A NOVEL METHOD FOR DETECTING AND CHARACTERIZING LOW VELOCITY IMPACT (LVI) IN COMMERCIAL COMPOSITE

S.N.A. Safri[1], T.Y. Chan[2], M.T.H. Sultan[3]

[1,2,3]*Aerospace Manufacturing Research Centre, Level 7, Tower Block, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor Darul Ehsan, Malaysia.*

Abstract

This paper presents low velocity impact testing on fibreglass reinforced polymer. The materials used in this experiment are Type C-glass/Epoxy 600 g/m^2 and Type E-glass/Epoxy 800 g/m^2. The materials were fabricated into 10 layer laminates. The drop weight low velocity impact tests were performed on 101.6 mm × 152.4 mm (4 in × 6 in) laminated plates using Imatek IM10 ITS Drop Weight Impact Tester in accordance with the Boeing Specification Support Standard Boeing BSS 7260 with variation in incident impact energy. As incident impact energy increases, the damage area also increases. Several damage modes occurred from delamination to matrix cracking. The 10-ply Type C-glass/Epoxy 600 g/m^2 laminate exhibited more severe matrix damage than the 10-ply Type E-glass/Epoxy 800 g/m^2 laminate at the same impact energy level. From this experiment, 10-ply Type E-glass/Epoxy 800 g/m^2 is recommended as the material for low velocity impact, as it has a higher impact resistance compared to 10-ply Type C-glass/Epoxy 600 g/m^2.

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

---***---

1. INTRODUCTION

Aircraft composite structures may be subjected to impact damage due to bird strike during high speed flight, high velocity hail, ice, and bullets hitting military aircraft. In addition, commercial aircraft or private jets may be subjected to impact/contact with ground service equipment (GSE) such as ground vehicles, cargo loaders, etc. Furthermore, the underside of the aircraft may be subjected to the impact in the form of projected tire fragments due to tire rupture [1]. The impact threat of foreign object damage (FOD) or tool drop during maintenance may cause damage to the composites. Horton et al [2] emphasised that impact damage is the most critical damage as it can cause a bigger reduction in strength due to holes and cracks. Fibre crack in the impact contact zone will result in a substantial decrease in residual tensile strength [3]. Impact also initiates delamination in composites. Due to the delamination, the composites will have a reduction in residual compressive strength. Delamination is hard to detect by visual inspection [4]. Although the outer skins of aircraft may not develop cracks, the internal sub-structure can still be damaged [5].

There are a few categories of impact responses, namely low velocity (large mass), intermediate velocity, high/ballistic velocity (small mass), and hyper velocity impact. Low velocity impact occurs at a velocity below 10 m/s due to conditions involving tools drop and impact by GSE. Intermediate impact occurs at 10 m/s and 50 m/s velocity range as a result of collision with a foreign object, debris on runways, and projectiles of tire fragments. High velocity (ballistic) impact occurs at a velocity from 50 m/s to 1000 m/s and is usually the result of explosive warhead fragments, hail ice, and birds strike during flight. Hyper velocity impact has a range of 2 km/s to 5 km/s, due to high-velocity projectiles such as orbital debris travelling in outer space [6].

Low velocity impact damage caused by ground vehicle (GSE) represents 30-40% plus of aircraft damage. IATA statistics shows that the 767 class aircraft experiences about 1.5 ground impact events per aircraft per year. A typical GSE impact could involve a vehicle of about 6,000 lbs travelling at 1.22 to 2.33 metre per second and the impact is distributed across an area of 0.1 to 0.37 square meters [7]. Drop weight impact testing is the most common test for impact damage in composite materials [8]. In drop weight tests, the damage is produced by the low-velocity range impact, using a heavy mass in order to produce a kinetic energy level of interest [9].

For tool drop, typical failure mechanisms are a combination of delamination, matrix failure, or back-face tension failure, with back-face fibre damage being the external visible damage [10]. Kim et al [11] stated that there was no correlation between dent depth, peak force of impact, and development of significant internal damage for thin composite plate and shell structures. There are two categories of damage. The first is clearly visible impact damage (CVID), which can easily be seen by the naked eye. The second type of damage is barely visible impact damage (BVID), which can seldom be seen by the naked eye. Evaluation of both types of damage can be enhanced through the use of post-impact testing [8].

