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Research article

Energy absorption of densified veneer-aramid hybrid composites subjected to ballistic impact

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ABSTRACT

Densified wood technology improves the wood properties such as strength, surface hardness, dimensional stability, and durability. However, the utilization of laminated veneer as densified wood which is used as an armor material, and its ability to absorb ballistic energy has not been researched. The strengthening of the Teak Platinum veneer, which was densified with a hot press, used pre-treatment methods such as partial delignification and self-assembly of bacteria cellulose using *Acetobacter xylinum.* This research used hybrid and non-hybrid panels. The hybrid panel used epoxy adhesive to combine the laminated aramid fabric and 2 types of densified veneer laminated. Two types of densified veneers consist of the densified veneer with and without stabilizing resin. A ballistic test was carried out on each sample at a distance of 5 m using 9 mm Luger ammunition according to NIJ 0108.01. The ballistic energy absorption was analyzed based on the difference between the initial velocity and the residual velocity of the projectile. The initial velocity and the residual velocity were measured by the chronograph. This result showed that the performance of the hybrid panels was lower than the non-hybrid panels at the same thickness. However, the hybrid panels using aramid and veneer ratio of 2:1 (by volume) and the configuring of fully aramid fabric on the inside was the best combination with a ballistic energy absorption of 78.64% at 354.70 J.

1. Introduction

The ability of defense equipment to counteract the threat of weapons is growing rapidly in the military industry. The safety of soldiers as users should be a top priority. The system of protection (armor) from the threat of weapon projectiles is the most needed thing in the conditions of armed conflict. These protection systems are the armor on combat vehicles and body armor. The armor on combat vehicles is made of high-strength metal and an additional layer of armor. It protects the personnel from fragments that are caused by projectile impacts. Soft body armor and hard body armor are the two types of personnel body armor. Soft body armor is intended for protection against low-to medium-energy projectiles. Meanwhile, hard body armor is designed for protection against high-level energy projectiles, which are usually combined with soft body armor. Medvedovski introduced multi-layer body armor, which consists of three major components [1]. A front layer breaks the projectile and dissipates its impact energy. It is usually made from a ceramic plate. Then an intermediate layer absorbs the energy and catches the fragments, which are made of synthetic fibers. The last, the back layer for trauma absorption, is made of a special ceramic-polymer. In several studies, aluminum alloy with a thickness of 5 mm was also used as a back layer in the multilayer armor system (MAS) with good performance [2, 3, 4, 5]

The material that is used as a component of the protective to absorb the bullet energy is synthetic fibers such as nylon, aramid, and ultra-high molecular weight polyethylene (UHMWPE). Aramid fiber, or Kevlar®, is more commonly used as a protective component. The advantage of using aramid fiber is that it is very strong and has a better strength-to-weight ratio and flexibility than metallic materials [6]. In addition, aramid fiber has good resistance to high temperatures. Therefore, people like to use synthetic fibers rather than metallic materials. However, aramid fiber also has the disadvantage that it is more sensitive to ultraviolet (UV) and has a low affinity for water. Aramid fiber has the highest production cost of any material [3, 7]. However, researchers are still looking for ways to combine aramid with other materials to make it more flexible and better able to stop bullets of different size [8].

In recent decades, some researchers have been interested in substituting synthetic materials with natural ones [9]. Because of the environmental awareness, renewable nature, and limited resources of

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synthetic fibers, researchers are investigating natural materials as light ballistic resistance in a hybrid composite. Hybrid composites made by mixing two or more types of materials can provide combined advantages, such as the strength gained from each component while reducing less desirable qualities. The energy absorption of natural-based laminated composites depends not only on how strong they are, but also on how well they can absorb and spread out the projectile's kinetic energy [10]. The hydrophilic nature of plant fibers is due to the hydroxyl groups present in the cellulose content. Reducing the cellulose content will give the fibers a tough, rough surface, which is important for absorbing and dissipating the kinetic energy of projectiles [11].

A polymer-based natural fiber composite is a type of hybrid composite that has the potential to be tested for ballistics. Early studies on the behavior of natural fiber polymer composites against ballistic impact have been carried out on flax, hemp, and jute fibers using the hot press compression molding method [12]. Similar studies have been carried out on multi-fiber reinforced epoxy matrix composites and polyester using some fibers or natural fabric. They have also been tested by the Brazilian Army Evaluation Center (CAEx) as the second layer in the structure MAS. Polymer composites with reinforcement of natural fiber have good performance as middle layers in hybrid structures. The protective panels made from the polymer composite are lighter, cheaper, and more environmentally friendly than those made from synthetic fibers [2].

In addition to natural fibers, a ballistic study has recently been carried out on natural wood, which has increased its mechanical strength through the compaction process. Based on ballistic tests using wind guns, the ballistic energy absorption on the densified wood increased seven times more than on natural wood [13]. The densified wood was produced by the partial delignification process, and it was followed by a heat stress process. This process caused the cell wall to collapse, and then wood densification occurred with the joining of cellulose fibers. The result showed that the wood was stronger than the metal alloy. It was supported by the formation of hydrogen bonds between the cellulose fibers [14]. The release of water molecules in the wood structure during the drying process and the compaction process affected the mechanical properties and morphological characteristics of cellulose fibers. Thermo-hydromechanical treatment (THM) is a wood modification technique using a combination of temperature, humidity, and mechanical action. This technique was used to improve the mechanical properties of wood in order to produce densified wood with the desired shape and function. This process was more environmentally friendly, consumes little energy, and does not lose the intrinsic properties of natural wood. The results of THM treatments showed that the wood characteristics, such as dimensional stability, strength, surface hardness, and durability, could be improved [15].

