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An Experimental Study of Low Velocity Impact (LVI) On Fibre Glass Reinforced Polymer (FGRP)

[1]S.N.A. Safri, [2]T.Y. Chan, and [3]M.T.H. Sultan
Aerospace Manufacturing Research Centre, Level 7, Tower Block, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor Darul Ehsan, Malaysia.
Email: [1]gs34928@mutiara.upm.edu.my, [2]tychanlz@hotmail.com, [3]thariq@upm.edu.my
Corresponding Author Email: thariq@upm.edu.my

ABSTRACT
This paper investigates the low velocity impact load and absorbed energy corresponding to the incident impact level of Type C-glass/Epoxy 600 g/m² and Type E-glass/Epoxy 800 g/m² composites. A number of low velocity impact test were performed under various incident impact energies ranging from approximately 5 to 20 J using a drop weight impact tester. Results showed that peak impact load and peak energy increase with an increase in incident impact energy. The absorbed energy increases with an increase in incident impact energy. 10-ply Type E-glass/Epoxy 800 g/m² has a higher impact resistance compared to 10-ply Type C-glass/Epoxy 600 g/m². Therefore, Type E-glass/Epoxy 800 g/m² is recommended as the material for low velocity impact.

Keywords **-** *Drop Weight Test, Fibre Glass Reinforced Polymer (FGRP), Low velocity Impact (LVI), Impact Damage, Non-destructive Testing (NDT).*

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I. INTRODUCTION

Recently there has been a lot of research on low velocity impact damage in composites [1-3]. Impact damage is one of the design criteria in composite aerospace structures design. Low velocity impact damages can be hazardous because of the invisible characteristics of the damage [4]. In the 1950s, the first appearance of the jet engines led to the investigation of a variety of impact threats: in-flight bird and hail strike, foreign object damage, and tool drop [5]. Due to these reasons, much research has been conducted in the past. Understanding the impact damage of composites is important in composite structure design. Following the evolution of lighter fighter aircraft B-2 bomber in 1970, impact damage resistance was studied on tool drop and runway debris. By using metallic impactors, a drop weight method can be used to study the low velocity impact threat of tool drop and foreign object damage (FOD).

Composites usually refer to materials that induce a combination of two or more fabrics. Rigorously speaking, composites are the materials having reinforcing fibres embedded in a weaker matrix (binder). Composites are usually employed in the aerospace industry to reduce the structural weight of the aircrafts. Composite structures are utilised for a broad range of air vehicles, from the four-seat general aviation aircraft such as Cirrus SR20 to the business and regional jets such as Raytheon Premier I, transport aircraft such as the Boeing 787, Airbus A350 and Bombardier 300, and also the combat aircraft such as F-22 [6].

Impact loading onto composite structures may produce damage which is difficult to characterise compared to metals, as the damage region is difficult to evaluate. For metals, the effects of low velocity impact on their load-carrying capability are usually minor, although permanent structural deformation may be caused [7]. In composites, even so, the possibility of plastic deformation is very restricted. The absorption of the incident energy in composites creates a large fracture area. As a result, both strength and stiffness of the composites are reduced. Moreover, it is more difficult to anticipate the post-impact load-bearing capacity of a composite structure [7]. Consequently, it is difficult to make a direct comparison between different composite materials [8].

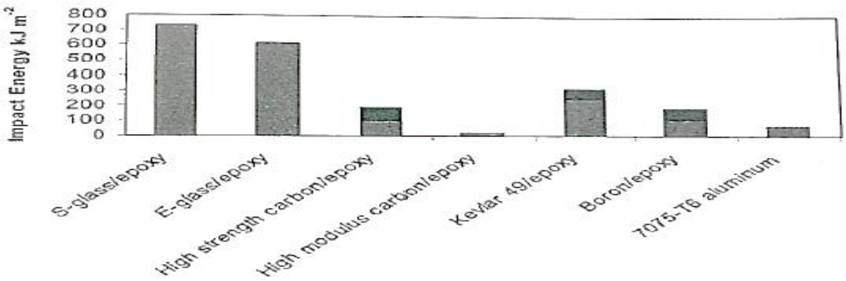

Figure 1: Charpy impact energy absorption of some materials [9]

Fibreglass has a superior ability to absorb impact energy, although it has lower mechanical and fatigue properties. Fig. 1 illustrates the impact energy absorption for fibreglass and other materials. The test was carried out using the Charpy test method [9]. The material that has the highest capacity for energy absorption is S-glass. This is because S-glass has high impact toughness. This is followed by E-glass and then aramid composites. Carbon/epoxy is of high strength but has lower energy absorption ability than these materials. High-modulus carbon/epoxy has the lowest energy absorption ability.

The material that has the highest impact energy is glass/epoxy composite. S-glass/epoxy composites are 4-7 times more impact resistant than high strength carbon/epoxy laminates. High strength carbon/epoxy laminates have higher impact-resistant by about 35 times compared to high-modulus carbon/epoxy laminates [10]. Impact refers to a collision between two or more bodies. The impact response can be elastic, plastic, fluid, or any combination of these. The impact response is fundamental to the study of impact dynamics of fracture, fragmentation and so on [11].