Matrix damage is the first mode of failure caused by low velocity impact applied transversely. It occurs in the form of matrix cracking and bonding between fibre and matrix. Matrix cracking occurs due to the property mismatch between the fibre and matrix [12]. Delamination is a crack which occurs between plies of different fibre orientation in the resin-rich area. Delamination is caused by bending mismatch between two neighbouring laminates, such as different fibre orientations between layers [13]. The delamination area is affected by material properties, stacking sequence, and laminate thickness. Fibre failure is a damage mode which occurs much later than delamination and matrix cracking. Fibre failure occurs due to local indentation effects of shear forces and on the non-impacted face due to high bending stress [14]. Lastly, when the fibre failure reaches a critical extent, penetration occurs. At this stage, the penetrators completely penetrate the material (macroscopic mode of failure).

Evaluation of both BVID and CVID damage can be enhanced through the use of post-impact testing [8]. There are several non-destructive techniques that can be used to analyse post-impact damage. The non-destructive damage assessment techniques utilised in aircraft industry include visual inspection, eddy current, radiography, and Ultrasonic C-scan [15]. Visual inspection is simple, fast and relatively inexpensive. Visual inspection can only provide a good general assessment about surface damage, i.e. the central zone of damage. Farooq et al [15] studied low velocity impact damage by visual inspection. The photographs of the laminates damaged were taken and it was found that at relatively higher energy impact, a relatively deeper dent can be seen.

However, sometimes low velocity damage is not visible. Barely visible impact damage (BVID) requires advanced damage detection techniques. Zhang et al [16] examined the area of impact damage using optical microscopy. This inspection revealed that matrix cracks occurred in the specimens impacted at 24 J. Glover [17] analysed the barely visible impact damage using C-scan. This inspection showed the depth damage of a specimen after an impact of 40 Joules. The mode of delamination was detected and it was found that delamination occurred at the interface of adjacent laminas. However, ultrasonic scanning will only define the depth and shape of the delamination closest to the surface if there are multiple delaminations [17].

Understanding the impact damage of composites is important in composite structure design. Consequently, many experimental techniques have evolved to analyse the impact response of composites [18]. 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). The damage in the composites subjected to low-velocity impact may be invisible as it consists of internal delamination [19]. It is vital to understand the damage involved in the impact of composites. Sultan et al [20] have provide a model that can be used to generate a general understanding on the prediction of damage and failure progression in CFRP as a function of the number of layers and impact energies. Glass fibre has been the most common form of reinforcement because of its low cost [21]. For these reasons, this research conducts experimental techniques to analyse the low velocity impact response of 10-ply Type C-glass/Epoxy 600 g/m^2 and 10-ply Type E-glass/Epoxy 800 g/m^2 laminates corresponding to incident impact energy. For this research, impact velocity of less than 35 m/s is tested with incident impact energy in the range of 5 Joule to 20 Joule.

2. METHODOLOGY

For this research, Type C-glass 600 g/m^2 and Type E-glass 800 g/m^2 were chosen as the materials for the test specimens. The fibreglass used was in the form of woven roving. These woven rovings were laminated with resin to increase impact strength. Type C-glass fibre with a mass of 600 g/m^2 is very much thinner than Type E-glass fibre with a mass of 800 g/m^2. The hardness of Type C fibre with a mass of 600 g/m^2 is low compared to Type E fibre with a mass of 800 g/m^2 since its fibre composition is less.

2.1 Specimen Fabrication

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. For this research, test specimens sizing for impact test were fabricated according to Boeing BSS 7260 impact testing specifications, i.e. 101.6 mm × 152.4 mm (4 inch × 6 inch). Currently, the 10-ply E-glass laminates are widely used in aviation [22]. Hence, in order to investigate a similar scenario, Type C-glass 600 g/m^2 and Type E-glass 800 g/m^2 fibreglass were fabricated into laminates of 10 plies. The stacking sequence of the glass fibre was set at 0°.

2.2 Low Velocity Impact Test

There were 12 specimen fabricated for each type of fibreglass. The drop weight low velocity impact tests were performed on 101.6 mm × 152.4 mm (4 in × 6 in) laminated plates using Imatek IM10 ITS Drop Weight Impact Tester in accordance with the Boeing Specification Support Standard Boeing BSS 7260 [23]. The impactor used in this research was a hemispherical nose striker with the mass of 0.787 kg and the diameter of 10 mm. The incident impact energy varied from 5 J to 20 J, with an increment of 5 J. The corresponding incident impact velocity was from 1.00 m/s to 2.08 m/s. This correlated to the typical low velocity GSE impact, which involved a vehicle of 1.33 m/s to 2.22 m/s [7].

