Research Article

Experimental Study on Drop-Weight Impact Response of Basalt Fiber Aluminum Laminates (BFMLs)

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The basalt fiber-reinforced polymer (epoxy resin), which has even better mechanical properties than glass fiber-reinforced polymer, is a good choice for making FML (fiber-metal laminate) composite. Herein, drop-weight impact tests of basalt fiber-based FMLs (called BFMLs) were conducted in the INSTON 9520HV testing machine to investigate the low-velocity impact properties of BFMLs. The specimens were of two diameters. And the impactors had two sizes of nose, dropping from different heights. The load-deflection behavior of aluminum sheet, BFRP (basalt fiber-reinforced polymer) panel, and BFML plate and their energy dissipation patterns during impact perforation were obtained. The test results showed that aluminum alloy sheet and BFMLs had no strain rate effect, while BFRP did. It was also concluded that the behavior of the thick BFML plate was clearly affected by debonding between aluminum sheet and BFRP panel, while the behavior of the thin BFML plate was controlled by membrane force. In failure analysis, it was found that the deformation and breakage of BFRP are the main contributions to energy absorption of BFMLs which counts for more than 75%. The energy absorbed by the aluminum sheet through plastic deformation and petaling is about 20%, while the energy absorbed in debonding can be ignored. In addition, with the help of ABAQUS simulation, it was found that decreasing the value of MVF (metal volume fraction) can increase the specific energy absorption of BFMLs, but the ductility of BFMLs may decrease.

1. Introduction

Fiber-metal laminates were firstly designed for aircraft structures [1, 2]. High-velocity impact events are the main problems that FMLs mostly faced in aviation industry [1, 3]. Along with the expansion of applications of FMLs to land transportation from aviation industry, low-velocity impact response of FMLs has been increasingly attracted attention since it quite often happens to vehicles on road [4–7].

Many researchers have studied low-velocity impact behavior of FMLs such as GLARE, ARALL, CARALL, and hybrid FMLs using two kinds of fibers and/or particular metals like magnesium and titanium [8, 9]. From those studies, people gain more understanding on how FMLs react to impacting events. Therein, delamination is the distinctive feature of FMLs during low-velocity impact. The deflection stiffness and energy absorption are closely related to delamination of FMLs, which also contributes to the complexity in analyzing mechanical behavior of FMLs [10, 11].

There are few articles discussing the fabrication of fiber-metal laminates [12], but it is the prerequisite step before conducting the experimental study. Surface treatment of the metal layer can have significant effects on the interlaminar properties and thus the overall properties of FMLs. Thus, Aghamohammadi et al. [13] investigated four different surface treatment methods on the aluminum layers and studied their effects on the flexural behavior of FMLs. The effect of metal layer distribution on FMLs was concerned by
Khan and Sharma [14, 15] in experimental and simulation ways. Norman Jones [16] made some theoretical predictions for the deformation and denting of fiber-metal laminates when subjected to low-velocity impact loads. The rigid plastic material approximation with modifications to reflect the actual cross section of a fiber-metal laminate was used to produce simple formulae which gave reasonable agreement with the corresponding experimental data.

However, of fibers applied in all types of FMLs, basalt fiber is rarely reported. Continuous basalt fiber has been widely used in automotive industry due to its superior mechanical properties in comparison to E-glass fiber, which can be seen in Table 1 [17]. In addition, basalt fiber has flame retardancy and is able to maintain high performance at high and low temperatures [18, 19]. Basalt fiber also has high abrasive and corrosive resistance, which can be used in the detrimental environment [20, 21]. Also, basalt fiber is nontoxic to human body [22].

Since basalt fiber has so many advantages, it is a potential substitute of glass fiber in FMLs’ fabrication that may be used in automobiles. Thus, basalt-based FMLs were studied in this paper.

