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Quasi-Static Indentation Response of Galvanized Iron Toughened Glass Fiber/Epoxy Laminates

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***Abstract:** This paper is aimed to study the quasi-static indentation response of fiber metal laminates (FMLs) that are made of various arrangement of galvanized iron (GI) alloy thin sheet, glass fibre and epoxy polymer. Unidirectional and woven types of glass fiber/epoxy pre-impregnated laminates and three different thickness of GI thin sheet, i.e. 0.5, 1.0 and 2.0 mm, were used to produce FML systems using combination of hand layup and hot press methods. The FML systems were coded as UGFRP, UGFML 1/2-2, UGFML 2/3-1, UGFML 4/5-0.5, WGFRP, WGFML 1/2-2, WGFML 2/3-1, WGFML 4/5-0.5 according to their types of glass fibers, thickness of GI and stacking sequence. Quasi-static indentation (QSI) tests were performed according to ASTM D6264 using hemispherical crosshead at 5 mm/min speed rate. It was found that both unidirectional and woven systems of FML 1/2-2 exhibited the highest energy absorption capacity, with enhancement of 28 times and 11 times more than UGFRP and WGFRP composite, respectively. At maximum compression, FML 2/3-1 displayed the highest ultimate load, while FML 1/2-2 displayed the highest displacement for both fiber systems. Damage area inspection revealed severe matrix crack, fiber fracture and delamination upon penetration and perforation.*

***Keywords**: Fiber metal laminate (FML), glass fiber reinforced polymer (GFRP), galvanized iron (GI), quasi-static indentation (QSI).*

I. INTRODUCTION

Fiber metal laminates (FMLs) are hybrid composite structures consisting of thin metal alloys and plies of fiber reinforced polymeric materials. These types of materials are introduced to overcome most of the disadvantages that associated with each constituent material. In FML, the benefit of metals such as high impact resistance, bearing strength and toughness is combined with excellent fatigue resistance, strength, stiffness and low density of FRP composite [1], making it favorable and very useful in various applications, especially aerospace and automotive. The first development of FMLs was ARALL (Aramid fiber reinforced aluminum laminate) at Delft University of Technology in the 80's.

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Later on, CARALL (Carbon fiber reinforced aluminum laminate) and GLARE (glass fiber reinforced aluminum laminate) were invented in order to improve ARALL laminates. GLARE has a structural efficiency of 72% higher than monolithic aluminum, saving approximately 1 ton of weight of an aircraft [2]. Today, GLARE is not only being used as lower wing and pressurize fuselage skin panel, but also applied in cargo floors, engine cowlings, patch repair, stringers, cargo containers, and seamless tubes, due to its excellent properties [3].

Impact damage is an important type of failure in aircraft structure, as it can impair their load capacity performance. They are prone to damage caused by tool drops, hail and bird strike, shock stone, runway debris, engine debris, and ballistic impact [4], [5]. Therefore, impact properties of FMLs especially that are being used in aircraft industries are widely investigated. Several factors affecting severity of the impact are material, size, angle of incident, and shape of impactor, and fiber/metal stacking sequence, fiber/metal type, fiber/metal bonding strength and thickness of metal [6]. For safety and economical reason of the aircraft, it is crucial to understand the impact damage regime, hence different type of impact tests was instigated, for example quasi-static indentation, low-velocity impact, high-velocity impact, and blast loading. Quasi-static indentation are often selected to analyze the damage events occurring during low velocity impacts since the maximum transverse force and displacement can be better controlled in this type of test [4], [7].

Study on laminate thickness was done by Yaghobi et al. [8] on GLARE 5 FMLs found that total thickness of the panel give outcome to two types of failure behavior modes, which are fiber critical and aluminum critical. Similar finding by Vasumathi and Murali [9] on the study of CARALL modified with jute fiber and magnesium metal, where 8-layer laminate exhibited better value of young's modulus, bending strength, flexural modulus, and impact toughness than 13-layer laminate. Between fiber architecture, another study conducted by Yaghobi et al [10] found that unidirectional fiber arrangement has least impact resistance, followed by cross-ply, angle-ply and the best is quasi-isotropic fiber arrangement. On the other hand, Sadighi et al. [11] found that using thicker aluminum ply would improve the impact performance of GLARE 5 under low velocity impact. Chen et al. [5] mentioned that from load-displacement curve, the first failure point of laminate varied depended on the type of GLARE, thickness of laminate and number of aluminum plies.

