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Low-Velocity Impact Response of Glass-Galvanized Iron Fiber Metal Laminates

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Abstract

This paper presents the low-velocity impact response of woven E-glass fiber/galvanized iron metal laminate. The fibre metal laminates were prepared with different stacking sequences of 2/1 and 4/5 using hot compression technique and subjected to drop-weight impact according to ASTM D7136 for three different impact loads, i.e., 10 J, 20J, and 30J. The impact response of the fiber metal laminates (FMLs) was compared to those of pure woven glass fiber reinforced polymer (WGFRP) laminate and plain Galvanized Iron (GI) sheet metal in terms of peak load, maximum deflection, absorbed energy, specific absorbed energy, load-deflection behaviour, and damage area. The increased impact energy was attributed to the higher peak load, maximum peak load, absorbed energy, and severe damage area. It was found that the FML with stacking sequence 4/5 (FML 4/5) exhibited the highest peak load when subjected to 20J and 30J impact energy loading and also exhibited the maximum deflection when compared to the other laminates. This indicates that FML 4/5 has high ductility and thus, absorbs a higher impact load. Based on the damage areas, it was observed that the FMLs were dominantly failed by composite/metal interface delamination.

Disciplinary: Mechanical Engineering (Engineering Mechanics), Materials Engineering, Polymer Composites.

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1 Introduction

The ever-increasing requirement of automotive and aeronautical industries that focuses on weight reduction, cost reduction, and higher damage resistance has contributed to the emergence of engineered materials such as fibre metal laminates (FMLs). FMLs were originally introduced to overcome the crack growth problem of metallic materials and the catastrophic failure of brittle materials. Materials such as advanced aluminium alloys and fiber-reinforced polymer (FRP) composites have greater potential to improve hybrid composite materials or FMLs. A hybrid structure could overcome the disadvantages of the individual materials such as poor fatigue strength and corrosion resistance in aluminium alloys, and poor impact resistance, low residual strength, and reparability of fibre reinforced composites [1].

These FMLs have shown improvement in their properties such as higher specific strength/stiffness, impact, fatigue, quasi-static, corrosion, and fire resistance when compared to individual metals or FRP laminate [2]. The first type of FML was developed in 1978 by a group of researchers from the Delft University of Technology in the Netherland that was called ARALL (Aramid-Aluminium Laminates). ARALL consists of the combination of alternating layers of high-strength aramid fibers and aluminium alloy sheet, then it was followed by CARALL (Carbon-Aluminium Laminate). In 1990, GLARE (Glass-Aluminum Laminates) was established [3]. These commercial FMLs are being used as structural materials for aircrafts such as Airbus A380, Fokker 27 lower wing skin panels, C-17 cargo doors, and Boing 777 cargo floors [1]. In fact, a wide range of materials and layup can be selected to develop the FMLs, as this depends on the application and required properties. The selection of metal layer thickness, fiber layer layup, and overall laminate layup will determine and influence the properties of the overall structure [4]. Recently, multiple pieces of research on the different types of metal alloys to produce FMLs, such as titanium [5], magnesium [6], and stainless steel wire mesh [7, 8], are increasingly apparent.

Aircraft structure experiences impact damage that is usually located around the doors, on the nose of aircraft, at the tail and cargo compartment. Fatigue and corrosion are the most common type of failure that can occur on such structures. There are four categories of impact according to its velocity; low-velocity impact (0-11 m/s), high-velocity impact (>11m/s), ballistic impact (>500 m/s), and hypervelocity impact (>2000 m/s). Examples of the low-velocity impact that may occur are the tools that drop during maintenance and the impact from the collision between cars or cargo and their structure [9]. Under low-velocity impact, the FMLs exhibit complex damage mechanisms that involve visible damages, such as plastic indentation or deformation and metal cracking, and internal damage or invisible damages, such as fiber failure, matrix cracking, and delamination [10]. Distinctive damage is influenced by various parameters such as the types of loading, the geometry of the impactor, boundary setting, material, types of metal, types of fibers, types of matrix, stacking sequence layup, and bonding of laminate structure [11], [12].

