR, and HDPE/LDPE/1.0CNF/CA/AR) were impacted within the Level III-A velocity tolerance of NBR 15000-2 (426 ± 15 m/s, i.e., 411–441 m/s). The other three formulations (HDPE/LDPE/CA/AR, HDPE/LDPE/1.0CLAY/CA/AR, and HDPE/LDPE/1.0GNP/AR) were impacted at 466.52, 480.20, and 481.31 m/s, respectively, i.e., above the upper tolerance limit, which, for the 8.0 g projectile, corresponds to kinetic energies of 871, 922, and 927 J, approximately 20–28% higher than the nominal 726 J. In all cases, only partial penetration (PP) occurred, and the DP values (22.19–29.07 mm) remained below the 44 mm limit [24]. Because a shot that exceeds the upper velocity tolerance without perforating the plate represents a more severe condition than that required by the standard, these over-velocity shots were considered valid for assessing resistance to penetration. The higher velocities of these three formulations do not result from a different test setup, but from the shot-to-shot dispersion inherent to the ammunition, whose velocity is fixed by the propellant charge and cannot be adjusted at the time of firing (Section 2.3.2); however, their DP values are not strictly comparable with those of the other formulations, since they were obtained at a higher impact energy. Considering also the limited number of impacts per plate (two to four, whereas NBR 15000-2 requires five per panel), the results indicate that all laminates met the Level III-A penetration and backface-deformation criteria under the conditions adopted, rather than constituting a formal Level III-A certification.

Within the CNF series, which was tested at comparable velocities (435.01–440.88 m/s), DP varied only from 25.50 to 26.15 mm, indicating that the CNF content had no significant effect on backface deformation (one-way ANOVA, $\alpha = 0.05$: $F = 0.15 < F_{crit} = 3.49$; $p = 0.93$; Supplementary Table S1). The backface deformation in the clay represents the transfer of impact energy that the human body would absorb if the material were used as body protection (ballistic vests and helmets).

The tensile and flexural properties of the CNF-series laminates are also summarized in Table 3. The incorporation of CNF affected the mechanical response of the composites, although the influence depended on both the nanofiller content and the loading mode.

Regarding the maximum tensile strength (Table 2), the laminate containing 0.5 wt. % CNF exhibited the highest average value among the evaluated formulations, corresponding to an increase of approximately 5.6% compared with the reference laminate (HDPE/LDPE/AR). However, this difference lies within the experimental scatter (83 ± 10 vs. 79 ± 5 MPa). Conversely, the laminate containing 1.0 wt.% CNF presented the lowest average tensile strength, while the laminate containing 1.5 wt.% CNF exhibited intermediate behavior. These results indicate that the incorporation of CNF affected the tensile response of the multilayer system, although the effect was not proportional to the nanofiller concentration. Similar behavior has been reported for polyethylene-based nanocomposites, where the reinforcing effect depends on the balance between filler content and the efficiency of stress transfer within the polymer matrix [14].

The flexural strength results (Table 2) showed a different trend from that observed in tension. While the laminates containing 0 wt.% and 0.5 wt.% CNF exhibited similar average values, the laminates reinforced with 1.0 wt.% and 1.5 wt.% CNF presented higher average flexural strengths, corresponding to increases of approximately 15.5% and 12.9%, respectively, relative to the reference laminate. This behavior suggests that the incorporation of higher CNF contents may have contributed more effectively to resisting bending loads, which involve simultaneous tensile and compressive stresses through the laminate thickness.

The maximum flexural deformation (Table 2) showed only small variations among the formulations, with average values ranging from 5.29% to 5.66%. The relatively small differences indicate that the incorporation of CNF did not substantially alter the deformation capacity of the multilayer laminates under flexural loading.

Similarly, the flexural modulus (Table 3) was not increased by CNF addition. The laminate containing 0.5 wt.% CNF presented the lowest average modulus (≈ 36% lower than the reference), whereas the laminates containing 1.0 wt.% and 1.5 wt.% CNF showed values comparable to that of the reference laminate. Overall, these results suggest that the incorporation of CNF had a greater influence on flexural strength than on laminate stiffness.