From the literature, impact properties of GLARE laminates have been investigated by many researchers. However, the effect of metal thickness and stacking sequence of galvanized iron on quasi-static indentation properties of GFRP laminates have not yet been reported. Therefore, the aim of present paper is to investigate the quasi-static indentation response of unidirectional and woven type of glass fiber/epoxy toughened with galvanized iron metal laminates, at different metal thickness and stacking sequence.

II. METHODOLOGY

A. Materials

Materials used in this study were unidirectional (UD) pre-impregnated S2-glass/epoxy, woven pre-impregnated 7781 E-glass/epoxy and Galvanized Iron (GI) metal sheet of thickness 2.0 mm, 1.0 mm, and 0.5 mm. The pre-impregnated sheets contain resin content up to 38% according to its technical specification. Burn off test was done beforehand indicated that the epoxy content is about 35 %, while the fiber content is about 65 %.

B. Fabrication of Specimen

Eight composite laminate systems were produced using unidirectional (UD) and woven types of glass fiber/epoxy pre-impregnated laminates as code as UGFRP, UGFML 1/2-2, UGFML 2/3-1, UGFML 4/5-0.5, WGFRP, WGFML 1/2-2, WGFML 2/3-1, WGFML 4/5-0.5 according to different stacking sequence as shown in Fig. 1. The pre-impregnated glass/epoxy and GI metal sheet were first cut into dimension of 250 mm x 250 mm and laid up according to stacking sequence. The laminates were then pressed under hot-press machine under pressure of 35 kg/cm^2 at temperature of 154 °C for one hour before left for post-cure at room temperature. The laminates were cut into dimension of 50 mm x 50 mm for Quasi-Static Indentation (QSI) test using waterjet cutting technique. The designation name and properties of all sample laminates produced are listed in Table I.

C. Quasi-Static Indentation Test

Quasi-static indentation (QSI) test was performed using Instron Universal Testing Machine (UTM) to evaluate the damage absorption of the samples by inflicting indentation damage. The test was performed in accordance to ASTM D6264. The indentation force was applied to the sample at cross head speed rate of 5 mm/min using hemispherical indenter. The test was repeated five samples for each systems and the average value of load, displacement and energy absorbed were recorded. The displacement was recorded the extension of damage until the indenter fully penetrated into sample. The damaged surface was observed using Leica Q550 MW optical microscope to measure its damage area length.

Table- I: Designation of Sample Laminates

Sample Name	Fiber Type	No. of Metal Ply	Metal Thickness (mm)	Total Thickness (mm)	Density (g/cm^3)
UGFRP	UD	-	-	4.8	1.576
UGFML 1/2-2	UD	1	2.0	4.8	3.771
UGFML 2/3-1	UD	2	1.0	4.8	3.563
UGFML 4/5-0.5	UD	4	0.5	5.0	2.720
WGFRP	Woven	-	-	4.8	1.612
WGFML 1/2-2	Woven	1	2.0	4.8	3.826
WGFML 2/3-1	Woven	2	1.0	4.8	3.655
WGFML 4/5-0.5	Woven	4	0.5	5.0	3.180

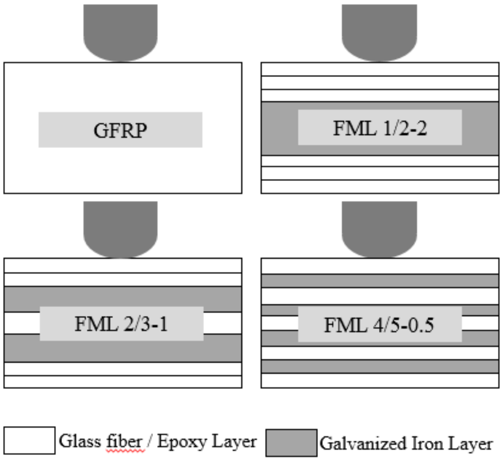

Fig. 1: Schematic diagram of glass fiber- galvanized iron stacking sequence laminates

III. RESULTS AND DISCUSSION

Figures 2 and 3 show a typical load-displacement curves of GFRP, FML 1/2-2, FML 2/3-1 and FML 4/5-0.5 systems, generated under quasi-static loading for unidirectional and woven type of glass fiber system, respectively. The load-displacement curves for all laminates present a similar trend of indentation response. UGFRP and WGFRP recorded standard range for fiber reinforced composite material, which are very low compared to curve of laminates toughened with metal sheet due to their difference in load carrying capacity. The trend of load-displacement curve of FMLs in both figures can be divided into three stages, as found by [4], [6], [12]. In first stage, the curve showed linear elastic increase of load up to first load drop or 'knee point' where the laminates dominantly exposed to elastic bending from the indenter.