According to Ghelli and Minak [10], differences in low velocity impact response and damage is due to the difference in specimen dimensions and support fixture production. Test configuration and stacking sequence do not affect the size of the delamination area in varying absorbed energy and maximum contact force. To investigate impact response, the dimension is investigated in different thickness.

In this paper, the low velocity impact response of 10-ply Type C-glass/Epoxy 600 g/m² and 10-ply Type E-glass/Epoxy 800 g/m² laminates is analyses corresponding to incident impact energy. Incident impact energy in the range of 5 Joule to 20 Joule with impact velocity of less than 35 m/s is tested. There is only a small amount of research that has been done on Type C-glass/Epoxy 600 g/m² and Type E-glass/Epoxy 800 g/m². There is a substantial demand for cheaper and more damage tolerant structural materials that can absorb sufficient impact energy.

II. MATERIAL SELECTION AND EXPERIMENTAL SETUP

The mechanical properties of fibreglass in terms of their density, tensile strength, Young's modulus and elongation percentage have all been identified. Table 1 shows mechanical properties of C-glass and E-glass.

Table 1: Mechanical properties of C-glass and E-glass [12]

Property	C-glass	E-glass
Density (g/cm^3)	2.52	2.58
Tensile strength at 23°C (MPa)	3310	3445
Young's modulus at 23°C (GPa)	68.9	72.3
Elongation percentage	4.8	4.8

Referring to Table 1, the density, tensile strength, and modulus of the elasticity of E-glass is higher than that of C-glass. Both C-glass and E-glass have similar elongation percentage. The density, tensile strength, and modulus of the elasticity of E-glass is higher than that of C-glass. Both C-glass and E-glass have similar elongation percentage. Specimen fabrication was carried out at the Aerospace Material Laboratory, Faculty of Engineering, Universiti Putra Malaysia. The hand lay-up method was used to fabricate the specimens. The test specimens sizing for impact test were fabricated according to Boeing BSS 7260 impact testing specifications, 101.6 mm × 152.4 mm (4 inch × 6 inch). Type C-glass 600 g/m² and Type E-glass 800 g/m² fibreglass were fabricated into laminates of 10 plies and the stacking sequence of the glass fibre was set at 0°.

The low velocity impact testing was carried out at the General Structure Laboratory, Kulliyyah of Engineering, International Islamic University Malaysia, Gombak using Imatek IM10 ITS Drop Weight Impact Tester. The impactor used in this research was a hemispherical nose striker with the diameter of 10 mm and the mass of 0.787 kg. The corresponding incident impact velocity was from 1.00 m/s to 2.08 m/s and the incident impact energy varied from 5 J to 20 J, with an increment of 5 J.

Figure 2: Hemispherical nose striker

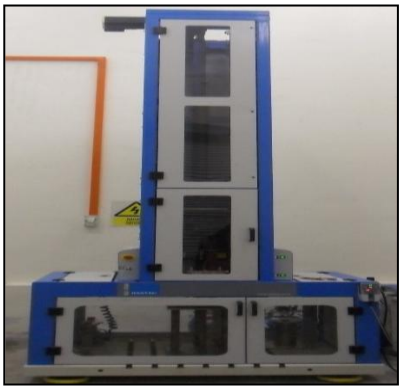

Figure 3: Imatek IM10 ITS drop weight impact tester

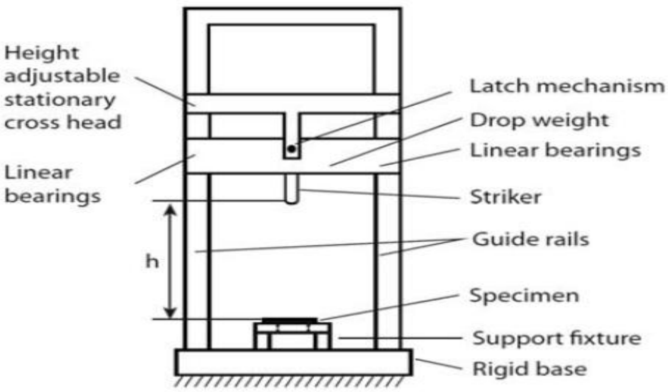

Figure 4: Schematic of drop weight impact test setup [13]

Fig. 4 illustrates the drop weight impact setup. Based on Fig. 4, the physics of the drop weight impact is related to the conservation of energy for free downfall event. The impact energy level can be determined by a known mass and the drop height, based on energy balance or it can be more accurately identified by measuring the initial velocity of the impactor. Since the impactor used in this research was of fixed mass, the desired incident impact energy was obtained by varying the height of the impactor.