Qiu and Netravali observed that acetic acid bacteria obtained bacterial cellulose, which would coat natural fibers to form a cellulose pellicle as additional reinforcement [16]. The strong interaction between plant cellulose and bacterial cellulose was constructed by hydrogen bonds between the cellulose molecular chains [17]. Furthermore, the presence of bacterial cellulose through natural fibers strengthened the surface bond between natural fibers and the polymer matrix, which was previously known to be extremely weak [18]. Because bacterial cellulose products can be degraded in the soil for 5–6 weeks, making them environmentally friendly [19]. We previously reported the ability of cellulose bacteria to penetrate the wood pores and the interaction of cellulose bacteria with fibers to form hydrogen bonds in the veneer [20, 21]. This process involved the self-assembly of bacterial cellulose in situ in a culture medium by *Acetobacter xylinum* in the veneer fibers. It was divided into 2 stages: the partial delignification process and the hot pressing process. As a result, the veneer's tensile mechanical strength and modulus of elasticity increased significantly.

Cellulose is very easily bound to water content because it has free hydroxyl groups and not all hydroxyl groups interact to form hydrogen bonds. This is a disadvantage of densified wood; the strength of the wood reduces as its dimensions expand over time in humid environments. This problem can be solved by using resin impregnated into the wood to stabilize it. To penetrate the wood pores, a stabilizing resin with low viscosity and high vacuum strength is required. The main component of stabilizing resin is hydroxypropyl methacrylate, a polar monomer that can improve the dimensional stability of wood [22]. This clear liquid resin is easy to polymerize, dissolves in water, alcohol, acetone, and other organic solvents, and has no color [23]. It also easily enters the accession reaction with a wide range of organic and inorganic substances.

Based on the literature study, there were limited studies on the ballistic capabilities of the modified wood-based materials. Furthermore, there has not been any study on the utilization of reinforced wood as a substitute for aramid. Considering the potential strength of the bacterial cellulose-reinforced densified veneer, we conducted testing and analysis on the hybridization effect of BC densified veneer and aramid on the ballistic impact of the composite panel. This research focuses on the performance of ballistic energy absorption by panels based on NIJ 0108.01 Ballistic Resistant Protective Materials. Ballistic energy absorption is the lost energy that is analyzed by measuring the initial velocity and residual velocity of the bullet on the penetrated composite panel. This study also provides a failure mode analysis from the visual image of damage due to ballistic impact.

2. Materials and methods

2.1. Materials

This study used a Platinum Teak veneer with an average thickness of 2.3 mm, and it was 15 years old. It was from the research garden of the Research Center for Biomaterials–BRIN, Cibinong, West Java, Indonesia. The log of Platinum teak with a diameter of 33–40 cm and a length of 120 cm was cut using a Rotary Slicer machine. Then the veneer was cut into 16 × 16 cm. After that, it was partially delignified using a 1 M NaOH solution at 90 °C for 90 min. After the delignification process, it was washed to remove the residual NaOH solution. Then it was soaked in the water for 3 days, and the water was changed every 8 h. After the veneer was cleaned, it was continued by the bacterial cellulose self-assembly process in situ in the culture media. This study used the *Acetobacter xylinum* starter, which was in liquid form. It was bought from the Biotechno Store Collection in Banten, Indonesia.

As a hybrid composite, we used aramid woven with an areal weight of 240 g/m^2 and a thickness of 0.26 mm. It was purchased from Sunshine Carbon Fiber Products Store in Haining, China. This study also used two types of resin as the composite matrix. They were hydroxypropyl methacrylate (Stick Fast®) based stabilizing resins and epoxy of the diglycidyl ether of bisphenol A (DGEBA) or Bisphenol-A Epoxy Resin. It is an epoxy resin designed for general use as an adhesive between layers. The resin is divided into two parts: resin and hardener (P*olyaminoamide*). Since these resins are mixed, they expedite the hardening and drying process. This commercial grade epoxy resin (SK®) was purchased from PT Megah Abadi Kimia in Banten, Indonesia.

2.2. Bacterial cellulose self-assembly

Bacteria culture media consisted of 5% white sugar, 1% acetic acid, and 0.1% urea for 1 L of coconut water. All the ingredients were boiled on low heat for 15 min. First, the clean veneer is put in a sterile container. Second, bacterial culture media solution in hot condition was poured into a sterile container until the veneer was completely submerged. Third, the container was covered with paper. It was to prevent contamination with outside air. After the solution temperature reached 30 °C, 10 mL of *Acetobacter xylinum* was added to the medium solution. In situ bacterial cellulose self-assembly was carried out during a 7-day fermentation period, and then the hybrid veneers could be harvested. During the fermentation process, the cellulose bacteria would enter and assemble the cellulose pellicle in the cracks and pores of the veneer, as shown in Figure 1a.