2. Preparation of Specimens

2.1. Materials. 2A12-T4 aluminum alloy sheets with a thickness of 0.5 mm were supplied by Southwest Aluminum (Group) Co., Ltd (China). The basalt fiber-reinforced polymer (epoxy resin) with a thickness of 1.32 mm was supplied by Sichuan Aerospace Tyoxin Basalt Industrial Co., Ltd (China). The adhesive film made of modified polyethylene acrylate was supplied by Shanghai Zhenghuan Adhesive Product Co., Ltd (China). The chemical components and basic mechanical properties of 2A12-T4 aluminum alloy are listed in Table 2 and Table 3, whilst the parameters of continuous basalt fiber (CBF) and its composite are listed in Table 4. Table 5 gives material properties of BFRP.

2.2. Specimen Design. A simple methodology was used to prepare BFMLs, with five steps listed as follows:

(1) Materials were cut in the light of BFMLs’ size in order to avoid direct clipping on BFMLs which may introduce damage in interfaces between aluminum alloy sheet and BFRP layer.

(2) Surface treatment was applied to both materials so as to improve bonding quality when using adhesive film. Polishing (abrasion) on BFRP surface aimed at increasing roughness which is beneficial to bonding quality, while chemical cleaning, including alkali wash, acid cleaning, and phosphoric acid anodizing of aluminum alloy sheet, was also applied for the same purpose.

(3) Adhesive film (AF) was laid between aluminum alloy sheet and BFRP layer to make them initially bonded through hot-rolling to form semifinished product of BFMLs.

(4) Semifinished product of BFMLs was placed into moulds, with the applied pressure of 5 MPa and heat of 160°C, followed by a curing period of 60 minutes.

(5) The specimen was air-cooled.

3. Drop-Weight Impact Tests

The drop-weight tests were conducted in the INSTON 9520HV testing machine, as shown in Figure 1. The acceleration transducer was mounted in the drop hammer to record the history of acceleration. Optical grating was mounted at underpart of a stand column to record the initial impact velocity of the projectile. After once and twice integrals of acceleration, the history of velocity and displacement of the projectile can be obtained. The reaction force between the projectile and the BFML specimen can be calculated by Newton’s second law. Moreover, the history of load, energy, velocity, and deflection during impact can also be obtained.

Table 1: Mechanical properties of E-glass fiber and basalt fiber.

|                        | E-glass fiber | Basalt fiber |
|------------------------|---------------|--------------|
| Density (g/cm³)        | 2.56          | 2.8          |
| Elastic modulus (GPa)  | 76            | 89           |
| Tensile strength (GPa) | 1.4–2.5       | 2.8          |
| Elongation (%)         | 1.8–3.2       | 3.15         |
| Specific modulus (GPa*cm³/g) | 30          | 31.78        |
| Specific strength (GPa*cm³/g) | 0.5–1      | 1            |

Aluminum alloy sheet and BFRP and BFML plates were tested by drop-weight impact. The specimens were clamped between two square steel plates with a circular opening at the center, as shown in Figure 1. The opening of steel plates has two diameters, i.e., 70 mm and 100 mm. The projectile is of hemisphere with the diameters of 10 mm or 20 mm and masses of the projectile of 5,666 kg, 14,353 kg, or 17,493 kg. The heights of the drop weight were set as 0.36 m, 0.48 m, or 0.76 m.

4. Results and Discussion

4.1. Strain-Rate Effect. In most cases, stiffness and strength of a material may increase with strain rate. The strain-rate effect during impact on a composite plate has a contribution to enhancing the bending stiffness and/or strength. While, if the load-deflection curve of a material under impact is similar to that under static loading, there is no strain-rate effect for such dynamic loading.

In order to investigate the strain-rate effects of the aluminum alloy sheet, BFRP layer, and BFML plate, drop-weight impact tests were conducted on the three types of materials, and the test results of drop-weight impact are listed in Table 6.