The impact mechanics can be analysed by Newton's second law of motion and conservation of energy [14]. In drop weight impact test, the initial impactor velocity can be related the free downfall height h and acceleration g as:

$$V_0 = \sqrt{2gh} \quad (1)$$

The maximum energy Eo in the instrumented tup prior to impact is given by

$$E_0 = 0.5mV_0^2 \quad (2)$$

where m is mass of the impactor.
When the impactor tup makes contact with the test specimen, the impactor energy is reduced by

$$\Delta E_0 = 0.5m(V_0^2 - V_f^2) \quad (3)$$

V_f is the velocity at the time after the initial contact between specimens and tup.
The absorbed energy is function of time that can be determined using equation 4.

$$E_{ab} = 0.5mV_0^2 - 0.5m(V_0^2 - (\tfrac{1}{m}) \int_0^t F\, dt)^2 \quad (4)$$

The test machine consists of a piezoelectric load sensor, accelerometer, drop-weight, release and crosshead brake. The crosshead brake is a catching mechanism attached to the test rig to prevent repeating/rebounding impacts on the laminate by the impactor. The brake system turns on and catches impactor immediately if the impactor rebounds after the impact. A tup was placed on the impactor used to strike the laminate. A strain gauge placed within the tup was used to measure the change in strain against time during the impactor strikes the laminate. The noise associated with the signal was removed by signal conditioning unit. The data display plots the measured data.

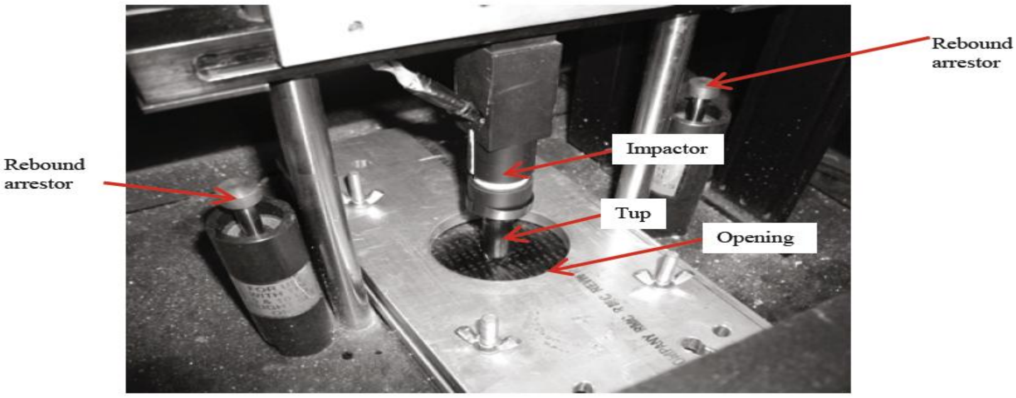

Figure 5: Rebound arrester spring back after first impact

Prior to impact test, the specimen was tightly clamped at four corners. All tests were conducted at room temperature. Experiments were conducted in a manner such that the complete failure of the specimen did not occur. During each test, initial height was adjusted from the drop-weight height release levels to hit the specimen with a specific velocity. Similarly, adjustments were made to ensure that the impact occurred at the centre of the laminate beneath the impactor head. To calibrate the brake system, the impactor was lowered to touch the surface of the specimen. The mass was released and allowed to impact the specimen once the machine was set to its correct configuration and all data acquisition software was running.

III. RESULTS

The average low velocity impact testing results for 10-ply laminate of Type C-glass/Epoxy 600 g/m² and Type E-glass/Epoxy 800 g/m² are used. Incident impact energy was the variable that was keyed into the data acquisition system before the experiment was carried out. The impact velocity for the corresponding initial impact velocity is shown in the data acquisition system. The peak load and peak energy were the results obtained from the impact test. Peak load is the maximum load of the impactor impacted on the specimen over the entire impact event, whereas peak energy is the energy when the impact load is maximum. The absorbed energy was obtained by integrating the force-displacement curve. The percentage of absorbed energy is the percentage ratio of absorbed energy to incident impact energy.