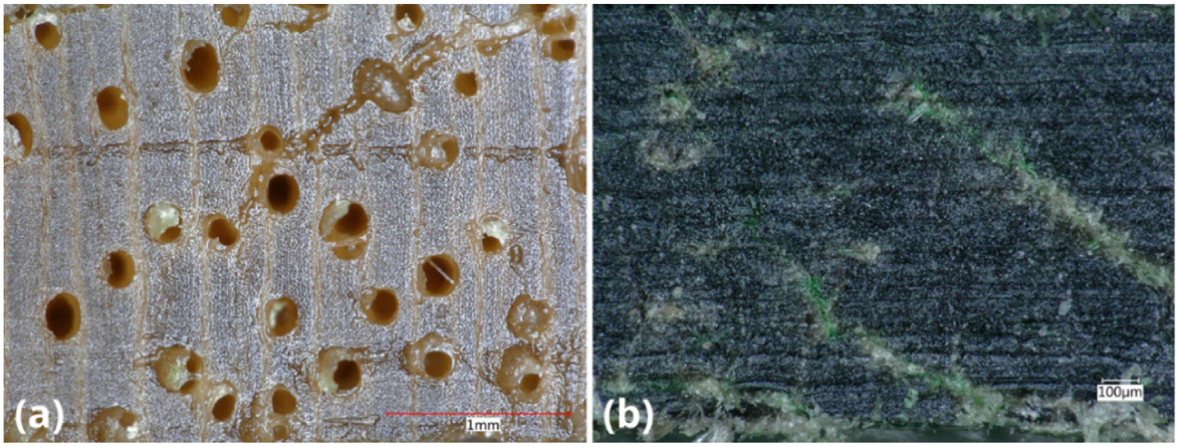

Figure 1. Microscopic observation of cross-sectional veneers with a microtome (a) After in situ self-adhesion-bacterial cellulose entered the veneer pores (b) After compaction and impregnation with stabilizing resin, green coloring pigment was observed as evidence of resin.

2.3. Densified and stabilization of veneer

The self-assembly veneer bacteria cellulose (BC) was densified using a hot press with an initial moisture content of 30–35%. The veneer was densified at a temperature of 135 °C in two stages. The first stage was 5 MPa for 30 min, and the second stage was 10 MPa for 30 min. These processes produced a densified veneer that was not damaged and had a density of 1.18–1.23 g/cm^3. After the veneers were densified, they were stabilized with hydroxypropyl methacrylate. This process uses an impregnation process in a tube with a vacuum pressure of 50 cm Hg for 30 min. Then, they were given high-pressure using a compressor for 60 min. After the impregnation process, the veneer was wrapped in aluminum foil and put into an oven at 95 °C for 1 h. This was to harden the resin. Through this process, the resin entrained the veneers and stabilized the densified veneer, as shown in Figure 1b.

2.4. Target panel production

The target panel was made of layers of densified veneers arranged crosswise and bonded with epoxy. The veneers are arranged crosswise. This method aimed to cover the weaknesses of the wood, which were fragile and easy to crack in the direction of the fiber. The target of panels in this study is 10 mm in thickness, while the thickness of the veneers produced in this study was 1.3–1.6 mm. Therefore, we need 6 layers for 1 panel. The veneers were coated with epoxy adhesive using the hand lay-up technique. The ratio of resin to hardener was 1:1. Next, the panel was pressed with a cold pressure of 1 MPa on the Teflon-coated plate for 24 h or until the resin hardened completely. Last, the panel was cut to a 15 × 15 cm square.

In this study, hybridization of densified veneer and aramid fiber as the composite panels was produced in various configurations. The first configuration used densified veneer BC and non-BC with and without resin st abilizer. In the second configuration, the volume ratios of aramid and densified veneer were 1:2 and 2:1. It was determined from the average thickness measurement that one veneer was equivalent to five sheets of epoxy-coated aramid fabric. The third configuration was a hybrid panel with two arrangements of veneers. Firstly, the veneer was on the outside and the aramid was on the inside, and second, the veneer was on the inside and the aramid was on the outside, as shown in Figure 2. For comparison, we made a panel using plain epoxy and aramid-epoxy. The panels with plain epoxy were made using a Teflon-coated mold for easy removal, whereas the panels with aramid-epoxy consisted of 30 layers of aramid fabric. Each configuration of the panels produced five samples. The specifications and configurations of the panels are presented in Table 1.

2.5. Ballistic testing

The ballistics test was conducted at the shooting range of Korps Brimob POLRI, Kedung Halang, Bogor, West Java, Indonesia. The ballistic test setup is according to standard NIJ 0108.01 as illustrated in Figure 3. All panels tested were 15 × 15 cm in size, and each type of panel consisted of five samples in one shot. In this test, we used a SIG MPX *submachine gun*, caliber 9 × 19 mm. Moreover, it was equipped with a shooting rest and a laser sight. In addition, we used 124 full metal jackets, and the bullet weighed 8.035 g. The shooting distance from the gun barrel to the target panel was 5 m.