The different trends observed between the tensile and flexural tests indicate that the effect of CNF depends on the loading condition. This may be associated with the distinct stress distribution generated during each mechanical test, as tensile loading produces a more uniform stress field, whereas bending subjects the laminate simultaneously to tensile and compressive stresses. Similar differences in mechanical response under different loading modes have been reported for polymer nanocomposites reinforced with cellulose nanofibers [14].

The Charpy impact strength of the CNF-series laminates is also given in Table 3. A progressive increase in impact resistance was observed with increasing CNF content, corresponding to gains of approximately 3.5%, 9.2%, and 19.3% for the laminates containing 0.5 wt.%, 1.0 wt.%, and 1.5 wt.% CNF, respectively, compared with the reference laminate. The higher average impact resistance indicates an increased capacity for dissipating impact energy, which is an important characteristic for multilayer composites intended for ballistic protection. Cellulose nanofibers have been reported to promote stress redistribution and delay crack propagation in thermoplastic matrices [11].

Although the laminates containing different CNF concentrations exhibited distinct responses depending on the mechanical test, the formulation containing 1.0 wt.% CNF, despite its lower tensile strength, showed the most balanced dynamic mechanical behavior when the tensile, flexural, impact, and SHPB results were considered together. In particular, this formulation presented the highest average toughness and maximum compressive stress under high strain-rate loading, while also exhibiting increased flexural strength and improved impact resistance. Considering that ballistic protection involves dynamic loading conditions [7], the 1.0 wt.% CNF formulation was selected for the subsequent comparison with the other

nanofillers (organoclay and graphene nanoplatelets), both incorporated at the same concentration (1.0 wt.%).

### Multilayer plates with CNF, CLAY, and GNP films, with and without coupling agent

Figure. 1e shows the stress (MPa) versus strain (mm/mm) results from the SHPB test of multilayer plates made with nanostructured HDPE/LDPE films, with and without the addition of a coupling agent. These tests were performed with specimens of 12 mm in diameter, which provided the most adequate dynamic response for this series, and with the striker bar accelerated at 15 psi.

According to the data, higher maximum stress values than the reference were observed for the laminates containing CLAY and GNP, whereas the HDPE/LDPE/CA/AR laminate showed a comparable peak stress. In contrast, the laminates reinforced with CNF showed lower maximum stresses, particularly the formulation without coupling agent (HDPE/LDPE/1.0CNF/AR), which also exhibited a distinct stress–strain profile. Among all formulations, the HDPE/LDPE/1.0GNP/AR laminate presented the highest stress values, followed by HDPE/LDPE/1.0CLAY/CA/AR. It should be noted that the lower peak stress of HDPE/LDPE/1.0CNF/AR in this series (≈ 80 vs. ≈ 108 MPa for the reference) contrasts with Section 3.1, in which the same formulation showed the highest peak stress (Table 3). This difference is attributed to the different test conditions of the two series (14 mm specimens and striker pressure of 20 psi for the CNF series vs. 12 mm and 15 psi for the nanofiller series), which change the strain rate and the stress state; therefore, absolute values from Fig. 1a–d and Fig. 1e should not be compared directly.

The differences observed among the formulations suggest that the dynamic mechanical response depends not only on the nanofiller type but also on the presence of the coupling agent. Graphene nanoplatelets and organoclays have been reported to improve stress transfer and energy dissipation owing to their high aspect ratio and platelet morphology, whereas coupling agents may enhance the interaction between polymeric phases. The higher average compressive stresses observed for the GNP- and clay-containing laminates are consistent with reinforcing mechanisms described in previous studies [12, 13]. It should be noted, however, that the CLAY laminate contained the coupling agent whereas the GNP laminate did not; therefore, the comparison between these two nanofillers is not fully independent of the effect of the coupling agent.