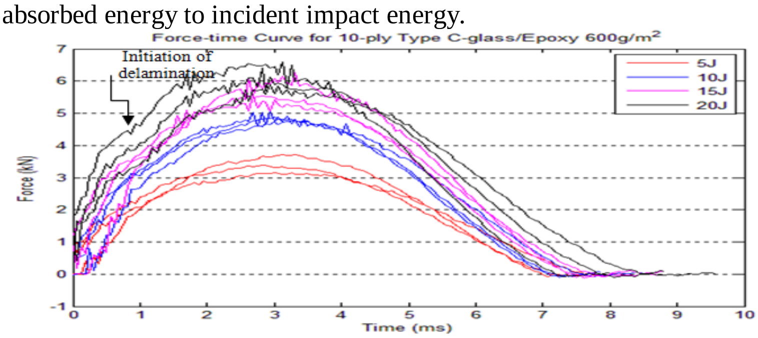

Figure 6: Force-time curve for 10-ply Type C-glass/Epoxy 600 g/m²

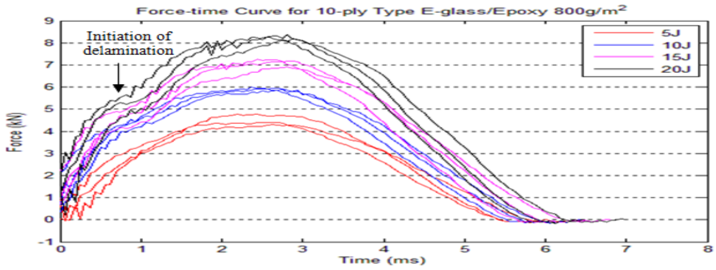

Figure 7: Force-time curve for 10-ply Type E-glass/Epoxy 800 g/m²

Fig. 6 and 7 show the impact force/load histories for the laminates at energy levels of 5 J, 10 J, 15 J, and 20 J. For each energy level, the testing was done three times. Based on Fig. 6 and 7, the impact force increases sharply in the beginning. After that, the force level increases slowly up to its peak and returns to zero. Both types of laminates possess the same trend of load history. This finding correlates to the experiment done by Heimbs, et al [15]: Peak load also increases as energy level increases.

Initially at 0 to 1ms, it shows that there is a region with high frequency oscillations. This is due to initial contact between the impactor and the specimen. From 1ms onwards, it is noted that irregular behaviour (oscillation) is followed as this indicates damage formation such as delamination. A drop in the impact load indicates the unloading of impactor due to the presence of damage [4]. Nevertheless, there is no sudden drop of the impact load after the initiation of progressive damage process. This signifies that there is no penetration.

From Fig. 6 and 7, the contact duration between the impactor and the laminate can be estimated [16]. The contact duration is the time duration where the load returns to zero after it reaches a peak. The contact time depends on the impact energy level. For 10-ply Type C-glass/Epoxy 600 g/m², the contact time for each energy level is 7 ms, 7.2 ms, 7.8 ms, and 8.2 ms respectively. Whereas, for 10-ply Type E-glass/Epoxy 800 g/m², the contact time for each energy level is 5.5 ms, 5.8 ms, 6.1 ms, and 6.3 ms respectively. The higher the energy level, the higher the contact time [16]. The contact time for 10-ply Type C-glass/Epoxy 600 g/m² is higher than that for 10-ply Type E-glass/Epoxy 800 g/m². This can be concluded that the failure mode in 10-ply Type C-glass/Epoxy 600 g/m² is more severe.

The oscillation in the curve represents loading and unloading of the impactor. Thus, the oscillation indicates the presence of progressive damage. A smoother curve signifies less severe damage [4]. From Fig. 6 and 7, the curve of incident impact of 5 J is smoother than the curve of incident impact of 20 J. Therefore the resultant damage from the incident impact of 5 J is less severe. There are more oscillations (irregular behaviour) in the curve of 20 J because the resultant damage from the incident impact of 20 J is more severe.

Comparing Fig. 6 and Fig. 7 more generally, the curve of 10-ply Type E-glass/Epoxy 800 g/m² is smoother than the curve of 10-ply Type C-glass/Epoxy 600 g/m². There are more oscillations (irregular behaviour) in the curve of 10-ply Type C-glass/Epoxy 600 g/m² because the resultant damage is more severe than for 10-ply Type E-glass/Epoxy 800 g/m². From this we can conclude that the progression of failure modes in 10-ply Type C-glass/Epoxy 600 g/m² is faster than that of 10-ply Type E-glass/Epoxy 800 g/m².