In this test, we used 2 units of the chronograph portable model Prochrono LTD. This unit was to measure the velocity of a bullet. The distance between each chronograph and the target panel was 1.5 m at the front and back of the panel. Initial energy (E_i), residual energy (E_r),

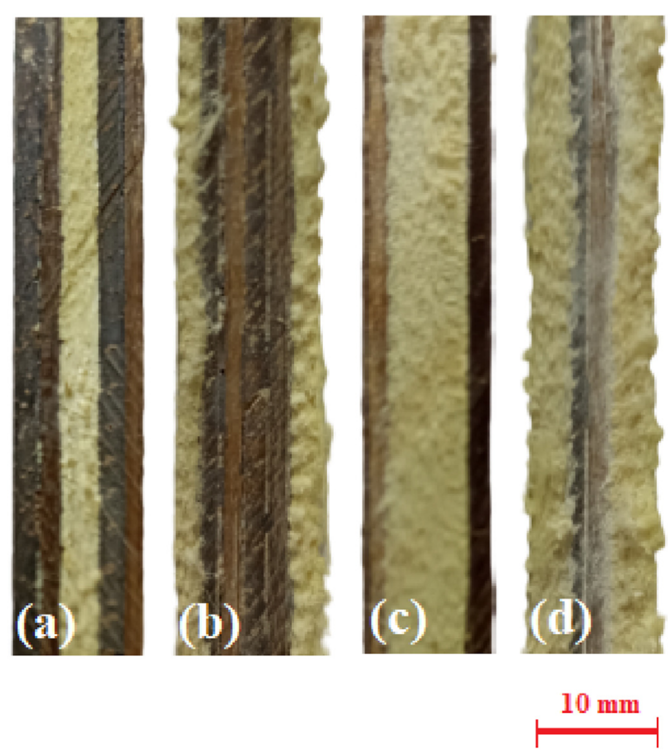

Figure 2. Configuration of densified veneer-aramid hybrid composites (a)VAV1 (b)AVA1 (c)VAV2 (d)AVA2.

Table 1. The specification and material configuration on the panels.

Sample	Panel types	Stabilizing Resin	Layering sequences V = veneer, A = aramid (Number of layers)	Ratio volume (aramid: veneer)	Thickness (mm)	Weight (g)
PE	Plain epoxy	-	-	-	11.40	256.96
AE	Aramid–epoxy	-	A (30)	-	10.44	269.18
DV	Densified veneer non BC–epoxy	No	V (6)	-	11.01	216.47
DV-BC	Densified veneer BC–epoxy	No	V (6)	-	12.06	254.74
VAV1	Densified veneer BC–Aramid–epoxy	No	V–A–V (2–10–2)	1:2	10.44	235.61
AVA1	Densified veneer BC–Aramid–epoxy	No	A–V–A (5–4–5)	1:2	11.42	241.09
VAV2	Densified veneer BC–Aramid–epoxy	No	V–A–V (1–20–1)	2:1	10.39	252.74
AVA2	Densified veneer BC–Aramid–epoxy	No	A–V–A (10–2–10)	2:1	10.60	251.40
SDV	Densified veneer non BC–epoxy	Yes	V (6)	-	9.19	234.01
SDV-BC	Densified veneer BC–epoxy	Yes	V (6)	-	9.54	255.88
S-VAV1	Densified veneer BC–Aramid–epoxy	Yes	V–A–V (2–10–2)	1:2	9.08	238.61
S-AVA1	Densified veneer BC–Aramid–epoxy	Yes	A–V–A (5–4–5)	1:2	10.75	234.75
S-VAV2	Densified veneer BC–Aramid–epoxy	Yes	V–A–V (1–20–1)	2:1	8.27	218.68
S-AVA2	Densified veneer BC–Aramid–epoxy	Yes	A–V–A (10–2–10)	2:1	9.30	218.26

energy absorbed (ΔE_{abs}), and percentage of energy absorbed ($\%E_{abs}$) were calculated according to Eq. (1), (2), (3), and (4), respectively. This equation is based on the bullet's initial velocity (Vi) before hitting the target and the residual velocity (Vr) after hitting the target.

$$E_i(J) = 1/2\, m\, V_i^2 \tag{1}$$

$$E_r(J) = 1/2\, m\, V_r^2 \tag{2}$$

$$\Delta E_{abs}(J) = 1\,/\,2\, m\, \left(V_i^2 - V_r^2\right) \tag{3}$$

$$\%E_{abs} = (\Delta E_{abs}\,/\,E_i) \times 100 \tag{4}$$

The hybridization effect was determined by comparing the energy absorption between hybrid and non-hybrid panels [24, 25]. Because of the small thickness variation in the panels, the specific energy absorption (Specific E_{abs}) was obtained by normalizing the results of ballistic energy absorption with the area density in each panel [26]. The specific energy absorption was calculated according to Eq. (5). The percentage of specific energy absorption (Specific $\%E_{abs}$) is calculated according to Eq. (6) based on the absorption of hybrid and non-hybrid specific energy (E_h and E_a).

$$Specific\ E_{abs}\ \left(Jm^2\,/\,kg\right) = \ (\Delta E_{abs})\,/\,(areal\ density) \tag{5}$$

$$Specific\ \%E_{abs} = \frac{(E_h - E_a)}{E_a} x\,100 \tag{6}$$

After the ballistic testing, the panels analyzed the damage by taking digital images. The cross-section of the panels was cut crosswise to evaluate the response and failure modes in hybrid and non-hybrid panels to the ballistic impact of 9 mm FMJ.

