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EXPERIMENTAL INVESTIGATION OF GLASS FIBRE-REINFORCED POLYMER (GFRP) WHEN SUBJECTED TO LOW AND HIGH VELOCITY IMPACT EVENTS

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By

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Chairman: Mohamed Thariq bin Hameed Sultan, PhD
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The motivation for this work is to identify the high velocity impact damage in structures made from a composite material and to conduct an experimental study of a low velocity impact test by changes in the type of materials, number of layers and impact energy level using an IM10 Drop Weight Impact Tester. The composite material chosen for this research is Glass Fibre Reinforced Polymer (GFRP) in two forms: Type C-glass 600 g/m^2 and Type E-glass 600 g/m^2. This material is fabricated using a heat blanket machine and vacuum bagging to produce laminated plate specimens of 100 mm × 100 mm with 6, 8, 10, and 12mm of thickness for high velocity impact testing. For low velocity impact test specimens, laminated plate specimens with a dimension of 100 mm × 150 mm were fabricated using a hand lay-up technique into 10 layers, 12 layers and 14 layers of GFRP woven roving plies. The high velocity impact test is performed on three specimens for each thickness using an instrumented Single Stage Gas Gun (SSGG) and the pressure of the gas gun is set to range from 5 bar to 60 bar. Each of the tests is performed using three types of bullet which are blunt, hemispherical and conical. The entire impact event capture from the impact test is recorded using the Ballistic Data Acquisition System. Meanwhile, the low velocity impact test is performed using an IM10 Drop Weight Impact Tester with a 10 mm hemispherical striker cap. The impact energy is set to 14, 28, 42 and 56 Joule with a velocity ranging from 1.73 m/s to 3.52 m/s for 10 layer specimens and 7, 14, 21, 28, 35, 42, 49 and 56 Joule for 12 layer and 14 layer specimens. The correlation between the impacted specimens and thicknesses is presented and discussed. A general trend was observed on the overall test which indicates that as the thickness or layers of the specimens and pressure increase, the energy absorbed also increases. The damage continues to increase as the velocity of the projectile increases. Impact damage was found to be in the form of fibre cracking, fibre breakage, matrix cracking and fibre pullout. Results from this research can be used as a reference in designing the structure of aircraft and body armour applications and in developing a better understanding of the test methods used to characterise impact behaviour.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

PENYIASATAN EKSPERIMEN UNTUK POLIMER BERTETULANG GENTIAN KACA APABILA DIKENAKAN HENTAMAN KELAJUAN RENDAH DAN TINGGI

Oleh

NOORSHAZLIN BINTI RAZALI

November 2014

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Motivasi untuk kerja-kerja ini adalah untuk mengenal pasti kerosakan hentaman halaju tinggi dalam struktur yang diperbuat daripada bahan komposit dan untuk menjalankan kajian eksperimen ujian hentaman halaju yang rendah oleh perubahan dalam jenis bahan, bilangan lapisan dan memberi impak kepada tahap tenaga menggunakan IM10 Drop Weight Impact Tester. Bahan komposit yang dipilih untuk kajian ini ialah Polimer Bertetulang Gentian Kaca (GFRP) dalam dua bentuk: Jenis C-kaca 600 g / m^2 dan Jenis E-kaca 600 g / m^2. Bahan ini direka menggunakan mesin selimut haba dan pembalut vakum untuk menghasilkan spesimen plat berlapis 100 mm × 100 mm dengan 6, 8, 10, dan 12 mm tebal untuk ujian hentaman halaju tinggi. Bagi spesimen ujian hentaman halaju rendah, spesimen plat berlapis dengan dimensi 100 mm × 150 mm telah direka menggunakan teknik tangan ke dalam 10 lapisan, lapisan 12 dan 14 lapisan GFRP. Ujian hentaman halaju tinggi dilakukan pada tiga spesimen bagi setiap ketebalan menggunakan alat Single Peringkat Gas Gun (SSGG) dan tekanan senapang gas dijangka dari 5 bar 60 bar. Setiap satu daripada ujian yang dilakukan dengan menggunakan tiga jenis peluru yang tumpul, hemisfera dan kon. Seluruh acara menangkap hentaman daripada ujian hentaman itu dirakam menggunakan Balistic Data Aquisition System. Sementara itu, ujian hentaman halaju rendah dilakukan menggunakan IM10 Drop Weight Impact Tester dengan 10 mm hemisfera. Tenaga hentaman ditetapkan kepada 14, 28, 42 dan 56 Joule dengan halaju antara 1.73 m / s hingga 3.52 m / s untuk spesimen 10 lapis dan 7, 14, 21, 28, 35, 42, 49 dan 56 Joule untuk 12 lapis dan 14 lapis. Hubungan antara hentaman spesimen dan ketebalan dibentangkan dan dibincangkan. Corak umum diperhatikan pada ujian keseluruhan yang menunjukkan bahawa ketebalan lapisan atau spesimen dan tekanan meningkat, tenaga yang diserap juga meningkat. Kerosakan ini terus meningkat kerana halaju peluru bertambah. Kerosakan impak didapati dalam bentuk keretakan serat, serat kerosakan, keretakan matriks dan serat sisipan. Hasil daripada kajian ini boleh digunakan sebagai rujukan dalam mereka bentuk struktur pesawat dan perisai badan aplikasi dan dalam membangunkan pemahaman yang lebih baik daripada kaedah ujian yang digunakan untuk mencirikan kelakuan hentaman.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