2.3 Dye Penetrant Inspection

There are many situations in the use of composites where an impact does not result in perforation of the material but causes damage that may not be visible, yet still causes a substantial reduction in structural properties [24]. Dye-penetrant increases the visibility of the damage. Dye penetrant inspection (DPI) is especially effective in detecting the breaking cracks on the surface and edge delaminations [15]. The low velocity impact damage area was examined by means of visual observation by dye penetrant. The dye penetrant used was Spotcheck SKL-SP2 dye penetrant. It is a solvent removable (or post emulsifiable), red coloured contrast penetrant with profound penetrating characteristics. Spotcheck SKL-SP2 is comply with ASME B & PV Code Sec V and ASTM E1417 standard. The dye penetrant managed to extend into the under layers of the damage region. The dye penetrant will only penetrate into the inner layer if there is damage.

2.4 Optical Microscopic Inspection

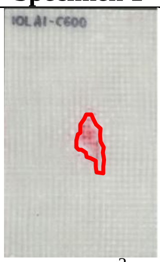
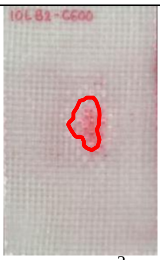
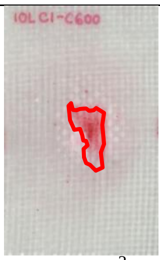
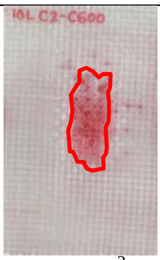
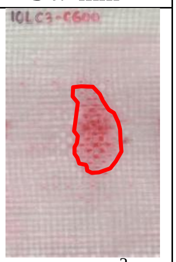
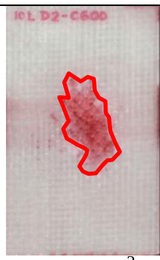
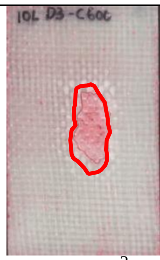
An optical microscope was used to examine the failure mode in the microstructure of the specimen. The microscope used was Olympus BX51 microscope, which had been available in the Aerospace Composite Laboratory, Faculty of Engineering, Universiti Putra Malaysia. The magnification of microscope was 50 times.

3. RESULTS AND DISCUSSION

3.1 Damage Area Progression

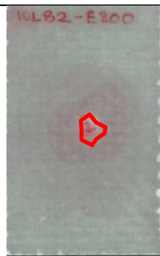
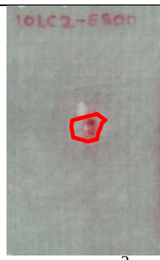
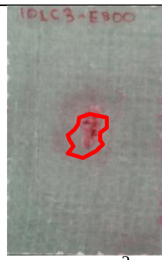
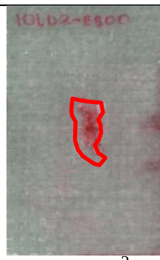
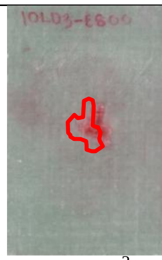
The pictures of damage area possessed by each specimen are presented in Table 1 and Table 2.

Table 1: Damage area for 10-ply Type C-glass/Epoxy 600 g/m^2

Energy	Specimen 1	Specimen 2	Specimen 3
5 J	 152 mm^2	 Delamination	 146 mm^2
10 J	 342 mm^2	 355 mm^2	 347 mm^2
15 J	 695 mm^2	 821 mm^2	 793 mm^2
20 J	 895 mm^2	 1059 mm^2	 978 mm^2

From Table 1, we can see that the damage area increases as incident impact energy increases. The damage area is only measured if there is a dye penetrated area visible. The dye penetrant will only penetrate into the inner layer if there is damage or crack. At incident impact energy of 5 J, there is no dye penetrated area for Specimen 2. Therefore, it can be concluded that there is no crack, as dye penetrant could not penetrate into the laminate: only delamination occurs.