At ‘knee point’, the laminates experienced matrix cracking and initiation of delamination. In second stage, the load once again increased with displacement, but with a smaller slope that indicate degraded laminate stiffness. In this stage, fiber delamination and rupture continued severely with indenter displacement until maximum load is reached and the indenter started to penetrate. In the last stage, the indenter continued to penetrate into the laminate causing complete perforation.

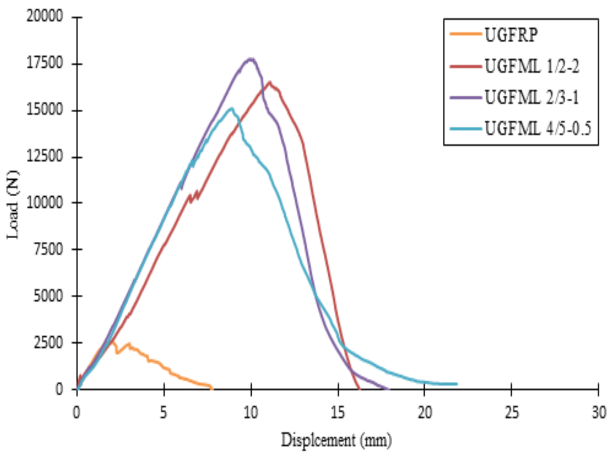

Fig. 2. Typical load-displacement curve of unidirectional glass fiber metal laminate systems under quasi static indentation test

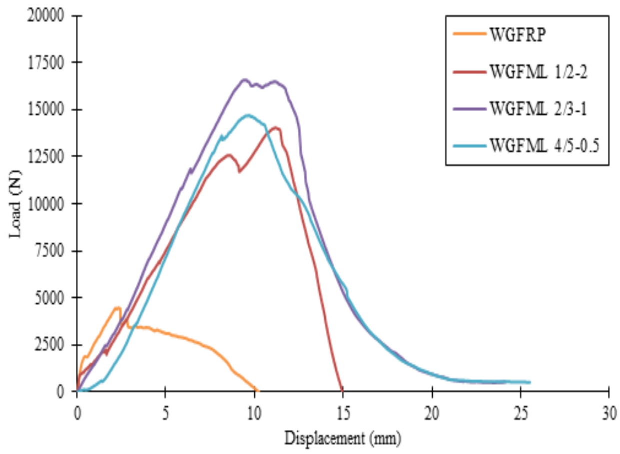

Fig. 3. Typical load-displacement curve of woven glass fiber metal laminate systems under quasi static indentation test

The QSI properties such as maximum load (F_{max}), maximum displacement (δ_{max}) and absorbed energy (E_a) for as UGFRP, UGFML 1/2-2, UGFML 2/3-1, UGFML 4/5-0.5, WGFRP, WGFML 1/2-2, WGFML 2/3-1, WGFML 4/5-0.5 are presented in

Table- II and Table- III, respectively. UGFRP and WGFRP laminates have the lowest indentation properties, as expected. Observing

Table- II, the highest maximum load achieved by the laminates before they start to fail, is shown by UGFML 2/3-1, then followed by UGFML 1/2-2, and UGFML 4/5-0.5. These maximum loads were achieved at displacement of 9.865 mm, 11.277 mm, and 8.751 mm, respectively.

Table- II: Quasi static indentation properties obtained for UGFRP and UGFML systems

Laminate	Load, F_{max} (N)	Displacement, δ_{max} (mm)	Energy Absorbed, E_a (J)
UGFRP	2730 ± 0.23	1.962 ± 0.56	3.434 ± 1.57
UGFML 1/2-2	16581 ± 0.71	11.277 ± 0.70	96.283 ± 11.40
UGFML 2/3-1	17078 ± 0.68	9.865 ± 0.38	87.462 ± 2.66
UGFML 4/5-0.5	14855 ± 0.26	8.751 ± 0.28	69.039 ± 2.19

The trend is similar for WGFRP and WGFML systems as shown in Table- III. The highest maximum load is exhibited by WGFML 2/3-1 at 17003 N, while the highest displacement is exhibited by WGFML 1/2-2 at 10.630 mm. The sequence is similar to UGFRP and UGFML laminates. Laminates with two layers of 1.0 mm thick metal sheet have highest indentation force indicates its higher perforation threshold [13], while higher displacement point at maximum load of laminates with one (1) layer of 2.0 mm thick metal sheet indicates its better stiffness properties [11], [14]. It should also be noted that displacement point is important in determining the energy absorption capacity, since energy absorbed is obtained by the area under the load-displacement curve [15].