3. Results and discussion

This study used a 9 mm submachine gun (SMG) for ballistic testing at type III-A based on NIJ 0108.01. The specifications of the bullets, such as the type, size, and weight of the required bullets, had fulfilled the requirements, but the velocity of the bullet, about 426 ± 15 m/s, was not fulfilled. The velocities of bullets during testing were 320.04–343.81 m/s. These velocities belong to the lower velocity range of 9 mm, which means that the mean velocity is 332 ± 12 m/s. This velocity is incorporated into type II-A for the same type of ammunition. This is due to the limitations of the quality of ammunition used or the shorter barrel length of the SMG MPX, which is only 16.5 cm short of the recommended barrel length for type III-A of 24–26 cm. On shorter gun barrels, the bullet will leave the barrel before it is pressed to its full pressure and it will move with lower velocity.

3.1. Ballistic energy absorption

The ballistic test data for the energy absorption from various types of panel laminates are shown in Table 2. The average initial velocity measured by the chronograph was 335.05 m/s with a standard deviation of 6.65 m/s. This initial velocity was acceptable for ballistic testing at level II-A with the same type of ammunition. As a comparison, the mean initial velocity was used to create the same initial conditions for all samples [26]. From the results of ballistic testing, almost all panels were penetrated, and there was complete penetration after an impact with a bullet 9 mm. Due to the impact of a bullet, some samples of plain epoxy (PE) were destroyed because of the brittle nature of the epoxy. The average ballistic energy absorption on plain epoxy panels was quite large; it reached 45.09%. However, these panels had limitations, such as being used once and not providing protection for a second shot. The exception was for samples with a composition of all aramid fabric with epoxy (AE). These panels could absorb 100% of the ballistic energy, so they only experienced partial penetration.

In non-hybrid samples with laminated densified veneer, it showed that the ballistic energy absorption of the panels with densified veneer-BC (DV-BC) was 3.5% higher than the non-BC (DV). When the result was compared statistically, the t-value was 2.353 and the p-value was 0.046. Therefore, the result was significantly different at a probability of 0.05. This indicated that the modified veneer with BC assembly treatment contributed to providing additional reinforcement to the densified veneer to absorb the impact energy. Meanwhile, for the hybrid samples, it showed that the more aramid arrangement in the panel provided greater energy absorption capability. This has been estimated because the tensile strength of aramid fiber is around 3000 MPa. It is stronger than the tensile strength of BC-densified veneer, which is about 140–190 MPa [21]. However, the BC-densified veneer with epoxy-reinforced laminate contributed to the absorption of ballistic energy in the hybrid panel. In addition, the contribution of BC-densified veneer laminated was more visible in the hybrid panel with a veneer configuration on the outside and an aramid layer on the inside (VAV). The outside veneer restrained the aramid-epoxy layer and kept the panel solid on the inside with an intact number of layers in ration and undivided. When the bullet is impacted, the aramid-epoxy layers on the inside will be weak in resisting impact energy. Therefore, the delamination happened.

The ballistic energy absorption of the non-hybrid panels with stabilized densified veneer was better than the non-hybrid panels without stabilized densified veneer. It can be seen that the ballistic energy absorption of the stabilized densified veneer (SDV-BC) was 3.59% greater than the non-BC (SDV). When the result was compared statistically, the t-value was 2.326 and the p-value was 0.048. Therefore, the result was

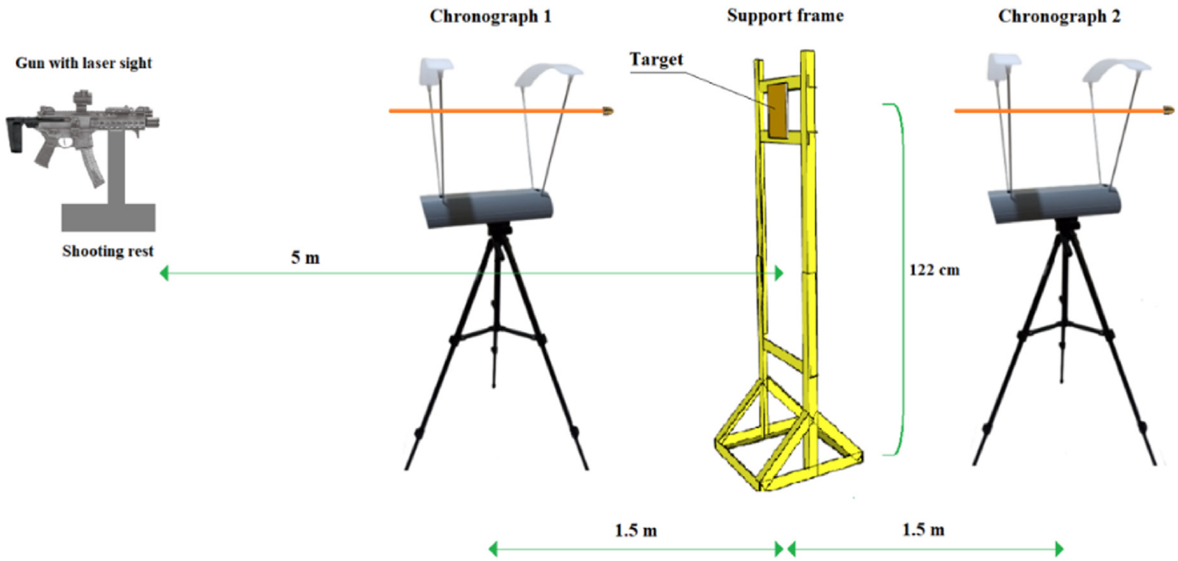

Figure 3. A graphical illustration of the ballistic test setup.