Table 2: Damage area for 10-ply Type E-glass/Epoxy 800 g/m^2

Energy	Specimen 1	Specimen 2	Specimen 3
5 J	 Delamination	 Delamination	 Delamination
10 J	 32 mm^2	 37 mm^2	 43 mm^2
15 J	 186 mm^2	 174 mm^2	 201 mm^2
20 J	 291 mm^2	 346 mm^2	 345 mm^2

From Table 2, we can see that the damage area increases as incident impact energy increases. The damage area is only measured if there is a dye penetrated area visible. The dye penetrant will only penetrate into the inner layer if there is damage or crack. At incident impact of 5 J, there is no dye penetrated area for all specimen of 10-ply Type E-glass/Epoxy 800 g/m^2. Therefore, it can be concluded that there is no crack, as dye penetrant could not penetrate into the laminate: only delamination occurs. Based on Table 1 and Table 2, as impact energy increases, the damage area also increases. After analysing the damaged area of each specimen, the damage progression was plotted using in Fig. 1. The average value of the damaged area was plotted against the incident impact energy.

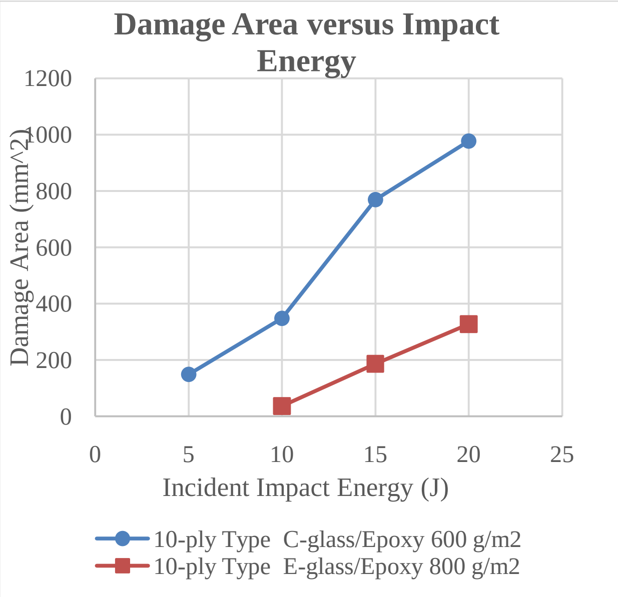


Figure 1: Damage area progression

Fig. 1 shows as impact energy increases, the damage area also increases. However, the damage area of Type E-glass/Epoxy 800 g/m^2 is lower. At the impact of 5 J, Type E-glass/Epoxy 800 g/m^2 does not show any damage. It shows only delamination. In addition, the gradient of the curve of Type E-glass/Epoxy 800 g/m^2 is smaller because the damage progression is slower. Therefore we can conclude that Type E-glass/Epoxy 800 g/m^2 is more resistant to impact compared to Type C-glass/Epoxy 600 g/m^2. This damage progression trend is the same as the previous research done by Glover (2010) [17]. There is a correlation between incident impact energy and delaminated area, i.e. the delaminated area increases with increase in incident impact energy [17]. The results also correlate with research done by Sjonlom, et al. (1988) [25]. This research found that the total energy absorbed by the plate corresponds to the amount of damage exhibited.

3.2 Failure Modes

Optical microscopy was used to study cross-sections through the impact centre to investigate the impact damage within the laminates. The magnification of the microscope was set at 50 times. Delamination and matrix cracking were observed in the microstructure of the damaged specimens. The microscopic images are shown in Table 3 and Table 4.

Table 3: Microscopic images for 10-ply Type C-glass/Epoxy 600 g/m^2

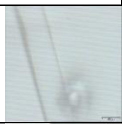
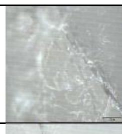
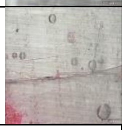
	Impact Energy, 5J	**Impact Energy, 10J**	**Impact Energy, 15J**	**Impact Energy, 20J**
Specimen 1				
Specimen 2				
Specimen 3				
Failure Mode	Delamination Matrix cracking	Matrix cracking (crack size is getting larger)	Matrix cracking (crack size is getting larger)	Matrix cracking (crack size is the largest)