Table- III: Quasi static indentation properties obtained for UGFRP and UGFML systems

Laminate	Load, F_{max} (N)	Displacement, δ_{max} (mm)	Energy Absorbed, E_a (J)
WGFRP	5294 ± 1.07	2.486 ± 0.30	8.096 ± 2.94
WGFML 1/2-2	14476 ± 1.63	10.630 ± 1.86	86.705 ± 31.44
WGFML 2/3-1	17003 ± 0.35	9.487 ± 0.06	82.522 ± 3.03
WGFML 4/5-0.5	15357 ± 0.60	9.481 ± 0.47	74.440 ± 7.75

The FMLs had also shown tremendous improvement in terms of energy absorbed compared to GFRP composite as shown in Fig. 4. The absorbed energy of both unidirectional and woven type glass fiber reinforced plastic (GFRP) was very low. With presence of galvanized iron metal sheet in between GFRP laminates was improved impact strength, stiffness and damage tolerance. The highest energy absorbed properties is shown by FML 1/2-2, followed by FML 2/3-1, and FML 4/5-0.5 for both types glass fiber systems. Both systems exhibited comparable and similar value of absorbed energy. The highest energy absorption capacity shown by FML 1/2-2 has improved up to 28 times for unidirectional glass fiber system, and 11 times for woven glass fiber system, compared to their constituent material. It is worth mentioning that FML 1/2-2 surpassed FML 2/3-1 in term of energy absorption capacity, which is inconsistent with that of maximum load, due to their higher displacement point.

The presence of thick (2.0 mm) GI metal sheet in the middle layer of the laminates seems more favorable than thin (1.0 mm and 0.5 mm) GI metal sheet laid up alternately between GFRP laminates. The thicker layer of GFRP laminate in front of thick GI metal sheet might help in distributing indentation force over a larger area of the metal sheet leading a petalling failure and therefore, higher energy absorption [16].

Fig. 5 displays the optical microscopy images of damaged surface of laminates for unidirectional and woven fiber systems. The length of penetration hole, h is measured and stated in the figure. All laminates showed similar mechanisms of damage, including matrix crack, fiber fracture, and delamination. It is also observed that woven fiber system exhibited larger damaged area than unidirectional fiber system, attributed by the difference in fiber architecture. In woven fiber system laminates, the delamination propagated along direction of warp and weft of the fibers, resulting in spherical hole in the top surface and '+' shaped crack in the bottom surface, while in unidirectional fiber system laminates, delamination propagates only in one direction, resulting in ellipse damage pattern [5]. This fiber arrangement of woven fiber enables it to absorb more energy than unidirectional fiber, as reported in [10], [17]. However, it is noticed that the energy absorption capacity of each FML were inconsistent between the two fiber systems, as seen in Fig. 4. One of the reason might due to poor adhesion bonding between GFRP laminates and GI metal sheet in the stack-up sequence [18]. The relationship between penetration hole area and energy absorption capacity of laminates required more analysis to understand its damage mechanism.