significantly different at a probability of 0.05. This showed that the BC in the stabilized densified veneer contributed to strengthening the veneer to withstand impact energy. In some hybrid panels, the stabilized densified veneer had almost the same pattern as without stabilization, but it had a different energy absorption value. As in the hybrid panel arrangement, the ballistic energy absorption of the veneer on the outside and the aramid layer on the inside (S-VAV) was better than the veneer on the inside and the aramid layer on the outside (S-AVA).

However, in the hybrid panels with a higher aramid ratio of 2:1, the ballistic energy absorption of the stabilized BC-densified veneers (S-VAV2 and S-AVA2) was lower than the BC-densified veneers without stabilization (VAV2 and AVA2). This could be due to poor adhesion between the hardened methacrylate resin on the veneer surface and the epoxy, especially in the layer between the aramid fabric laminated to the veneer. This indication could be seen from the outer layer of veneer that was delaminated and damaged in the middle until it was detached. Different conditions were found in the hybrid panel with BC-densified veneer without resin stabilization. The resilience and the bonding were better. Table 2 shows the result of the comparison of the panels. It could be seen that the highest ballistic energy absorption of 100% was in the non-hybrid panel with full laminated aramid-epoxy (AE). Especially for the hybrid panel, which has good performance in the VAV2 with a percentage absorption energy of 78.64%–354.70 J. This was better than the 10 mm thick full aramid laminated. It was glued with polychloroprene that was tested by Nascimento et al. with an energy absorption of 51.55% at 221.20 J [27]. Furthermore, the energy absorption capacity of ballistic panels is greater than that of kenaf-kevlar composites, which provide an energy absorption capacity of less than 200 J [25].

3.2. Effect of areal density on the energy absorption

The ability of ballistic energy absorption was influenced by areal density, and the areal density depended on the weight and volume of the sample. Meanwhile, the volume represented by the thickness of the panels depends on the configuration of the material and the composition. Epoxy hardening time during manual hand production indirectly affected the final result, including the thickness of the panels. Table 1 presents the thickness and weight of the panels for each sample. It shows that utilization of densified veneer caused the sample to be thicker, as well as that the thickness of the BC veneer was greater than the non-BC veneer. Furthermore, BC has a tendency to bind moisture around it, resulting in set recovery. The thickness of the panel samples was found to be less than that of the stabilized BC solid veneer samples, indicating that there was no set recovery.

Table 2. The ballistic energy absorption of various panel laminates.

Sample	V_i average (m/s)	E_i average (J)	V_r average (m/s)	E_r average (J)	ΔE_{abs} (J)	$\%E_{abs}$
PE	335.05	451.00	247.74	247.64	203.37	45.09
AE	335.05	451.00	-	-	451.00	100.00
DV	335.05	451.00	306.08	376.40	74.61	16.54
DV-BC	335.05	451.00	299.56	360.62	90.38	20.04
VAV1	335.05	451.00	293.40	346.33	104.67	23.21
AVA1	335.05	451.00	297.91	356.91	94.09	20.86
VAV2	335.05	451.00	154.53	96.30	354.70	78.64
AVA2	335.05	451.00	246.46	244.59	206.41	45.77
SDV	335.05	451.00	281.94	319.65	131.35	29.12
SDV-BC	335.05	451.00	274.69	303.50	147.50	32.71
S-VAV1	335.05	451.00	274.93	303.70	147.30	32.66
S-AVA1	335.05	451.00	277.61	309.73	141.27	31.32
S-VAV2	335.05	451.00	209.76	176.97	274.03	60.76
S-AVA2	335.05	451.00	255.54	262.57	188.43	41.78