The study of the low-velocity impact on FMLs material mostly involves either woven fabric [4, 13, 14, 10] or unidirectional type of fiber, whereby most studies opted for the quasi-isotropic sequence of 0/90/90/0 fiber layup. Carrillo et al. [4] researched the low-velocity impact and tensile properties of aramid fiber reinforced polypropylene aluminium alloy Al 5052-H32 laminate at different stacking sequences and impact energies. The stacking sequences were FML 2/2 (aluminium/fiber) and FML 3/4 which gave aluminium weight content of 62.4% and 55.4%, respectively. It showed that FMLs have a moderate stress-strain behaviour, a higher perforation energy threshold, and a specific peak force compared to that of plain aluminum and composite material. Sarasini et al. [13] studied the low-velocity impact response of a newly developed basalt fiber reinforced polypropylene laminate (BFML) made of different stacking sequences, impact energy, and temperature, to be compared with glass fiber aluminum laminate (GFML). The findings revealed that BFML has a better specific energy level, causing first crack (FC) due to the greater deformation ability of basalt fiber, with thinner FML (2/1) outperformed thicker FML (3/2). Mugica et al. in their study found that Magnesium (Mg)-FML did not perform as well as Al-FML in terms of perforation resistance and its capacity to dissipate impact energy. The interaction between metal and composite constituents plays a very important role in impact performance [6]. It can be summarised that the low-velocity impact of FMLs has been studied by various researchers, especially on commercialized FML. However, studies on the impact response of newly developed galvanized iron FMLs are still limited. Thus, in this study, the low-velocity impact under different impact energies on woven glass fiber composite and galvanized iron (GI) metal sheet FMLs that were made of different metal thickness and stacking sequences were investigated and reported.

2 Method

2.1 Materials

The glass prepreg used was plain weave 7781 E-glass fabric (pre-cured thickness = 0.2 mm) with epoxy resin as the polymer matrix. The prepreg contained about 30% epoxy and 70% fiber according to the burnt-off test. The sheet metal used was galvanized iron (GI) with thicknesses of 0.5 mm, 1.0 mm, and 5.0 mm. The 5.0 mm GI was used as reference material.

2.2 Specimen Fabrication

FMLs were designed with stacking sequences of 1/2 and 4/5 with a GI sheet interleaf between several composite prepreg layers. The interleaf sequences created a unique laminated structure for FML. For FML 1/2, the laminate consists of ten layers of glass fiber prepreg at the top and bottom of the 1.0 mm GI sheet. For FML 4/5, the laminate consists of three layers of glass fiber prepreg alternating between a 0.5 mm GI sheet. Both laminates have an overall thickness of 5.0 mm. Pure glass prepreg of similar thickness was also fabricated as a reference specimen. The FML plates with dimensions of 250 mm x 250 mm were produced by using a hot press machine under 35 kg/cm^2 at a temperature of 154 °C for one hour before the plates were left for post-cure at room temperature for one hour. The plates were then cut into specimens with the dimension of 50 mm x 50 mm x 5 mm using the waterjet cutting technique. The designation, composition, stacking sequences, and properties of all specimens fabricated in this study are summarized in Table 1.

Table 1: Designation, composition, stacking sequence, and properties of specimen laminates

Specimen ID	Stacking Sequence	Metal Thickness (mm)	Total Thickness (mm)	Average Density (g/cm^3)	Average Hardness
WGFRP	[GF_{24}]	-	4.8	1.612	123.3 HRR
FML 1/2	[GF_{10} / GI / GF_{10}]	1.0	5.0	2.834	111.3 HRR
FML 4/5	[GF_3 / GI / GF_3 / GI / GF_3 / GI / GF_3 / GI / GF_3]	0.5	5.0	3.18	121.5 HRR
GI sheet metal	-	5.0	5.0	7.85	41.2 HRA

2.3 Low-velocity Impact Test

The low-velocity impact test was conducted using Instron DYNATUP 8250 Drop Weight Impact Tester according to ASTM D7136. The impact test was carried out at three different impact energies (10J, 20J, and 30J) by varying the height of the impactor with a fixed mass. The impactor used was a hemispherical striker with a diameter of 12 mm and a mass of 6 kg. Five identical specimens were tested for each energy level and an average was measured. Time (ms), energy (J), load (N), deflection (mm), and velocity (m/s) were recorded and visual inspection of the damaged areas was observed using a Leica Q550 MW optical microscopy.