As discussed in Section 3.1, all laminates of this series exhibited only partial penetration (Table 2); however, the HDPE/LDPE/CA/AR, HDPE/LDPE/1.0CLAY/CA/AR, and HDPE/LDPE/1.0GNP/AR laminates were impacted above the upper velocity tolerance of Level III-A.

The HDPE/LDPE/1.0CLAY/CA/AR and HDPE/LDPE/1.0GNP/AR laminates were impacted at average velocities of 480.20 and 481.31 m $s^{-1}$, respectively, corresponding to values 12.7% and 13.0% higher than the nominal velocity (426 m/s) and approximately 9% above the upper tolerance limit (441 m/s), i.e., about 27–28% more kinetic energy than at the nominal velocity.

Supplementary Figure. S2 shows the front faces of the multilayer plates before and after the ballistic test. No images are available for the HDPE/LDPE/1.0CNF/AR plate.

The HDPE/LDPE/AR laminate was impacted four times, whereas the remaining laminates were impacted twice because the plate dimensions (200 × 200 mm) limited the number of valid shots per specimen. Visual inspection (Supplementary Fig. S2) revealed different deformation patterns among the formulations. The laminates containing organoclay and graphene nanoplatelets exhibited larger deformation areas on the front face while producing lower indentation depths in the backing clay. In contrast, the HDPE/LDPE/1.0CNF/CA/AR laminate showed a smaller visible frontal deformation but a greater DP value. These observations suggest that the CLAY- and GNP-reinforced laminates absorbed a larger fraction of the projectile energy within the composite structure before transferring it to the backing material, in agreement with the ballistic results.

Table 4 presents the tensile, flexural, and Charpy impact properties of the laminates with different nanofillers, with and without coupling agent. None of the modified laminates exceeded the tensile strength of the reference (≈ 79 MPa): the HDPE/LDPE/1.0CLAY/CA/AR laminate showed a comparable value (≈ 79 MPa), whereas the incorporation of CNF without coupling agent (HDPE/LDPE/1.0CNF/AR) reduced it by approximately 16% (≈ 66 MPa). The incorporation of CNF with coupling agent (HDPE/LDPE/1.0CNF/CA/AR) and GNP (HDPE/LDPE/1.0GNP/AR) did not provide a significant increase in the maximum tensile strength of the plates. The different responses observed among the nanofillers indicate that their reinforcing efficiency depends on their morphology and interaction with the polymer matrix. Previous studies have reported that platelet-shaped nanofillers, such as graphene nanoplatelets and nanoclays, can improve stress transfer and restrict polymer chain mobility more effectively than fibrous nanofillers under tensile loading [12–14, 16].

**Table 4.** Tensile, flexural, and Charpy impact properties of the multilayer plates with different nanofillers, with and without coupling agent (mean ± standard deviation, n = 5). Sample names abbreviated: all plates are HDPE/LDPE/…/AR.

| | (ref.) | AR | F/ AR | / CA/ AR | Y/ CA/ AR | P/ AR |
|---|---|---|---|---|---|---|
| Tensile strength (MPa) | 79 ± 5 | 71 ± 5 | 66 ± 3 | 74 ± 10 | 79 ± 9 | 72 ± 11 |
| Flexural strength (MPa) | 19.9 ± 1.5 | 23.8 ± 1.4 | 23.0 ± 1.8 | 22.6 ± 1.7 | 22.7 ± 1.4 | 23.9 ± 1.1 |
| Maximum flexural strain (%) | 5.52 ± 0.40 | 5.52 ± 0.50 | 5.29 ± 0.40 | 5.36 ± 0.30 | 5.35 ± 0.30 | 5.12 ± 0.35 |
| Flexural modulus (MPa) | 2590 ± 470 | 4380 ± 950 | 2690 ± 690 | 3730 ± 550 | 3060 ± 1000 | 3740 ± 700 |
| Charpy impact strength (kJ/m²) | 66.0 ± 1.0 | 93.7 ± 2.5 | 72.1 ± 4.0 | 96.4 ± 1.0 | 83.8 ± 0.5 | 83.8 ± 1.0 |

Values obtained from the original data plots.