4.1.1. 2A12-T4 Aluminum Alloy Sheet. According to Damith [23], aluminum alloy shows hardly any strain-rate effect when the strain rate is less than 800 s⁻¹. As the strain rate on the aluminum alloy sheet by a drop-weight impact in the
The present study is no more than 110 s⁻¹, the strain-rate effect on the 2A12-T4 aluminum alloy sheet was therefore ignored. Figure 2 shows the load-deflection curves of 2A12-T4 aluminum alloy sheets under drop-weight impact. It can be seen that, in moderate strain-rate regime, there was no significant difference between curves in the impact velocity regime of 2.63–3.70 m/s. As for the deviation of the static result from impact curves, difference of the corresponding global deflection may attribute to it. Response of the 2A12-T4 aluminum alloy sheet under static loading is always global, while that under impact loading gave rise to more localized indentation in the vicinity of the impact region so that the stiffness of 2A12-T4 aluminum alloy sheet bending under impact is somewhat higher than that under static loading during early stage, say, deflections less than 2 mm. Afterwards, the bending stiffness showed no difference between static and impact curves considering slope and peak load.

4.1.2. BFRP. The strain rate of the BFRP plate can be estimated by means of average impact velocity being divided by radius [24]. Although BFRP plates do show some strain-rate effect, such effect in the range of 25–97 s⁻¹ seems minimal, which almost covers the strain rate range in the present study, as shown in Figure 3. The bending stiffness and ultimate load carrying capacity of BFRP plates under impact are nearly twice of that under static loading. However, the peak load of BFRP plates under impact was independent of projectile’s diameter.

4.1.3. BFMLs. BFMLs showed no strain-rate effect. Similar to the 2A12 aluminum alloy sheet, localized indentation is responsible for the higher initial bending stiffness, which explains why the initial segment (where deflection is less than 2 mm) of the load-deflection curve of impact is steeper than that of static, as shown in Figure 4. Therefore, no strain-rate effect of BFMLs is considered in prediction of impact behavior of BFMLs plates in Section 4.2.

4.2. Loading-Deformation Relationship of BFML Plates. When the loading rate was not high, such as drop-weight impact, the analysis of dynamic behavior of structures may be converted to that of quasi-static process based on the modal analysis method [25].

2A12 aluminum alloy is an elastic-plastic ductile material, while BFRP is a linear elastic brittle material. In order to obtain analytical expressions for the load-deflection
response of BFMLs, 2A12 aluminum is idealized as a rigid plastic material with linear strain hardening and BFRP is idealized as a linear elastic material, as shown in Figure 5.

4.2.1. Thin Plate. The principle of minimum potential energy was applied to derive the load-deflection relation of thin BFML plates (type of 2/1 BFML plate).

Table 6: Test results of the drop-weight impact.

| Material Code | Peak load (kN) | Maximum Deflection (mm) | Impact velocity (m/s) | Radius of specimen (mm) | Strain rate (s\(^{-1}\)) |
|---------------|----------------|-------------------------|-----------------------|-------------------------|-------------------------|
| 20-Al-70-1\(^1\) | 3.41 | 6.95 | 2.630 | 35 | 75 |
| 20-Al-70-2 | 3.00 | 5.07 | 3.268 | 35 | 93 |
| 20-Al-100-1 | 3.31 | 8.50 | 1.644 | 50 | 33 |
| 20-Al-100-2 | 3.20 | 7.81 | 2.529 | 50 | 51 |
| 20-Al-100-3 | 4.22 | 10.35 | 2.654 | 50 | 53 |
| 20-FML2/1-70-1 | 6.92 | 5.24 | 3.542 | 35 | 101 |
| 20-FML2/1-100-2 | 8.78 | 9.56 | 3.229 | 50 | 65 |
| 20-FML3/2-70-1 | 7.22 | 4.18 | 3.309 | 35 | 95 |
| 20-FML3/2-100-3 | 13.14 | 8.89 | 3.117 | 50 | 62 |
| 20-BFRP-70-1 | 3.00 | 5.53 | 2.47 | 35 | 71 |
| 20-BFRP-70-2 | 3.37 | 5.85 | 3.328 | 35 | 95 |
| 20-BFRP-100-1 | 2.97 | 7.49 | 1.897 | 50 | 38 |
| 20-BFRP-100-2 | 3.46 | 8.90 | 2.244 | 50 | 45 |
| 20-BFRP-100-3 | 3.52 | 7.73 | 3.106 | 50 | 62 |
| 10-Al-70-1 | 2.35 | 4.99 | 3.686 | 35 | 105 |
| 10-Al-100-1 | 2.38 | 6.77 | 3.317 | 50 | 66 |
| 10-FML2/1-70-1 | 5.63 | 5.97 | 2.826 | 35 | 81 |
| 10-FML2/1-100-1 | 5.72 | 7.70 | 2.561 | 50 | 51 |
| 10-FML3/2-100-2 | 9.93 | 7.27 | 2.923 | 50 | 58 |
| 10-FML4/3-70-1 | 15.58 | 6.79 | 2.682 | 35 | 77 |
| 10-BFRP-70-1 | 2.05 | 5.16 | 0.864 | 35 | 25 |
| 10-BFRP-70-2 | 2.48 | 5.63 | 3.409 | 35 | 97 |
| 10-BFRP-100 | 2.40 | 5.46 | 3.458 | 50 | 69 |