3 Result and Discussion

3.1 Impact Response

The impact responses were measured in terms of peak load, maximum deflection, impact energy, absorbed energy, and dissipated energy. The results are summarized in Table 2. Impact energy recorded is equal to the kinetic energy of the impactor right before it makes contact with the specimen during impact. Absorbed energy is calculated from the load-deflection curve which represents the unrecoverable energy dissipated.

The peak load versus impact energy graphs for all specimens are plotted in Figure 1. The observation shows that the peak load increased with the increasing impact energy from 10J to 30J. Plain GI sheet metal exhibited the highest peak load. This is as expected for plain GI metal. At 10J impact energy, the peak load of WGFRP outperformed both FMLs (FML1/2 and FML 4/5) while FML 4/5 performed the worst. However, FML 4/5 surpassed other laminates at a higher impact energy of 20J and 30J, by 26.75% 13.53%, respectively as compared to WGFRP, which suggested greater carrying capability and resistance to deformation of the former [13, 15]. The addition of several plies of thinner metal sheet (0.5mm) resulted in only a slightly higher peak load than the use of fewer plies of thicker metal sheet (1.0mm).

Table 2: Parameters obtained for specimens under 10J, 20J, and 30J impact energy

Specimens	Peak load (N)	Maximum Deflection (mm)	Impact Energy (J)	Absorbed Energy (J)	Energy at Peak Load (J)	Dissipated Energy (J)
Impact Energy: 10J						
WGFRP	6003.98 ±138.80	3.12 ±0.02	9.92 ±0.03	14.10 ±0.04	12.96 ±0.31	1.14
FML 1/2	5909.25 ±119.28	3.23 ±0.18	9.88 ±0.08	13.78 ±0.09	11.98 ±0.82	1.79
FML 4/5	5574.89 ±51.73	4.48 ±0.32	9.77 ±0.01	14.01 ±0.06	12.53 ±0.12	1.48
GI	12077.44 ±271.75	1.40 ±0.01	9.95 ±0.06	14.60 ±0.02	10.47 ±0.33	4.13
Impact Energy: 20J						
WGFRP	6203.66 ±8.77	3.70 ±0.51	17.41 ±0.27	19.11 ±0.34	18.25 ±3.22	0.86
FML 1/2	7432.89 ±355.55	4.45 ±0.19	19.19 ±0.22	21.43 ±0.51	19.74 ±0.95	1.69
FML 4/5	7862.84 ±511.37	4.52 ±0.04	18.62 ±1.11	20.89 ±1.54	19.18 ±0.70	1.71
GI	15023.73 ±69.65	1.96 ±0.27	21.53 ±0.09	25.50 ±0.08	19.72 ±3.64	5.78
Impact Energy: 30J						
WGFRP	9200.45 ±68.24	4.40 ±0.21	30.34 ±0.07	31.49 ±0.37	26.29 ±1.82	5.20
FML 1/2	10310.91 ±49.67	5.25 ±0.19	33.09 ±0.04	34.18 ±0.08	31.40 ±2.33	2.78
FML 4/5	10445.73 ±648.56	6.27 ±0.58	33.03 ±0.05	35.10 ±0.32	32.41 ±1.21	2.69
GI	16357.13 ±0.00	2.46 ±0.00	30.23 ±0.00	34.22 ±0.00	28.22 ±0.00	6.00

Figure 2 displays the maximum deflection recorded for the specimens that are subjected to different impact energies. The maximum deflection of material gives insight into its stiffness and ductility properties [15]. The observation shows that the plain GI metal charted the least deflection after being subjected to these different impact energy. This is as expected since metal has high stiffness in nature. FMLs have a higher value for maximum deflection than those of WGFRP laminate. The higher deflection is due to the presence of sheet metal in the composite laminate, which improves the ductility of the laminate.