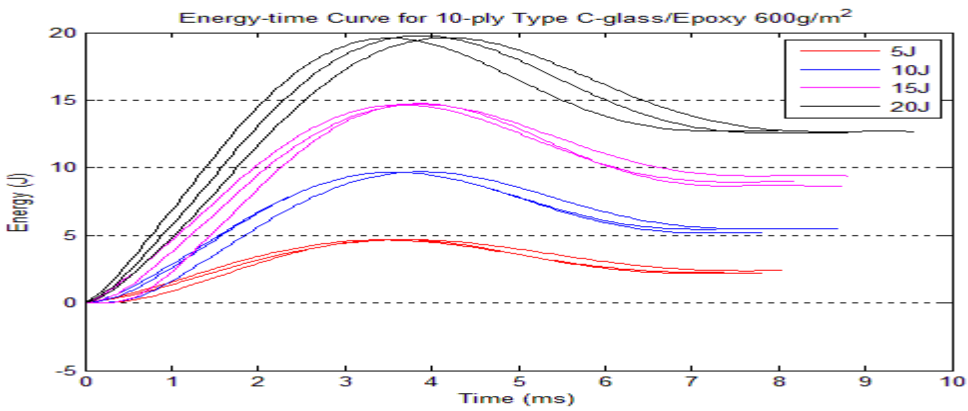

Figure 8: Energy-time curve for 10-ply Type C-glass/Epoxy 600 g/m²

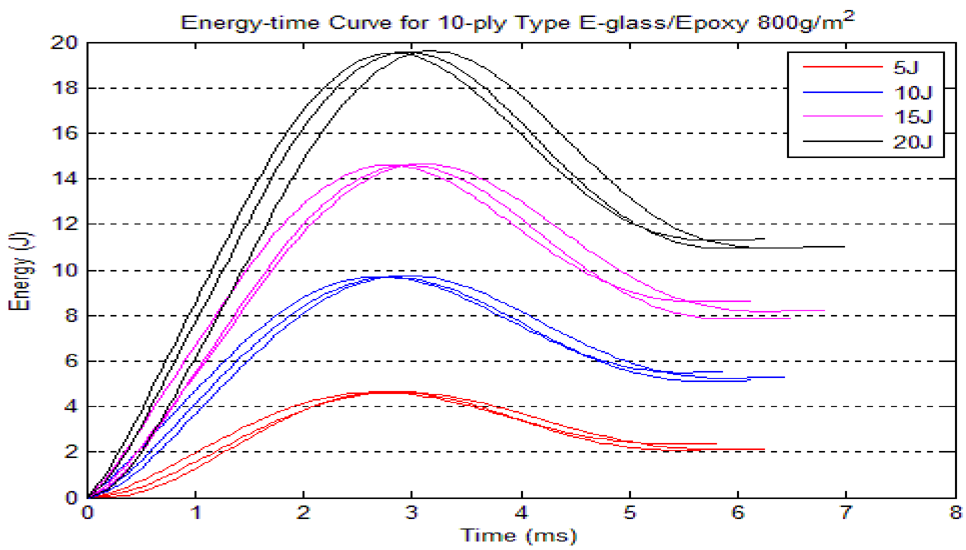

Figure 9: Energy-time curve for 10-ply Type E-glass/Epoxy 800 g/m²

Based on Fig. 8 and Fig. 9, the energy level increases slowly up to its peak and returns to zero. Both types of laminates display the same trend of energy curve. According to Vaidya [17], the absorbed energy can be analysed from the energy-time curve. The absorbed energy is the energy level when the curve becomes constant with time. The absorbed energy increases with an increase in the incident impact energy.

A more accurate amount of absorbed energy was obtained by integrating the area under the force-displacement curve. The force-displacement curve that was acquired from the data acquisition system for every specimen of Type C-glass/Epoxy 600 g/m² and Type E-glass/Epoxy 800 g/m² are presented in Fig. 10 and 11 respectively.