Regarding the flexural properties (Table 4), all modified laminates exhibited higher flexural strength than the reference laminate (22.6–23.9 vs. 19.90 MPa), corresponding to increases of approximately 13–20%, with similar values among them. This result is consistent with Section 3.1, in which the HDPE/LDPE/1.0CNF/AR laminate showed a 15.45% increase in flexural strength. In contrast, the maximum flexural strain was practically unaffected by the incorporation of nanofillers or coupling agent, ranging from 5.1% to 5.5%. The flexural modulus increased by 69% for HDPE/LDPE/CA/AR, 44% for HDPE/LDPE/1.0CNF/CA/AR and HDPE/LDPE/1.0GNP/AR, and 18% for HDPE/LDPE/1.0CLAY/CA/AR, relative to the reference laminate. Since the coupling agent alone produced the largest stiffness gain and the CNF laminate without coupling agent showed no increase (≈ 2690 MPa), the higher modulus can be attributed mainly to the coupling agent rather than to the nanofillers.

Unlike tensile loading, flexural loading simultaneously subjects the laminate to tensile and compressive stresses through its thickness. Therefore, the similar flexural strengths observed among the modified formulations suggest that the incorporation of nanofillers appeared to have a greater influence on dynamic loading conditions than on quasi-static flexural behavior. Similar trends have been reported for polyethylene-based nanocomposites reinforced with nanofillers, where improvements under impact and high strain-rate loading are generally more pronounced than under conventional flexural tests [3].

The Charpy impact results are also given in Table 4. The impact strength increased for all modified laminates, being more significant for the HDPE/LDPE/CA/AR and HDPE/LDPE/1.0CNF/CA/AR samples, with 42 and 46% increases in relation to the HDPE/LDPE/AR sample, respectively. Plates incorporating CLAY and GNP present a 27% increase in impact resistance compared to HDPE/LDPE/AR. As the coupling agent alone increased the impact strength by 42%, compared with 9% for CNF without coupling agent, improved adhesion between the polymer films and the aramid fabric appears to have contributed more than the nanofillers themselves. The increase in impact resistance observed for all nanofiller-containing laminates indicates that nanoscale reinforcement contributed to improving the energy absorption capability of the multilayer system. Previous studies have shown that nanofillers may delay crack propagation, promote stress redistribution, and increase resistance to localized deformation during impact loading [12, 13].

Overall, the results indicate that the incorporation of nanofillers modified the mechanical response of the multilayer laminates according to the morphology and nature of each reinforcement. While cellulose nanofibers promoted a balanced response under dynamic loading, graphene nanoplatelets and organoclay exhibited superior ballistic performance, characterized by lower indentation depths, even at higher impact velocities, and higher resistance under SHPB loading. These findings are consistent with previous reports suggesting that different nanofillers may activate distinct energy dissipation mechanisms within multilayer polymeric composites. The combined analysis of SHPB, impact, tensile, flexural, and ballistic tests provide evidence that nanofiller selection plays an important role in optimizing the mechanical performance of HDPE/LDPE–aramid multilayer systems [3, 16].

### Comparison with Previous Studies on Nanofiller-Reinforced Multilayer Composites

Prior studies show that ballistic response depends on strain rate, inter-yarn friction, fiber pull-out, matrix deformation, and damage evolution rather than static strength alone [17–20]. The present results are consistent with this view: 1.0 wt.% CNF gave the best dynamic response within the CNF series, whereas GNP and CLAY produced the lowest backface deformation, including under higher-than-target impact velocities. Because the SHPB strain rate was not determined and impact counts were limited, these comparisons should be interpreted as trends rather than definitive rankings.

## Conclusions

This study evaluated multilayer aramid laminates using HDPE/LDPE films containing CNF, CLAY, or GNP. Within the CNF series, 1.0 wt.% CNF provided the best overall dynamic response, with the highest average compressive stress and toughness. CNF also increased flexural strength and Charpy impact resistance, although tensile strength did not improve consistently.