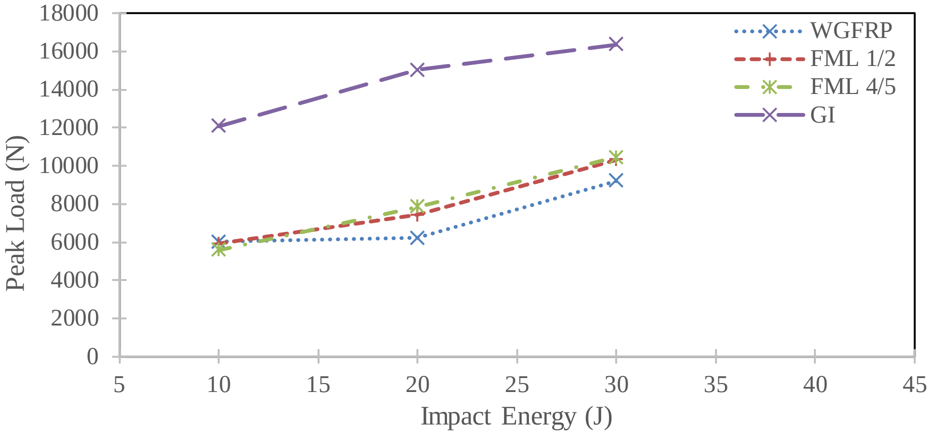


Figure 1: Peak load vs Impact energy for series fibre reinforced fibre-GI and plain GI laminates

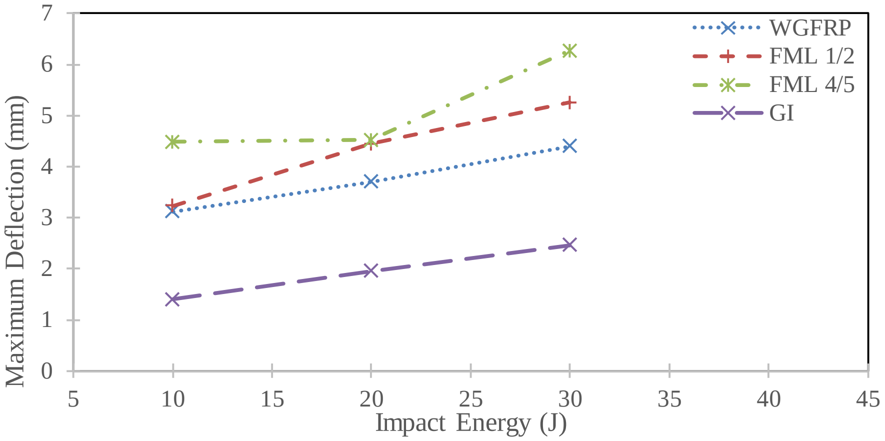


Figure 2: Maximum deflection vs Impact energy for four series of fiber-reinforced, fibre-GL, and plain GI specimen

For a better understanding, the load-deflection curve and area under the curve for all specimens are plotted and shown in Figures 3-5. The Load-deflection curve provides an inclusive description of damage initiation and growth as well as the transformation of specimen stiffness [11]. The stiffness affects the magnitude of contact force and interferes with the damage extension of the material [14]. Each curve shown in the figures has an ascending curve of the loading section up to a maximum load value and descending curve of the unloading section. The plain GI sheet metal curve displays a distinct pattern of a steep ascending curve and has the lowest deflection, due to its high yield strength and stiffness [12]. All curves show a closed pattern whereby load and deflection decreased to axis origin, indicating that some elastic energy was recovered, resulting in the impactor's rebounding [10, 11, 14, 16]. The smooth trace of the unloading curve might suggest a non-critical failure e.g. minimal damage and non-penetration of samples after the impact [11, 13]. The peak load and area under the curves increased with impact energy which indicated that more energy was absorbed by the specimens [11, 16]. WGFRP and FMLs show a higher deflection than GI, as aforementioned, indicating properties of higher ductility [15]. Among FMLs, FML 4/5 exhibited the highest maximum deflection, as a consequence of having several thin sheets of metal in the layup [17], resulting in lower stiffness and higher ductility [18]. The area under these curves increases with the increased impact energy, corresponding to the increased absorbed energy, see Figure 6.