\(^1\)20-Al-70-1 represents the testing condition as follows: projectile diameter is 20 mm, specimen material is aluminum sheet, specimen diameter is 70 mm, and serial number of specimen is 1.

Figure 2: Load-deflection curves from static and drop-weight impact tests on the 2A12-T4 aluminum alloy sheet with a diameter of 100 mm loaded by the hemispherical projectile with a diameter of 20 mm.

The total strain energy of the BFML panel consists of bending and membrane energy. Since the in-plane deformations are negligible compared to the transverse deflections, the strain energy can be expressed in terms of transverse deflections only.

For the symmetric BFML plate, the strain energies of aluminum alloy sheets and BFRP panels due to bending are given by
Figure 3: Load-deflection curves of the BFRP plate under drop-weight impact: (a) 100 mm specimen and (b) 70 mm specimen.

Figure 4: Load-deflection curves of 2/1 BFMLs.

Figure 5: Idealized material behavior for 2A12 aluminum alloy and BFRP.
The membrane strain energies of aluminum alloy sheets and BFRP plates can be expressed by the von Kármán strain-displacement relations:

\[ U_{\text{m}}^{\text{Al}} = \frac{1}{4} \int_S \left[ N_{x0} \left( \frac{dw}{dr} \cos \theta \right)^2 + N_{y0} \left( \frac{dw}{dr} \sin \theta \right)^2 \right] + 2N_{xy0} \left( \frac{dw}{dr} \cos \theta \right) \sin \theta \cos \theta | r dr d\theta, \]

\[ U_{\text{m}}^{\text{BF}} = \frac{1}{8} \int_S \left[ A_{11} \left( \frac{dw}{dr} \cos \theta \right)^4 + A_{22} \left( \frac{dw}{dr} \sin \theta \right)^4 \right] + (2A_{12} + 4A_{66}) \left( \frac{dw}{dr} \cos \theta \right)^2 \sin \theta \cos \theta | r dr d\theta, \]

where \( N_{x0} = N_{y0} = \frac{n+1}{2} \sigma_0 h_{\text{Al}} \), \( N_{xy0} = \frac{n+1}{2} \sqrt{3} \sigma_0 h_{\text{Al}} \), where \( \sigma_0 \) is the yield strength of the aluminum alloy sheet. The deformation profile of BFMLs needs to be considered when applying the principle of minimum potential energy. Tsamasphyros and Bikakis [26] proposed a velocity profile of GLARE panels under low-velocity impact as

\[ \dot{w}(r) = \dot{w}_0 \left( 1 - \frac{nr}{2a} \right), \quad 0 \leq r \leq a. \]