All tested plates resisted complete perforation, and measured backface deformations were 22.19–29.07 mm, below the 44 mm criterion. However, three formulations were impacted above the specified velocity tolerance and the number of impacts per plate was below the standard requirement; therefore, the results demonstrate performance under the conditions tested, not formal Level III-A certification.

GNP- and CLAY-containing laminates exhibited the lowest backface deformation and higher dynamic compressive stresses. The coupling agent, rather than nanofiller addition alone, was associated with the largest increases in flexural modulus (up to 69%) and Charpy impact strength (up to 46%).

Overall, nanofiller type and interlayer formulation affected energy dissipation differently: CNF favored dynamic mechanical performance, while GNP and CLAY favored lower backface deformation. Limitations include the limited ballistic shots, undetermined SHPB strain rate, and absence of direct morphological characterization; future work should address these points.

## Acknowledgments

No funding was received.

### Authors' Contribution

D. Dallé: Conceptualization, Methodology, Writing - original draft, formal analysis, investigation; L. K. Lazzari: Writing – original draft, Investigtion; C. Borsoi: Writing – review and

editing, Supervision, Methodology; H. Ornaghi júnior: Writing – review and editing, Investigation; L. V. R. Beltrami: Writing – review and editing, Investigation: A. J. Zattera: Conceptualization, Resources, Writing – review and editing, Supervision, Project administration. All authors have approved the final version of the manuscript.

**Conflicts of interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Supplementary Material

Supplementary materialassociated with this article can be found online at: https://doi.org/10.18226/23185279.e261603.

## References


[1] M. S. Selim, S. A. El-Safty, M. A. Shenashen, A. Elmarakbi. Advances in polymer/inorganic nanocomposite fabrics for lightweight and high-strength armor and ballistic-proof materials. *Chemical Engineering Journal*, vol 493, pp. 152422, 2024. DOI: 10.1016/j.cej.2024.152422

[2] A. Biradar, S. Arulvel, J. Kandasamy. Significance of ballistic parameters and nanohybridization in the development of textile-based body armor: A review. *International Journal of Impact Engineering*, vol 180, pp. 104700, 2023. DOI: 10.1016/j.ijimpeng.2023.104700

[3] H. Barhoumi, N. Bhouri, I. Feki, A. Baffoun, M. Hamdaoui, S. B. Abdessalem. Review of ballistic protection materials: properties and performances. *Journal of Reinforced Plastics and Composites*, vol 42, pp. 685–699, 2023. DOI: 10.1177/07316844221137920

[4] I. Rubio, B. Valverde-Marcos, J. A. Loya, M. H. Miguélez. From low velocity to real ammo impact behaviour of advanced aramid and UHMWPE composites. *Thin-Walled Structures*, vol 216, pp. 113715, 2025. DOI: 10.1016/j.tws.2025.113715

[5] A. Joshi, A. Mishra, V. K. Saxena. Impact response and energy absorption mechanisms of UHMWPE fabric and composites in ballistic applications: a comprehensive review. Composites Part A: Applied Science and Manufacturing, vol 184, pp. 108314, 2024. DOI: 10.1016/j.compositesa.2024.108314

[6] M. A. Abtew, F. Boussu, P. Bruniaux, C. Loghin, I. Cristian. Ballistic impact mechanisms – A review on textiles and fibre-reinforced composites impact responses. *Composites Structures,* v. 223, pp. 110966, 2019. DOI: 10.1016/j.compstruct.2019.110966

[7] K. Rana, Z. Sajid, A. H. Baluch, P. Spatenka. Aramid fibre composites for ballistic impact protection: a mechanistic review of recent advances. *Applied Composite Materials*, vol 33, pp. 103, 2026. DOI: 10.1007/s10443-026-10485-y

[8] S. B. Sapozhnikov, O. A. Kudryavtsev, M. V. Zhikharev. Fragment ballistic performance of homogenous and hybrid thermoplastic composites. *International Journal of Impact Engineering, v. 81, pp. 8-16,* 2015. DOI: 10.1016/j.ijimpeng.2015.03.004