Figure 6 displays the energy absorbed by the specimen subjected to different impact energies. Impact energy is obtained by calculating the area under the load-deflection curve. Higher absorbed energy indicates the ability of the sample to absorb a large amount of impact energy before failure [12]. Figure 6 shows the absorbed energy exhibited by each of the specimens at one particular impact energy was similar. Comparing between specimens, the plain GI sheet metal outperforms the other samples at 10J and 20J impact while FML 4/5 performs the best at 30J impact. On the other hand, WGFRP exhibited better energy absorption capability than the FMLs at low impact energy i.e 10J, similar to that of peak load. At 20J and 30J impact, both FMLs outperform WGFRP, indicating a better impact performance of the former attributed to the presence of sheet metal in the laminate, where the plain GI sheet metal absorbed a great amount of energy, protecting glass fiber from breaking [19].

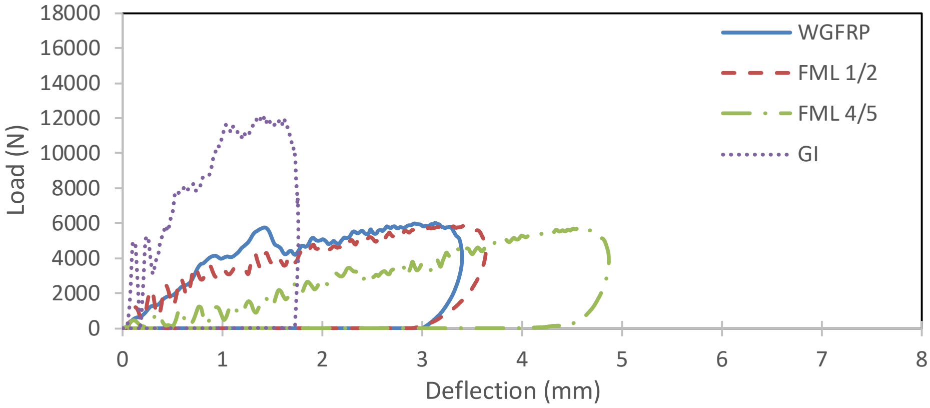


Figure 3: Load-deflection curve of the specimen subjected to 10J impact energy.

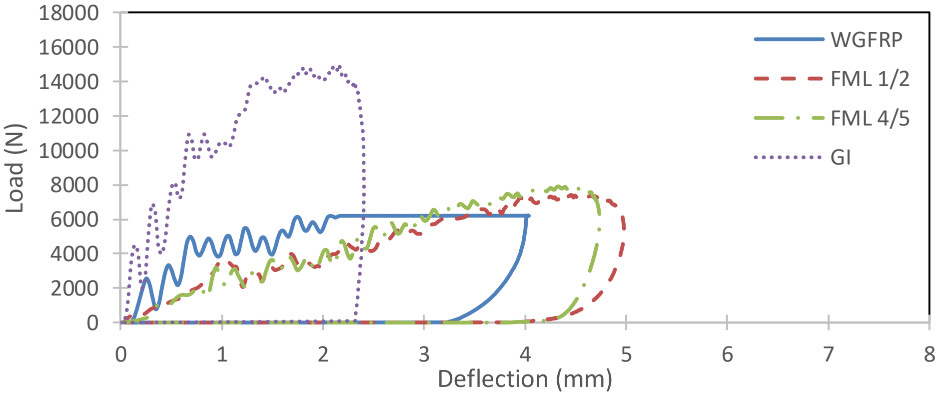


Figure 4: Load-deflection curve of the specimen subjected to 20J impact energy.