Table 4: Microscopic images for 10-ply Type E-glass/Epoxy 800 g/m^2

	Impact Energy, 5J	**Impact Energy, 10J**	**Impact Energy, 15J**	**Impact Energy, 20J**
Specimen 1				
Specimen 2				
Specimen 3				
Failure Mode	Delamination	Delamination Matrix cracking	Matrix cracking (crack size is getting larger)	Matrix cracking (crack size is the largest)

Impact failure is affected by various factors, including reinforcement properties, fibre/matrix adhesion, thickness, and matrix properties, lay-up scheme, etc. [16]. Table 3 and 4 show that the failure mode here is from delamination to matrix cracking. A white matrix interlayer delamination was observed on the surface of the delaminated specimen. Matrix cracking was observed from the microscopic image, at which a crack could be seen. At the lowest energy level of

5 J, for Type E-glass/Epoxy 800 g/m^2, the failure mode is only small delamination. However, for Type C-glass/Epoxy 600 g/m^2, the failure modes are delamination and matrix cracking. This shows that Type C-glass/Epoxy 600 g/m^2 specimens exhibited more severe damage than the Type E-glass/Epoxy 800 g/m^2 at the same impact energy level. Therefore, the Type E-glass/Epoxy 800 g/m^2 contributed to slower damage progression (higher impact resistance) compared to the Type E-glass/Epoxy 800 g/m^2.

At the lowest energy level of 5 J, the failure mode was only a small delamination for the Type E-glass/Epoxy 800 g/m^2. This correlates with Table 2 and the damage area progression curve in Fig. 1. Hence, there was no dye that penetrated in the area at incident impact of 5 J. From Table 3, there was only delamination for the Type C-glass/Epoxy 600 g/m^2, as shown in Specimen 2 at incident impact of 5 J. This correlates with Table 1 as there was no dye that penetrated in the area in Specimen 2 at incident impact of 5 J. At the energy level of 10 J and onwards, the failure modes of delamination and matrix cracking were observed for both types of fibreglass. At the energy level of 10 J and onwards, the size of the matrix cracking kept on enlarging. At incident impact of 20 J, the matrix cracking had become more severe because the crack was bigger. In conclusion, as for incident impact energy from 5 J to 20 J, the failure mode was from delamination to matrix cracking.

4. CONCLUSIONS

The objectives of this research are to analyse the impact damage progression on the laminate of Type C-glass/Epoxy 600 g/m^2 and Type E-glass/Epoxy 800 g/m^2. As incident impact energy increases, the damage area also increases. However, the damage area for 10-ply Type E-glass/Epoxy 800 g/m^2 is lower. At the impact of 5 J, 10-ply Type E-glass/Epoxy 800 g/m^2 does not show any damage. It shows only delamination. Therefore, 10-ply Type E-glass/Epoxy 800 g/m^2 is more impact resistant. For incident impact energy from 5 J to 20 J, the failure mode is from delamination to matrix cracking. The Type C-glass/Epoxy 600 g/m^2 specimens exhibited more severe matrix damage than the Type E-glass/Epoxy 800 g/m^2 at the same impact energy level. From this experiment, 10-ply Type E-glass/Epoxy 800 g/m^2 is recommended as the material for low velocity impact as it has a higher impact resistance compared to 10-ply Type C-glass/Epoxy 600 g/m^2.

ACKNOWLEDGEMENTS

This work is supported by UPM under GP-IPM grant, 9401300.

REFERENCES

[1] G. Davies, and P. Robinson, Predicting Failure by Debonding/Delamination, AGARD: 7th Structures and Materials Meeting, Debonding/Delamination of Composite, (1992).

[2] R.E. Horton, and J.E. McCarty, Damage tolerance of composites, in T. J. Reinhart & Ohio (Eds.), Engineered Materials Handbook. USA: ASM. (1993).

[3] A.P. Christoforou: Impact dynamics and damage in composite structures. Composite Structures, Vol. 52(2) (2001), p. 181–188.

[4] A.K. Kaw, Mechanics of composite materials (2nd ed.). CRC press, (2006).

[5] G. DeFrancisci, Z.M. Chen, J. Rhymer, S. Funai, M. Delaney, S. Fung, and S. White: Impact Damage Formation on Composite Aircraft Structures. UCSD FAA JAMS Paper (2012).

[6] U. Vaidya: Impact Response of Laminated and Sandwich Composites. In S. Abrate (Ed.), Impact Engineering of Composite Structures SE – 4, Springer Vienna, Vol. 526 (2011), p. 97–191.