[9] F. O. Braga, L. T. Bolzan, F. S. Da Luz, P. H. L. M. Lopes, E. P. Lima Jr., S. N. Monteiro. High energy ballistic and fracture comparison between multilayered armor systems using non-woven curaua fabric composites and aramid laminates. *Journal of Materials Research Technology,* v. 6, pp. 417-422, 2017. DOI: 10.1016/j.jmrt.2017.08.001

[10] S. D. Salman, Z. Leman, M. T. H. Sultan, M. R. Ishak, F. Cardona. Effect of kenaf fibers on trauma penetration depth and ballistic impact resistance for laminated composites. *Textile Research Journal, v. 87, pp. 2051-2065,* 2017. DOI: 10.1177/0040517516663155

[11] S. A. Jose, N. Cowan, M. Davidson, G. Godina, I. Smith, J. Xin, P. L. Menezes. A comprehensive review on cellulose nanofibers, nanomaterials, and composites: manufacturing, properties, and applications. *Nanomaterials*, vol 15, pp. 356, 2025. DOI: doi.org/10.3390/nano15050356

[12] E. Dias, H. Chalse, S. Mutha, Y. Mundhe, N. Ambhore, A. Kulkarni, A. Mache. Review on synthetic/natural fibers polymer composite filled with nanoclay and their mechanical performance. *Materials Today: Proceedings*, vol 77, pp. 916-925, 2023. DOI: 10.1016/j.matpr.2022.12.059

[13] L. Mandal, B. Verma, P. K. Patel. Review on polymer nanocomposite for ballistic & aerospace applications. *Materials Today: Proceedings,* v. 26, pp. 3161-3166, 2020. DOI: 10.1016/j.matpr.2020.02.652

[14] B. Gayretli, R. Shanthar, T. T. Opoz, C. Abeykoon. Mechanical properties of LDPE and PS polymer matrix composites reinforced with GNP and CF – A critical review. International Journal of Lightweight Materials and Manufacture, vol 7, pp. 572-596, 2024. DOI: 10.1016/j.ijlmm.2024.03.005

[15] B. S. Butola, A. Majumdar, A. Jain, G. Kaur. Multilayered flexible uni-polymer and hybrid composites for ballistic applications. *Fibers and Polymers,* v. 18, pp. 786–794, 2017. DOI: 10.1007/s12221-017-6959-4

[16] Md. Syduzzaman, S. E. Chowdhury, N. M. Pritha, A. Hassan, S. Hossain. Natural fiber reinforced polymer composites for ballistic protection: design, performance, and challenges. *Results in Materials*, vol 24, pp. 100639, 2024. DOI: 10.1016/j.rinma.2024.100639

[17] A. Lavoratti, L. C. Scienza, A. J. Zattera. Dynamic-mechanical and thermomechanical properties of cellulose nanofiber/polyester resin composites. *Carbohydrate Polymers,* v. 136, pp. 955–963, 2016. DOI: 10.1016/j.carbpol.2015.10.008

[18] M. Zanini, A. Lavoratti, L. K. Lazzari, D. Galioto, M. Pagnocelli, C. Baldasso, A. J. Zattera. Producing aerogels from silanized cellulose nanofiber suspension. *Cellulose,* v. 24, pp. 769–779, 2017. DOI: 10.1007/s10570-016-1142-4

[19] B. T. Tessari, N. Vargas, R.R. Dias, I. M. Pereira, L. V. R. Beltrami, A. Lavoratti, M. Poletto, A. J. Zattera. Influence of the addition of graphene nanoplatelets on the ballistic properties of HDPE/aramid multi-laminar composites. *Polymer-Plastics Technology and Materials*, v. 61, pp. 363-373, 2022. DOI: 10.1080/25740881.2021.1988966

[20] M. Bajya, A. Majumdar, B. S. Butola, S. Arora, D. Bhattacharjee. Ballistic performance and failure modes of woven and unidirectional fabric based soft armour panels. *Composites Structures,* v. 255, pp. 112941, 2021. DOI: 10.1016/j.compstruct.2020.112941