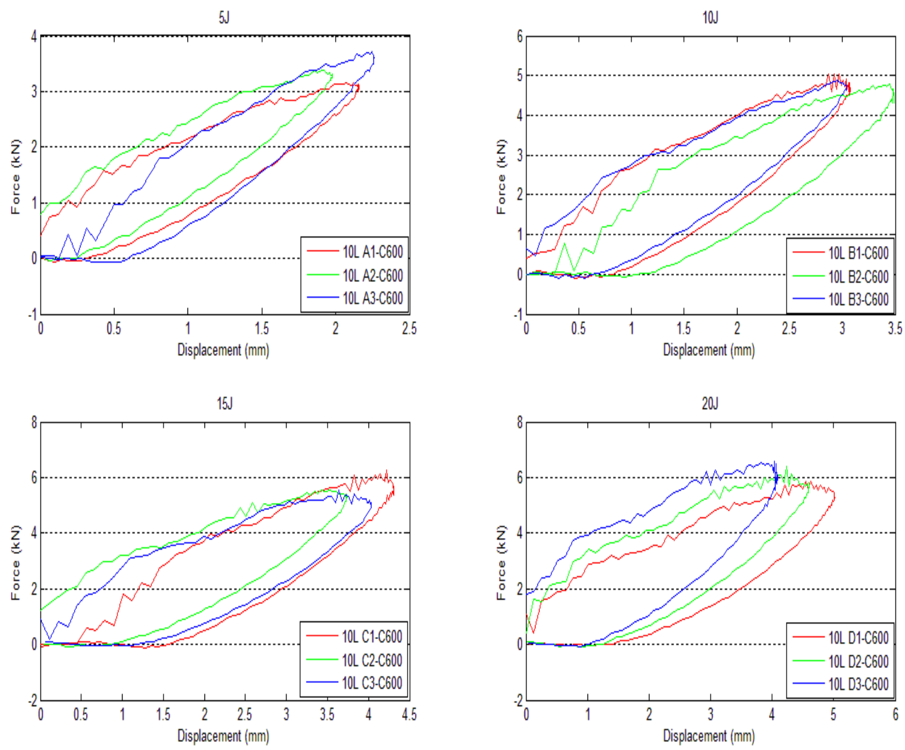

Figure 10: Force-displacement curve for 10-ply Type C-glass/Epoxy 600 g/m²

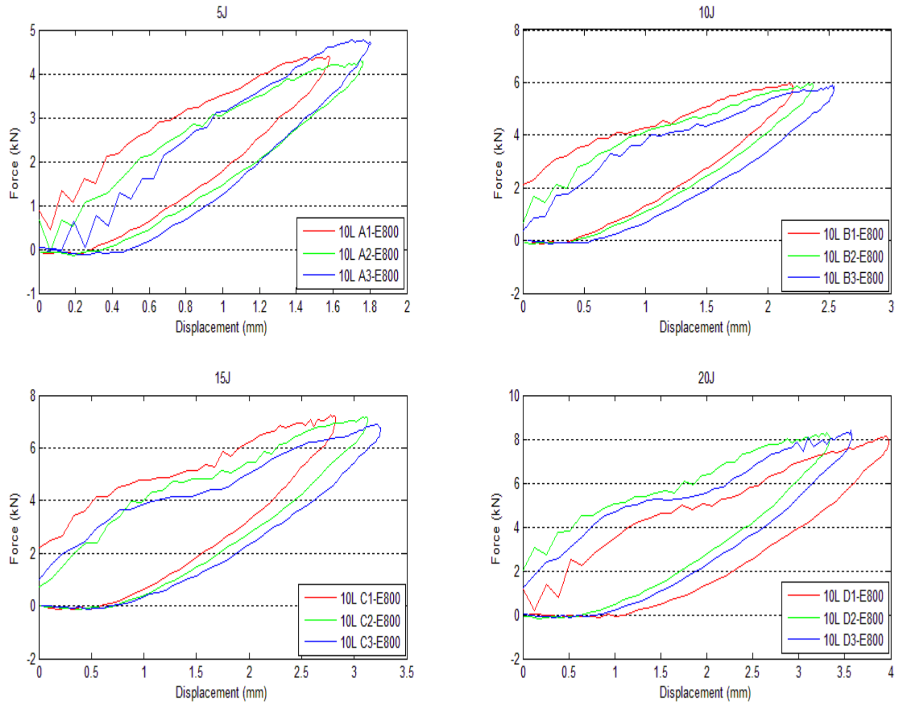

Figure 11: Force-displacement curve for 10-ply Type E-glass/Epoxy 800 g/m²

Fig. 10 and Fig. 11 show the force-displacement curve for the laminates at incident energy levels of 5 J, 10 J, 15 J, and 20 J. The absorbed energy, as labelled in the graph, is the average absorbed energy for the three repetitions of the experiment. Since the force-displacement curve is a closed contour, it can be concluded that all specimens do not experience penetration, as the incident energy was fully transferred back to the specimen at the point of maximum displacement. After the maximum displacement, the specimen transfer elastically stored impact energy back to the impactor.

The maximum deflection can be found from the graph at the point when the force curve returns to zero [18]. For 10-ply Type C-glass/Epoxy 600 g/m², the maximum deflections for each energy level are about 2.2 mm, 3 mm, 4 mm, and 4.5 mm respectively. For 10-ply Type E-glass/Epoxy 800 g/m², the maximum deflections for each energy level are about 1.7 mm, 2.3 mm, 3 mm, and 3.5 mm respectively. The maximum deflection of 10-ply Type E-glass/Epoxy 800 g/m² is lower than that for 10-ply Type C-glass/Epoxy 600 g/m².

According to the principle of conservation of energy, the energy absorbed by the specimen is equivalent to the energy that is taken up for the creation of damage [4]. Therefore, a severely damaged specimen would have high absorbed energy. The amount of absorbed energy increases as incident impact energy increases. For 10-ply Type C-glass/Epoxy 600 g/m², the absorbed energy is 2.29 J, 6.45 J, 9.01 J, and 12.67 J for incident impact of 5 J, 10 J, 15 J, and 20 J respectively. For 10-ply Type E-glass/Epoxy 800 g/m², the absorbed energy is 2.22 J, 6.36 J, 8.25 J, and 11.12 J for incident impact of 5 J, 10 J, 15 J, and 20 J respectively.

10-ply Type E-glass/Epoxy 800 g/m² has a lower energy absorption compared to 10-ply Type C-glass/Epoxy 600 g/m². 10-ply Type E-glass/Epoxy 800 g/m² exhibits less severe damage compared to 10-ply Type C-glass/Epoxy 600 g/m² at the same incident impact energy level. Therefore, it can be concluded that 10-ply Type E-glass/Epoxy 800 g/m² is more impact resistant.