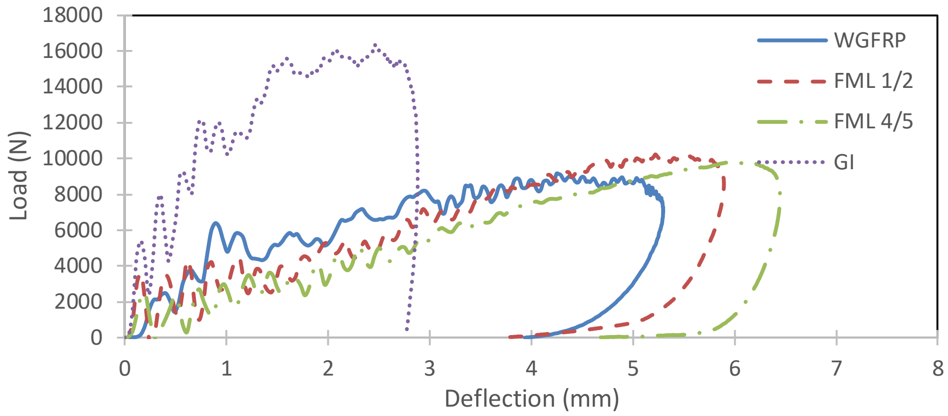
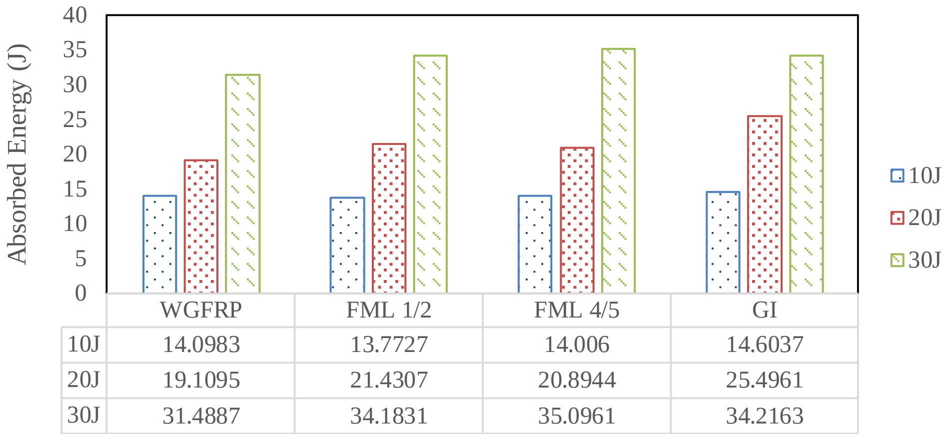


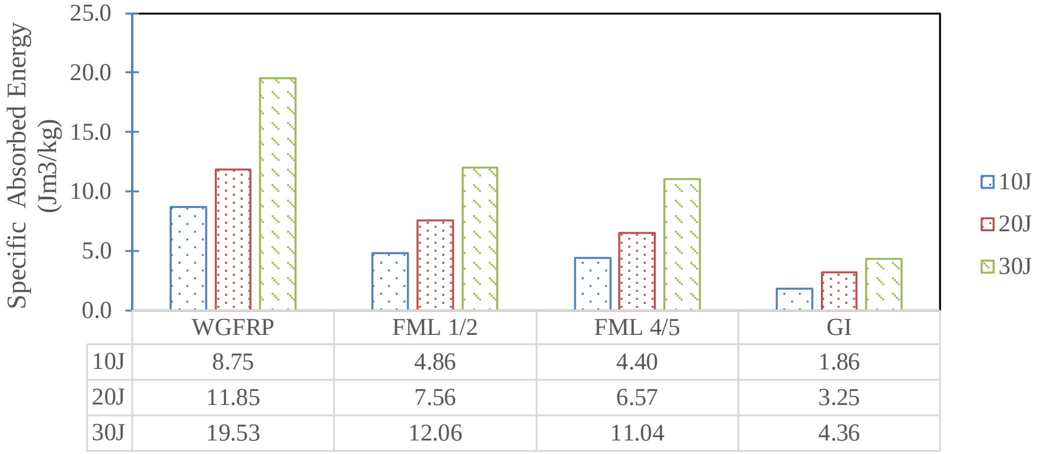
Figure 5: Load-deflection curve of the specimen subjected to 30J impact energy.