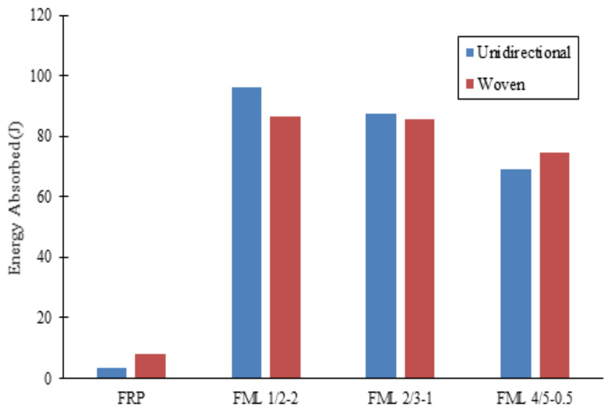

Fig. 4: Energy absorption of unidirectional and woven fiber system laminates

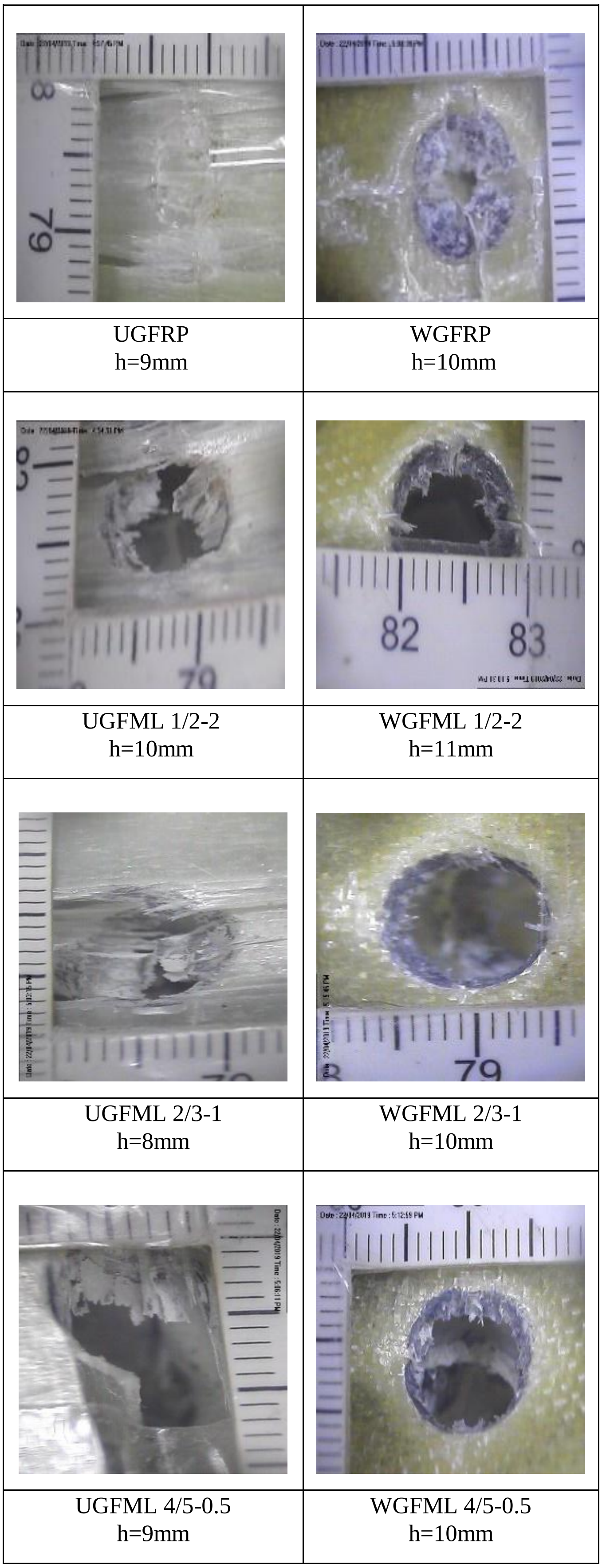

Fig. 5: Visual observation of damaged surface and holes length of FML composites systems after full perforation

IV. CONCLUSION

The investigation on quasi-static indentation response of unidirectional and woven glass fiber reinforced composites toughened with different thickness of galvanized iron was successfully conducted. The results of load-displacement curve of both fiber systems exhibited almost similar and comparable indentation properties. In overall, FML 2/3-1 recorded the highest ultimate load while FML 1/2-2 recorded the highest displacement at maximum compression, for both types of glass fiber systems (unidirectional and woven). The thickness of 2.0mm GI metal sheet inside FML systems proved to have better load carrying capacity than other thickness of GI metal sheet (1.0 and 0.5 mm). UGFML 1/2-2 and WGFML 1/2-2 exhibited the highest energy absorption properties, up to 28 times and 11 times higher than UGFRP and WGFRP laminates, respectively. The thicker metal sheet, in this case 2.0 mm, tends to absorb more energy before failure, therefore improved indentation properties of the FMLs. Damage mechanism was mainly matrix crack, fiber fracture, and delamination upon penetration and perforation.

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