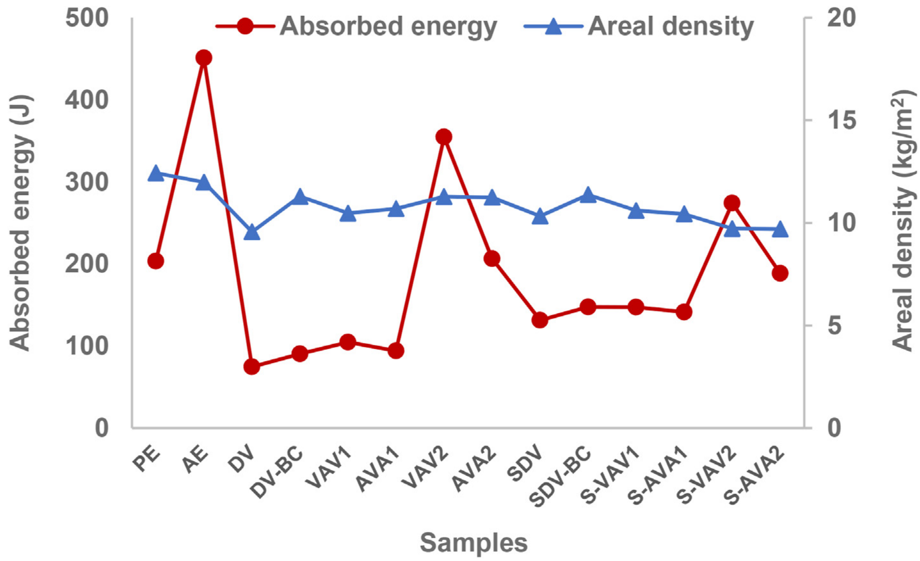

Figure 4. Relation between the absorbed energy and areal density.

Figure 4 shows the relationship between the absorbed energy and the areal density. It was known that the epoxy in the composite panel contributed a lot to increasing the areal density and played an important role in ballistic energy absorption. The utilization of epoxy and aramid fibers increased the areal density and strength of the aramid laminated in absorption energy. It could be seen in the non-hybrid panels, for example, in full-aramid epoxy and in hybrid panels with a higher ratio of aramid. Meanwhile, the utilization of densified veneer was lower in the epoxy absorption, and it caused a decrease in areal density and the ability of energy absorption. Although there was a slight increase in areal density and energy absorption after the densified veneer was stabilized with resin, its strength was lower than aramid fibers, which absorbed more epoxy.

3.3. Hybridization effect on ballistic energy absorption

The specific energy absorption of each hybrid panel is shown in Figure 5. The specific energy absorption of hybrid panels was lower than that of non-hybrid panels, which used aramid and epoxy. The highest decrease in energy absorption ability was in the AVA 1 panel at −76.62%, and the lowest decrease in energy absorption ability was in the VAV2 panel at -16.47%. The use of a volume fraction of BC densified veneer resulted in a decrease in energy absorption ability. From these results, the volume fraction of densified veneer BC is as much as 33.33% (aramid and veneer volume ratio is 2:1) better at ballistic energy absorption.

3.4. Failure modes analyze

It is very important to know the failure modes after ballistic testing as an evaluation material for the development and performance improvement of composite armor in the future. Figure 6 shows the failure mode of non-hybrid samples. The non-hybrid sample of aramid and epoxy shown in Figure 6a was capable of retaining bullets up to the 14th layer. The bullets had changed shape, so the energy spread out and obstructed the bullet's rate of penetrating further. The impact surface showed a failure mode due to shear plugging, which caused the aramid fiber to be cut. While at the back, there was compression, stretching, and delamination of aramid fibers. In the non-hybrid samples with a laminated densified veneer as shown in Figure 6b, the bullets were able to break the panel. Moreover, there was compression damage on the impact surface and a fracture due to flexural tension on the back surface.

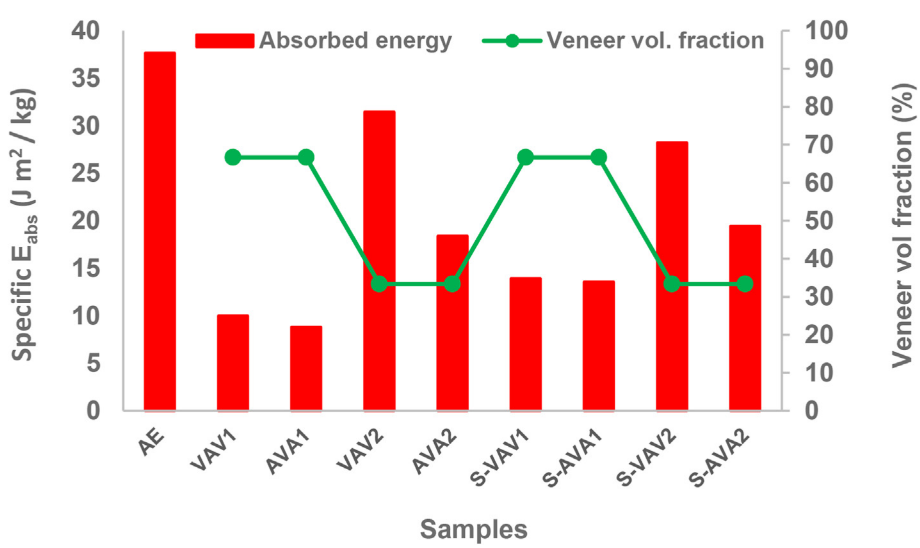

Figure 5. Specific energy absorption of the hybrid samples.