	WGFRP	FML 1/2	FML 4/5	GI
10J	14.0983	13.7727	14.006	14.6037
20J	19.1095	21.4307	20.8944	25.4961
30J	31.4887	34.1831	35.0961	34.2163

Figure 6: Absorbed energy of specimen under different energy of low-velocity impact loading.

To have a better understanding of absorbed energy, specific energy was calculated by normalizing absorbed energy to their density, and the said density values are given in Table 1. This is to compare the impact performance for specimens made of different thicknesses and densities, as discussed by Carrillo et al. [4]. From Figure 7, it appears that the plain GI specimen possesses a very low specific absorbed energy property due to its highest density compared to those of composite laminate and FMLs. The highest specific absorbed energy is exhibited by WGFRP specimens ascribed to its lowest density. FMLs have lower specific absorbed energy properties than WGFRP, however, it is favourable for its higher peak load and its lightweight properties.



	WGFRP	FML 1/2	FML 4/5	GI
10J	8.75	4.86	4.40	1.86
20J	11.85	7.56	6.57	3.25
30J	19.53	12.06	11.04	4.36

Figure 7: Specific Absorbed Energy of Specimens under different energies of Low-velocity Impact loadings.

3.2 Damage Characterization

Figure 8 displays the top view of the damaged area of (a) Plain GI sheet metal, (b) WGFRP, (c) FML 1/2 and d) FML 4/5 specimens as the impact energy grows. It was observed that the damaged area increased with the increasing of impact energy loading for all specimens. The damage that appeared on composite laminates was found to be severe at higher impact energies, corresponding to their increased absorbed energy. However, all specimens did not reach penetration or the perforation stage, inferring that they have a higher energy threshold than 30J energy. The dominant damage mechanism observed on the plain GI sheet metal was plastic deformation with no visible cracks [4]. The dents recorded were 5mm, 6mm, and 7mm horizontally when the specimens were subjected to 10J, 20J, and 30J impact energy, respectively. Dominant damage for composites was a dent on the impacted face with signs of matrix cracking, bending and cracking of fiber, and delamination [4, 11].