[7] J. Halpin, and H. Kim: Managing Damage Threats for Composite Structures : Unifying Durability and Damage Tolerance Perspective. In FAA/EASA Meeting. JAL Headquarters, Tokyo, (2009). Retrieved from https://www.niar.wichita.edu/niarworkshops/Portals/0/23_UCSD_JCH(KimHalpin).pdf

[8] J.M. Duell: Impact Testing of Advanced Composites. Advanced Topics in Characterization of Composites, (2004), p. 97–112.

[9] T.M. Tan and C.T. Sun: Use of statical indentation laws in the impact analysis of laminated composite plates. Journal of Applied Mechanics, Vol. 52(1) (1985), p. 6–12.

[10] G.A.O. Davies and X. Zhang: Impact damage prediction in carbon composite structures. International Journal of Impact Engineering, Vol. 16(1) (1995), p. 149–170.

[11] H. Kim, J.C. Halpin, and G.K. DeFrancisci: Impact damage of composite structures. In Long-Term Durability of Polymeric Matrix Composites (2012), p. 143–180. Springer.

[12] M.O.W. Richardson and M.J. Wisheart, M. J: Review of low-velocity impact properties of composite materials. Composites Part A: Applied Science and Manufacturing, Vol. 27(12) (1996), p. 1123–1131.

[13] M.F.S. De Moura and J.P. Gonçalves: Modelling the interaction between matrix cracking and delamination in carbon–epoxy laminates under low velocity impact. Composites Science and Technology, Vol. 64(7-8) (2004), p. 1021–1027.

[14] P.N.B. Reis, P. Santos, J.A.M. Ferreira and M.O.W. Richardson: Impact response of sandwich composites with nano-enhanced epoxy resin. Journal of Reinforced Plastics and Composites, Vol. 32(12) (2013), p. 898–906.

[15] U. Farooq and P. Myler: Prediction of barely visible impact damage in composite panels subjected to blunt nose impact. Research and Innovation Conference (2009).

[16] J. Zhang, B.L. Fox, D. Gao and A.W. Stevenson: Inspection of Drop-weight Impact Damage in Woven CFRP Laminates Fabricated by Different Processes. Journal of Composite Materials, Vol. 43(19) (2009), p. 1939–1946.

[17] A.C.J. Glover: Non-Destructive Testing Techniques for Aerospace Applications C-Scan B-Scan D-Scan. (2010) Retrieved from http://www.dsto.defence.gov.au/attachments/Glover_A_Non-Destructive_Testing_Techniques_for.pdf

[18] Z. Aslan, R. Karakuzu, and B. Okutan: The response of laminated composite plates under low-velocity impact loading. Composite Structures, Vol. 59(1) (2003), p. 119–127.

[19] Z. Aslan, R. Karakuzu, and O. Sayman, O: Dynamic Characteristics of Laminated Woven E-Glass-Epoxy Composite Plates Subjected to Low velocity Heavy Mass Impact. Journal of Composite Materials, Vol. 36(21) (2002), p. 2421–2442.

[20] M.T.H. Sultan, K. Worden, W.J. Staszewski, A. Hodzic: Impact damage characterisation of composite laminates using a statistical approach. Composites Science and Technology, Vol. 72 (2012), p. 1108–1120.

[21] G. Lubin: Handbook of composites, New York: Van Nostrand Reinhold, (1982), p. 3.

[22] G.S. Chandekar, and A.D. Kelkar: Experimental and Numerical Investigations of Textile Hybrid Composites Subjected to Low Velocity Impact Loadings. The Scientific World Journal, (2014).

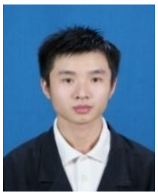
[23] Boeing Specification Support Standard BSS 7260. Advanced Composite Compression Tests. Seattle, Washington: The Boeing Co. (1988).

[24] M.T.H. Sultan, A. Hodzic, W.J. Staszewski and K. Worden: A SEM-Based Study of Structural Impact Damage. Applied Mechanics and Materials, Vol. 24-25 (2010), p. 233-238.

[25] P.O. Sjoblom, J.T. Hartness, and T.M. Cordell: On Low-Velocity Impact Testing of Composite Materials. Journal of Composite Materials, Vol. 22(1) (1988), p. 30–52.

BIOGRAPHIES

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).