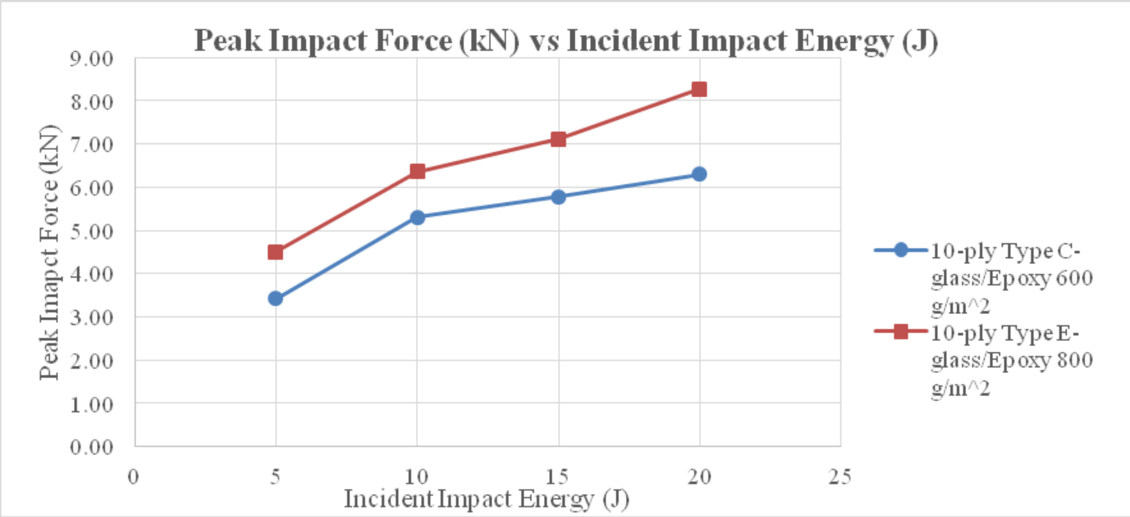

Figure 12: Variation of peak impact force and incident impact energy

Fig. 12 illustrates the variations for the averages of peak impact force and incident impact energy for the both types of fibreglass. From Fig. 12, the 10-ply Type C-glass/Epoxy 600 g/m² resulted in peak impact force of 3.42 kN, 5.31 kN, 5.78 kN, and 6.30 kN respectively. On the other hand, as for the 10-ply Type E-glass/Epoxy 800 g/m², the peak impact force were 4.50 kN, 6.36 kN, 7.11 kN, and 8.28 kN respectively.

Based on Fig. 12, the higher the initial impact energy, the higher peak impact force experienced by the specimen. The trend demonstrates peak impact force increasing with the increase in incident impact energy. This correlates to the research done by Kim and Chung [16]: maximum impact force was increased with the increase of the impact energy.

A high impact resistant material needs greater force to initiate damage as the impact strength of the material is high. For 10-ply Type C-glass/Epoxy 600 g/m², the peak impact force is lower than that of 10-ply Type E-glass/Epoxy 800 g/m². Therefore, this result concludes that Type E-glass/Epoxy 800 g/m² has a higher impact resistance than Type C-glass/Epoxy 600 g/m².

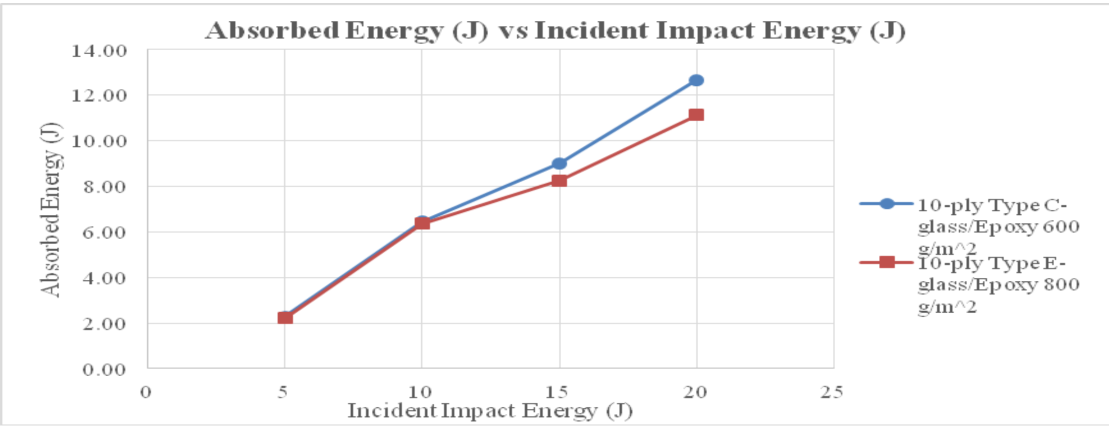

Figure 13: Variation of absorbed energy and incident impact energy

Fig. 13 illustrates the variations for the averages of absorbed energy and incident impact energy for the both types of fibreglass. From Fig. 13, the 10-ply Type C-glass/Epoxy 600 g/m² showed that the absorbed energy were 2.29 J, 6.45 J, 9.01 J, and 12.67 J respectively, whereas the 10-ply Type E-glass/Epoxy 800 g/m² showed that the absorbed energy were 2.22 J, 6.36 J, 8.25 J, and 11.12 J respectively.

Based on Fig. 13, the higher the initial impact energy, the higher impact energy is absorbed by the specimen. The trend of absorbed energy increases with the increase in incident impact energy. This correlates with the research done by Kim and Chung [16]: the absorbed energy is increased with the increase of the incident impact energy. The total absorbed energy by the impacted plate corresponds to the amount of damage. A unique failure mechanism is exhibited in a laminated plate in the ability to delaminate, i.e., preventing penetration [19]. According to the principle of conservation of energy, the energy absorbed by the specimen is equivalent to the energy that is taken up in the formation of damage [4]. Therefore, a severely damaged specimen would have high absorbed energy.

For the incident impact energy of 5 J and 10 J, absorbed energy is almost the same for both 10-ply Type C-glass/Epoxy 600 g/m² and Type E-glass/Epoxy 800 g/m². Beyond incident impact energy of 10 J, the absorbed energy of 10-ply Type C-glass/Epoxy 600 g/m² is lower than that of 10-ply Type E-glass/Epoxy 800 g/m². For the incident impact of 5 J, the absorption is the least as there is not much energy lost due to failure. By inspecting the laminate, we can see that the damage is only minor delamination. Although the energy loss for 10 J is the highest, however, it is quite close to 15 J and 20 J. The damage at the impact of 10 J and above is matrix cracking.