The deformation profile of BFMLs can be obtained by integrating the above equation:

\[ w(r) = w_0 \left( 1 - \frac{nr}{2a} \right), \quad 0 \leq r \leq a, \]

where \( a \) is the radius of the BFML plate. Under symmetrical loading conditions, the in-plane shear force and twisting moment are zero. By substituting Equation (8) into Equations (1), (2), (4), and (5), we can get the bending strain energy and membrane energy as follows:

\[ U_b^{\text{Al}} = 4M_{xy0} w_0 = K_b^{\text{Al}} w_0, \]

\[ U_b^{\text{BF}} = \left[ (1.659 + 1.453 \ln a) (D_{11} + D_{22}) - (4.062 - 0.969 \ln a) D_{12} \right] \frac{w_0^2}{a^2} = K_b^{\text{BF}} w_0^2, \]

\[ U_m^{\text{Al}} = (0.288N_x + 0.288N_y) w_0^2 = K_m^{\text{Al}} w_0^2, \]

where \( m \) is the number of aluminum sheets, \( z_k \) is the distance of neutral surface of the aluminum sheet from that of the BFML plate, and \( h_{\text{Al}} \) is the thickness of the aluminum alloy sheet.
where

\[ U^\text{BF}_m = 0.155A_{11} + 0.155A_{22} + 0.103A_{12} \frac{w_0^4}{d^4} = K^\text{BF}_m w_0^4. \]  

(12)

The work of external load is

\[ W = Pw_0. \]  

(13)

By calculating the minimal value of the potential energy, \( \Pi = U_b + U_m - W = U_b^\text{Al} + U_b^\text{BF} + U_m^\text{Al} + U_m^\text{BF} - W, \) \( \) there is

\[ P = K_b^\text{Al} + (2K_m^\text{Al} + 2K_b^\text{BF})w_0 + 4K_m^\text{BF}w_0^3, \]  

(15)

where

\[ K_m^\text{Al} = (0.288N_x + 0.288N_y), \]

\[ K_m^\text{BF} = \frac{1}{d^3} [0.155A_{11} + 0.155A_{22} + 0.103A_{12}], \]

\[ K_b^\text{BF} = 4M_{xy}, \]

\[ K_b^\text{BF} = \frac{1}{d^3} [(1.659 + 1.453 \ln a)(D_{11} + D_{22}) - (4.062 - 0.969 \ln a)D_{12}]. \]  

(16)

The deflection of the thin BFML plate (type of 2/1) was several times the thickness of the BFML plate, and thus membrane force is dominant in responding to external loading. By ignoring the bending force, the following expression can be obtained:

\[ P = 2K_m^\text{Al}w_0 + 4K_m^\text{BF}w_0^3. \]  

(17)

The theoretical prediction by Equation (17) is in a good agreement with the related test results, which is shown in Figure 6.

4.2.2. Thick Plate. The small deflection profile of the clamped circular plate under lateral loading was given by the classical theory of plates:

\[ w = \frac{P}{16\pi D} \left( 2r^2 \ln \frac{r}{a} + a^2 - r^2 \right), \]  

(18)

where \( P \) is the load, \( a \) is the radius of the plate, and \( D \) is the bending stiffness which is

\[ D = \frac{Eh^3}{12(1 - \nu^2)}. \]  

(19)

The deflection at the center of loading can be obtained through Equation (18):

\[ w_0 = \frac{Pa^2}{16\pi D}. \]  

(20)

Therefore, the peak load is

\[ P = \frac{16\pi D}{a^2} w_0. \]  

(21)

The average elastic modulus of the BFML plate can be calculated by

\[ E = \frac{E_{\text{Al}}h_{\text{Al}} + E_{\text{BF}}h_{\text{BF}}}{h_{\text{Al}} + h_{\text{BF}}}, \]  

(22)

where \( E_{\text{Al}} \) is the hardening slope of 2A12 aluminum alloy and \( E_{\text{BF}} \) is the static elastic modulus of BFRP.