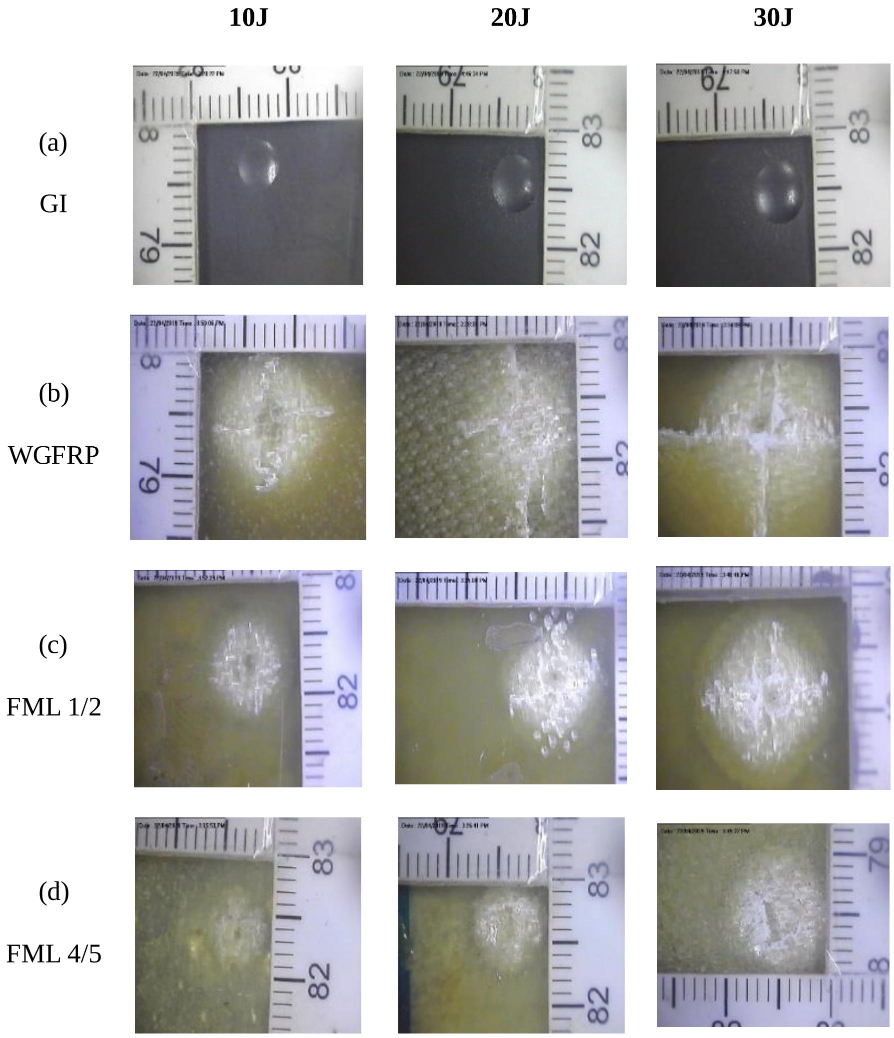


Figure 8: Damage area for (a) Plain GI sheet metal, (b) WGFRP, (c) FML 1/2 and d) FML 4/5 under 10J, 20J, and 30J Impact energy loading

The '+' or cross sign that is typically formed for woven type fibers was clearly seen on the WGFRP specimen, together with a circular shape around the impact point, indicating the propagation of fiber delamination from the center going outwards in direction of warp and weft strand of fibers [15, 16]. In this study, FMLs were developed using GFRP laminate as its front and back covers while plain GI sheet metal is placed at the middle layer. This is different from the conventional FMLs in which it is usually constructed based on sheet metal layers as the covers, while the FRP laminate is in the middle. The reason for employing sheet metal in the middle layer is to improve the impact resistance of the FRP laminates.

Based on Figures 8(c) and (d), it is suggested that the dominant damage mechanism for FML 1/2 and FML 4/5 is the composite/metal interface delamination instead of matrix cracking and fiber failure. This is mainly caused by interfacial shear stress due to bending [10]. Therefore, it can be seen that the '+' sign shown in Figure 8 (c) and (d) were less visible compared to the one in Figure 8 (b) for all impact energies. This indicates that the FMLs have higher energy absorbed when compared to the WGFRP laminate. Among the FMLs, FML 4/5 specimen has the least amount of damage, since it exhibited the least amount of specific absorbed energy [4].

4 Conclusion

The investigation of impact response for different stacking sequences of WGFRP/GI metal laminates was successfully performed under different impact energies. It can be concluded that:

- The increase in impact energy results in an increase in peak load, maximum deflection, absorbed energy. and damaged surface area for E-glass fiber/galvanized iron metal laminate specimens.
- The WGFRP specimen exhibited the highest peak load and absorbed energy when subjected to 10J impact energy.
- At 20J and 30J impact energies, the highest peak load is shown by FML 4/5
- It is found that FML 4/5 exhibited the highest deflection for all impact energies when compared to the other composite laminates. This indicates that FML 4/5 has high ductility.
- Specimens with a lower density displayed the highest specific absorbed energy and vice versa. Therefore, WGFRP laminate demonstrated the highest specific absorbed energy while plain GI showed the lowest.
- The observation on the fractured surface of the composites/laminates revealed several types of fracture mechanisms such as dent on the impacted face, matrix cracking, bending and cracking of fiber, and delamination between GI and fiber.
- FMLs showed less severe damage when compared to WGFRP. This suggests that composite/metal interface delamination is the main damage mechanism involved during impact loading that could increase the damage tolerance of the laminates.

5 Availability of Data and Material

Data can be made available by contacting the corresponding author.

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