10-ply Type E-glass/Epoxy 800 g/m² has a lower energy absorption compared to Type C-glass/Epoxy 600 g/m². This shows that 10-ply Type E-glass/Epoxy 800 g/m² specimens exhibited less severe damage than the 10-ply Type C-glass/Epoxy 600 g/m². Therefore, it can be concluded that 10-ply Type E-glass/Epoxy 800 g/m² is more impact resistant.

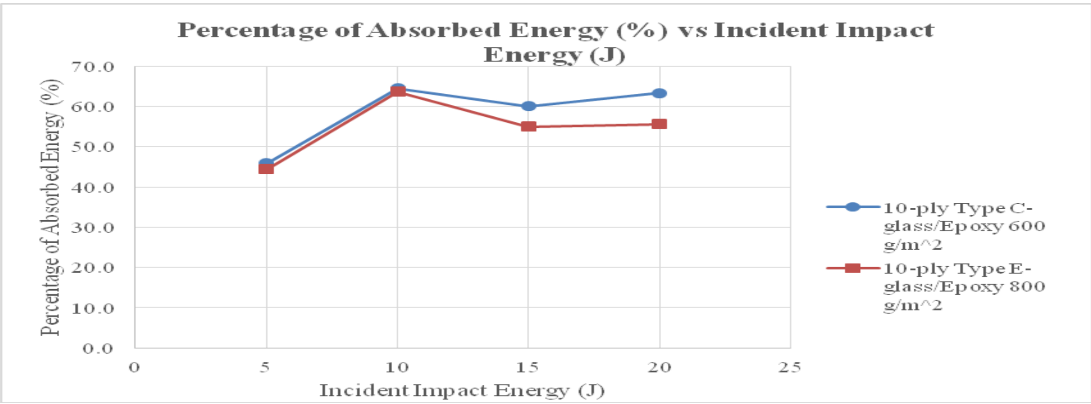

Figure 14: Variation of percentage of absorbed energy and incident impact energy

Based on Fig. 14, the percentage of absorbed energy increases and goes down at the point of the incident impact of 10 J. From Fig. 14, for 10-ply Type C-glass/Epoxy 600 g/m², the percentage of absorbed energy is 45.8%, 64.5%, 60.1%, and 63.4% respectively. For 10-ply Type E-glass/Epoxy 800 g/m², the percentage of absorbed energy is 44.4%, 63.6%, 55%, and 55.6% respectively. Not all impact energy is absorbed as fracture energy. Other energy such as elastic and vibrational energy, and plastic deformation can cause loss in energy absorption. At incident impact energy of 10 J, a sudden increase in the percentage of absorbed energy indicates that much energy was lost due to plastic deformation.

Vaidya [17] stated that the total energy is composed of absorbed energy by laminate and elastic energy loss. If a percentage of absorbed energy is high, the energy converted to elastic energy is low. This means more failure mechanisms. The percentage of absorbed energy of the 10-ply Type C-glass/Epoxy 600 g/m² was higher. Therefore, the 10-ply Type C-glass/Epoxy 600 g/m² has lower impact resistance.

IV. CONCLUSION

The objectives of this research are to investigate the low velocity impact load and absorbed energy corresponding to the incident impact level of Type C-glass/Epoxy 600 g/m² and Type E-glass/Epoxy 800 g/m² composites. The peak impact load increases with increase in incident impact energy. The time of contact of impactor also increases as incident impact energy increases. At the same incident impact energy, Type C-glass/Epoxy 600 g/m² has a lower peak load compared to Type E-glass/Epoxy 800 g/m. The absorbed energy increases with increase in incident impact energy. For the incident impact of 5 J, the absorption is the least as there is not much energy lost due to failure of minor delamination. 10-ply Type E-glass/Epoxy 800 g/m² has a lower energy absorption compared to Type C-glass/Epoxy 600 g/m². Therefore, it can be concluded that 10-ply

Type E-glass/Epoxy 800 g/m² is more impact resistant compared to 10-ply Type C-glass/Epoxy 600 g/m² and it is recommended as the material for low velocity impact.

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Biographies and Photographs

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SYAFIQAH NUR AZRIE SAFRI currently a fulltime research student for Master of Science in Aerospace Engineering. Her research area is focused on impact damage problem for composite materials.

CHAN TENG YAN currently a final year student for Bachelor of Aerospace Engineering. His research area is focused on low velocity impact testing for composites.

DR. MOHAMED THARIQ HAMEED SULTAN is a senior lecturer in Department of Aerospace Engineering, Universiti Putra Malaysia (UPM). He specializes in Structural Health Monitoring (SHM), Damage Detections And Repairs, Low And High Velocity Impact Studies & Composite Materials. He is also the Head of Aerospace Manufacturing Research Centre (AMRC).