Figure 7 shows the predicted load-deflection curves compared with the test results of 4/3 BFMLs. The test results began to deviate from the predicted curve which did not take debonding (dashed line) into account when the deflection was more than 1 mm. Debonding may occur even when the impact load on the BFML plate is well below the peak load, as shown in Figure 8, which reduces the bending stiffness of the BFML plate. Therefore, the effect of debonding on the BFML plate stiffness must be considered during drop-weight impact. The debonding radius \( r_{\text{deb}} \) can be given in terms of the lateral load \( (P_d) \) and the interlaminar shear strength (ILSS) between aluminum alloy sheet and BFRP [26]:

\[ \frac{r_{\text{deb}}}{h_{\text{ILSS}}^3} = \frac{P_d}{2\pi h_{\text{ILSS}}}. \]  

(23)

The bending stiffness of debonding area, as shown in Figure 9, can be calculated by

\[ D_{\text{deb}} = \sum (iD_{\text{Al}} + jD_{\text{BF}}), \]  

(24)

where

\[ D_{\text{Al}} = \frac{E_{\text{Al}}h_{\text{Al}}^3}{12(1 - \nu_{\text{Al}}^2)}, \]  

(25)

\[ D_{\text{BF}} = \frac{E_{\text{BF}}h_{\text{BF}}^3}{12(1 - \nu_{\text{BF}}^2)}. \]  

(26)

where \( i \) and \( j \) are the numbers of the aluminum alloy sheet and BFRP plate, respectively. The stiffness of bonding area is calculated by Equations (19) and (22). Then, the deflection...
composes of two parts \( w_1 \) and \( w_2 \) that are formed in bonding and debonding areas (Figure 9).

Figure 9 shows that the predicted load-deflection curve after considering debonding is in a good agreement with the test results, which demonstrates that the behavior of the thick BFML plate is closely related to the debonding phenomenon. It was further analyzed in the case that there was no debonding occurred, as shown in Figure 10. When the debonding is not dominated in the BFML plate after drop-weight impact, the predicted load-deflection curve without considering debonding is more accurate than that considering debonding. It is worth pointing out that, in Figure 10, the initial bending stiffness of the load-deflection curve (less than 0.5 mm of deflection) should be calculated based on the elastic modulus of 2A12 aluminum alloy rather than the hardening slope \( E_p: E_p = 70.1 \text{ GPa} : 1.5 \text{ GPa} \).

4.3. Failure Mode. The failure modes of the 2A12 aluminum alloy sheet and BFRP plate were both different on whether they are impacted alone or as components of BFMLs. The monolithic aluminum alloy sheet tends to form a plug during impact but petals during quasi-static loading as shown in Figure 11. The evident cross crack lines can be seen in loading area of the BFRP plate after static indentation while serious breakage was formed after impact as shown in Figure 12. As components of BFMLs, 2A12 aluminum alloy sheet and BFRP layer failed under impact were more like the way that both materials failed under static indentation, as shown in Figure 13. This means that the calculated energy based on static tests should be preferred in energy analysis of failure.

4.4. Energy Partition. The kinetic energy of the projectile was absorbed by global deformation of the BFML plate, debonding, fiber breakage, and plastic deformation and damage of 2A12 aluminum alloy during perforation. The energy balance equation is as follows:

\[
E_{\text{abs}} = E_{\text{deb}} + E_{\text{tensile}} + (E_m + E_{\text{petal}}),
\]

where \( E_{\text{abs}} \) is the total absorbed energy and \( E_{\text{deb}}, E_{\text{tensile}}, E_m \) and \( E_{\text{petal}} \) are energies absorbed in debonding, tensile fracture of BFRP, deformation, and petaling of the 2A12 aluminum alloy sheet, respectively.

4.4.1. Energy Absorbed in Debonding. Debonding will propagate in mode II at a critical force [27]:

\[
P_d = \left( \frac{8m^2E_yh^3G_{\text{IC}}}{9(1-\nu^2)} \right)^{1/2},
\]
where $v$ is Poisson’s ratio, $E_{av}$ is the plate stiffness, and $G_{IIc}$ is the mode II critical interlaminar shear fracture toughness. The radius of debonding area is

$$R_{deb} = \frac{P_d}{2\pi h \text{ILSS}}$$

Figure 10: Load-deflection relation of the thick BFML plate without debonding.