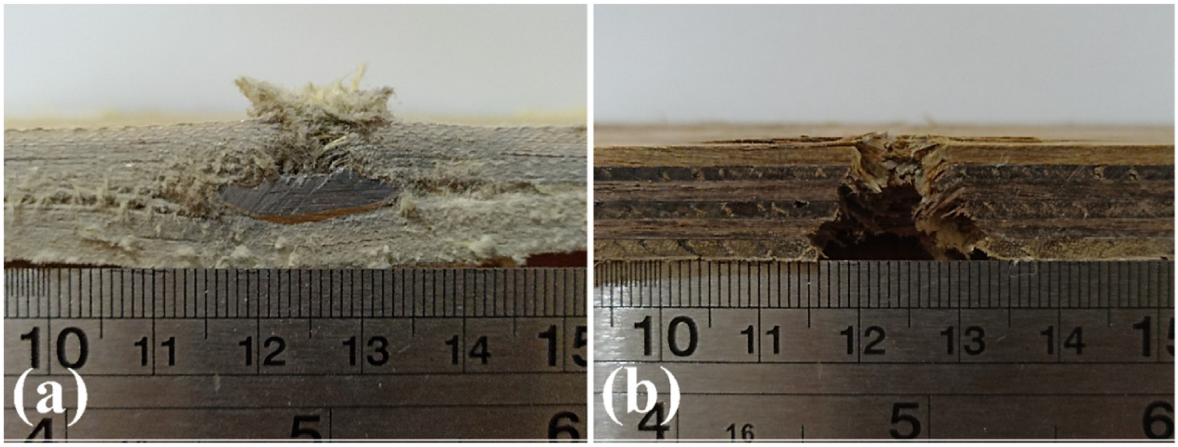

Figure 6. Failure modes of the non-hybrid sample (a) Sample AE (b) Sample DV (the direction of the bullet came from the top of the images).

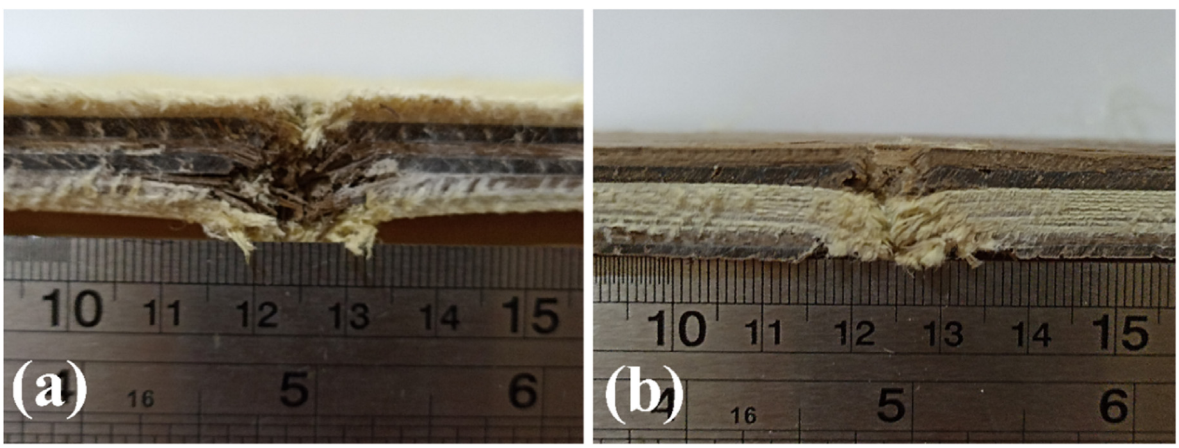

Figure 7. Failure modes of the hybrid sample (a) sample AVA (b) sample VAV (the direction of the bullet came from the top of the images).

Figure 7 shows the failure mode of the hybrid samples. The hybrid samples with a configuration of densified veneer on the inside and aramid on the outside (AVA) as shown in Figure 7a had not been able to restain the bullets, therefore the panel had perforated. This failure mode was caused by shear plugging of the aramid fibers on the impact surface, bending and delamination in the center of the densified veneer, and tensile failure of the aramid fibers on the back surface. Meanwhile, the hybrid samples (VAV) with a densified veneer on the outside and aramid on the inside had perforated, as shown in Figure 7b. The samples with mode compression failure had the failure occur on the impact surface of the densified veneer and delamination with the aramid layer. Shear and tensile failure of aramid fiber occurred in the middle, followed by a fracture due to flexural tension on the back surface. The failure of the hybrid panel occurred on densified veneer because the densified veneer was brittle and easy to split in the direction of fibers. In addition, these parts are the weakest in fiber.

4. Conclusion

Based on the results and the evaluation, several conclusions were obtained:

1. The non-hybrid panel with full aramid-epoxy (AE) absorbed 100% of the energy from a bullet at the highest energy level, 451.00 J.
2. Pre-treatment of bacterial cellulose (BC) on densified veneer contributes significantly to the absorption of ballistic energy in panels.
3. The effect of stabilizing resin on densified veneer enhances ballistic energy absorption at the same panel type for a larger volume of veneer fraction.
4. The best hybrid panel configuration is with a 2:1 aramid-to-veneer ratio and a layering sequence of veneer-aramid-veneer, which absorbs 78.64% of the ballistic energy at 354.70 J.
5. The failure of hybrid panels was caused by a combination of shear plugging of aramid fibers on the impact surface, bending, delamination, and tensile failure of aramid fibers on the back surface.

Declarations

Author contribution statement

Ananto Nugroho: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper. Triastuti: Performed the experiments; Wrote the paper. Sandi Sufiandi: Analyzed and interpreted the data. Anne Zulfia Syahrial: Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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