Figure 11: Failure modes of the 2A12 aluminum alloy sheet: (a) petaling under static indentation; (b) plugging under drop-weight impact.

Figure 12: Failure modes of the BFRP plate under two sizes of projectile: (a) static indentation; (b) drop-weight impact.

where $\text{ILSS}$ is the shear strength of interface which was obtained by conducting tensile shearing tests on bonding surface between aluminum alloy sheet and BFRP plate. In the present study, $\text{ILSS} = 30.0 \text{ MPa}$.

Energy absorbed in debonding is
Combining Equations (27)–(29) gives
\[
E_{\text{deb}} = \pi R_{\text{deb}}^2 G_{\text{IC}}.
\] (29)

Therefore, the energy absorbed in tensile fracture of BFRP in BFMLs during impacting perforation is given by
\[
E_t = 8n_{\text{BF}}r_0ah_{\text{BF}},
\] (31)

where \(n_{\text{BF}}\) is the number of BFRP layers, \(r_0\) is the radius of projectile, \(a\) is the radius of BFML plate, and \(h_{\text{BF}}\) is the thickness of the single BFRP layer.

The membrane energy absorbed by the secondary fiber area where no fiber breakage occurred was calculated by Equation (12).

4.4.2. Energy Absorbed by BFRP. The fracture energy density of BFRP can be obtained based on the area under strain-stress curve of the tension test, which is \(E_t = 2.85 \times 10^6\) J/m³. The fracture energy of the BFRP plate under static indention can be calculated by making the product of energy density to tensile failure by the volume of primary fiber region, shown in Figure 14. The calculated fracture energy is nearly equal to the test results, as shown in Table 7.

4.4.3. Energy Absorbed by 2A12 Aluminum Alloy Sheet. Based on the previous analysis, the membrane strain energy of the aluminum alloy sheet in BFMLs can be expressed as...
Taking $w_0$ as the maximum deflection of BFMLs, the plastic strain energy of the single aluminum alloy sheet can be obtained by

$$U_m^{Al} = \left(0.288N_x + 0.288N_y\right)w_0^2 = K_m^{Al}w_0^2.$$  \hspace{1cm} (32)

Taking $w_0$ as the maximum deflection of BFMLs, the plastic strain energy of the single aluminum alloy sheet can be obtained by

$$E_m = K_m^{Al}w_{\text{max}}^2.$$  \hspace{1cm} (33)

Furthermore, as the projectile perforating specimen, aluminum sheet bends back around projectile’s periphery. The plastic work in petaling of $n$ layers is

$$E_p = \frac{1}{4}n_{Al}r_0^2\sigma_0h_{Al}^2,$$  \hspace{1cm} (34)

where $n_{Al}$ is the number of aluminum alloy sheets and $r_0$ is the radius of the projectile.

Therefore, the energy partition of BFMLs is now clear, which is summarized in Table 8. The proportions of energy absorbed by constituent materials are shown in Figure 15. It can be seen that the energy absorbed by BFRP accounts for more than 75% of the total energy absorbed. The calculated total energy absorption is compared with the test results in Figure 16. Most of the calculated energies are in a good agreement with the test results. The reason for the

**Table 7: Failure energy of the BFRP plate under static indentation.**

| Specimen diameter (mm) | 70 | 100 |
|------------------------|----|-----|
| Projectile diameter (mm) | 20 | 10 | 5 | 20 | 10 | 5 |
| Tested (J)             | 14.42 | 5.90 | 2.92 | 16.39 | 6.61 | 3.53 |
| Calculated (J)         | 10.53 | 5.27 | 2.63 | 15.05 | 7.52 | 3.76 |

**Table 8: Energy partition of BFML plates under drop-weight impact.**

| Specimen | Debonding (J) | BFRP (J) | Aluminum alloy (J) | Total energy (J) |
|----------|---------------|----------|--------------------|------------------|
|          | Membrane      | Breakage | Membrane           | Petaling         |
| 20-FML2/1-70-1 | 0.58       | 13.49    | 10.53             | 5.16             | 4.02 | 33.78 | 36.11 |
| 20-FML2/1-100-2 | 0.58      | 72.95    | 15.05             | 17.15            | 4.02 | 109.75 | 71.27 |
| 20-FML3/2-70-1 | 2.28      | 5.46     | 21.07             | 4.93             | 6.03 | 39.77 | 31.57 |
| 20-FML3/2-100-3 | 2.28     | 54.55    | 30.10             | 22.25            | 6.03 | 115.20 | 122.48 |
| 10-FML2/1-70-1 | 0.58      | 22.60    | 5.27              | 6.68             | 2.01 | 37.14 | 32.55 |
| 10-FML2/1-100-1 | 0.58      | 30.81    | 7.52              | 11.15            | 2.01 | 52.07 | 32.22 |
| 10-FML3/2-70-2 | 2.28      | 24.40    | 15.05             | 14.88            | 3.01 | 59.62 | 67.08 |
| 10-FML4/3-70-1 | 5.10      | 37.91    | 15.80             | 17.31            | 4.02 | 80.14 | 125.46 |

**Figure 15: Energy partition upon materials of BFML plates under drop-weight impact.**

**Figure 16: Comparison of calculated impact energy with the test results of BFML plates under drop-weight impact.**
discrepancies in the second and last ones may be due to the dispersiveness of ductility of the 2A12 aluminum alloy sheet as shown in Table 3.

If the total energy absorbed is divided by area density of the BFML plate, the specific energy absorption can be obtained. Figure 17 shows the specific energy absorption varies with metal volume fraction (MVF). The curves of MVF represent only the trends it varies. The two lines of MVF originate from two series of BFMLs, as shown in Figure 18. Series I was generated from numerical simulation using the commercial code ABAQUS (the corresponding properties such as absorbed energy were necessarily obtained from simulation in ABAQUS), while series II consisted of the specimens in the test. Both series of BFMLs (Figure 17) show that decreasing the MVF brings the higher specific energy absorption. However, the ductility of BFMLs is inevitably weakened with a low amount of ductile aluminum alloy.

5. Conclusions

Load-deflection relationships of 2A12 aluminum alloy sheets, BFRP plates, and BFML plates under drop-weight impact were obtained. The strain rate was calculated as impact velocity divided by specimen diameter, which was the averaged result over specimen span. It was used as an indicator in strain-rate effect analysis. Its accuracy is not high, but it is a convenient way to qualitatively inspect strain rate-related properties. Only BFRP plates showed strain-rate effect. As a result, drop-weight impact behavior of BFML plates was analyzed based on the static indentation.

Moreover, the failure modes of 2A12 aluminum alloy sheets and BFRP layers in BFML plates were more or less similar to those of both monolithic materials failed in static indentation. Therefore, the fracture energies of each material in BFML plates were calculated based on properties obtained in static tests.

Thin and thick BFML plates under impact behaved quite differently. The behavior of thin BFML plates is controlled by membrane stress, while the bending stiffness of thick BFML plates is dependent on debonding between aluminum alloy sheet and BFRP layer.

The energy absorbed by BFRP layers in BFML plates accounts for more than 75% of total absorbed energy, indicating that BFRP is the main energy absorbing material. Decreasing MVF can raise the specific energy absorption of BFML plates. However, there must be a limit of MVF for the guarantee of the necessary ductility.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare no conflict of interest.

Authors’ Contributions

Dongliang Zhang and Qingyuan Wang were responsible for the conceptualization. Dongliang Zhang and Yunrong Luo were responsible for the methodology. Xiaoyan Zhang was responsible for the software. Qingyuan Wang and Yunrong Luo were responsible for the funding acquisition.

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