BVID	Barely Visible Impact Damage
CFRP	Carbon Fibre Reinforced Polymer
CMC	Ceramic Matrix Composites
E_a	Energy Absorbed
F	Force
g	Acceleration of gravity
g/m^2	Gram per meter square
GFRP	Glass Fibre Reinforced Polymer
GPa	Giga Pascal
h	height
HVI	High Velocity Impact
J	Joule
KE	Kinetic Energy
LVI	Low Velocity Impact
m	mass
m/s	Meter per second
mm	millimeter
MMC	Metal Matrix Composites
MPa	Mega Pascal
N	Newton
NDE	Non Destructive Evaluation
PE	Potential Energy
SSGG	Single Stage Gas Gun
v	velocity

CHAPTER 1

INTRODUCTION

1.1 Overview

Fibre-reinforced composite materials are widely used in aircraft, modern vehicles and lightweight structures. Composite structures have a high strength-to-weight and stiffness-to-weight ratio, however, because they are laminar systems with weak interfaces, they are susceptible to impact loading. This may cause invisible cracks and delaminations to occur in the material, which are often difficult to predict and detect. The damage of composite structures from impact events is one of the most important aspects of behaviour that inhibits more widespread application of composite materials. Understanding the deformation and damage mechanisms involved in the impact of composite targets is important in the effective design of a composite structure. A prerequisite for increasing the use of composite materials is the need to predict damage from low velocity impacts.

There are a many research studies being conducted to evaluate the impact damage of composite materials. Impact events can be categorised into four velocity ranges which are low, high, ballistics and hypervelocity. A low velocity impact may include a situation such as a dropped tool (< 31 m/s), whereas a high velocity impact may include a situation such as a bird colliding with an airplane (31 m/s – 240 m/s). Ballistic impacts are situations such as a projectile fired from a gun at speeds exceeding 240 m/s and finally orbital debris that travels in outer-space at velocities up to 15,240 m/s are considered to be hypervelocity impact events [1].

1.2 Problem Statements

Composites are defined as a material which has two or more different elements that when combined, produces a stronger, stiffer, tougher and more durable material than the individual elements. Composite can be divided into three types which are polymer matrix composites (PMC's), metal matrix composites (MMC's), and Ceramic Matrix Composites (CMC's). The most commonly used and the ones discussed here is the Polymer Matrix Composites, also known as Fibre Reinforced Polymers, FRP (or Plastics). This material has proven to be a highly favourable material for the aerospace applications. When composites were introduced in aircraft components and aerospace industries, unexpected impacts occurred. These may have been due to damages during flight operations such as runway debris on composite airframes, bird strike during flight operations and dropping of hand tools during maintenance work. For this research, the impact velocity is set to be less than 31 m/s which indicates low velocity testing. For high velocity testing, the impact velocity is in the range of 31 m/s - 240 m/s. In this study, low velocity and high velocity impact test has been chosen to conduct a test on GFRP since this material has been used widely in many applications. Previous researchers have conducted studies on the comparison between different types of composite. Moreover, the studies of low velocity and high velocity in comparison between two types of GFRP have not been done before. Therefore, this study needs to be done in order to analyse and to study the impact behaviour of GFRP in the form of chemical durability (Type C) and electrical conductivity (Type E). When these materials are subjected to high and low-velocity impacts, the structural integrity, stiffness and the toughness of the material are significantly reduced, which may result in a catastrophic failure to the structure in extreme scenarios [2]. Matrix cracking, fibre fracture, fibre pullout and delamination are major undetected hidden damages faced by composite materials after the event of an impact. Therefore, there is a need to study the behaviour under impact loading of composite materials since impacts occur mainly during maintenance and work manufacturing.

Presumably, all designers base their choices of material on cost and performance. However, their conclusions differ. The most economical choice depends on the cost of the material, the production cost, the life cycle cost and the material's properties. Weight saving and performance naturally play a major factor in the choice of materials. For aerospace structures, it is clear that carbon fibre is superior to glass fibre from a performance/cost standpoint since superfluous weight is very costly [3].

Therefore, for this research study, fibreglass has been chosen as the experimental material. Fibreglass is less expensive than carbon fibre and Kevlar. Due to the cost of production nowadays, this material is chosen to test its strength and its impact behaviour in low velocity impact and high velocity impact situations. To implement this, two types of different fibreglass will be studied, which are E-Type 600 g/m^3 and C-Type 600 g/m^3. Both materials are woven roving cloth. The main interest in this research is to compare the two different types of fibreglass in terms of stiffness, toughness and impact resistance subjected to changes in the test specimen thickness on impact loading. Finally, at the end of this research, conclusions can be drawn about the type and thickness of these materials which are safe to be implemented in structural and body armour applications as a replacement for existing materials(such as type S-glass and Kevlar) due to their high cost and availability.

A prerequisite for increasing the usage of composite materials is the need to predict damage during impact events. Many researchers have employed an experimental approach to evaluate impact damage to composite materials. To implement this, an instrumental impact tester - namely the Single Stage Gas Gun- which is well equipped with a Ballistic Data Acquisition System, has been used to predict and study the damage area. An IM10 Drop Weight Impact Tester is used to perform the low velocity impact test.

1.3 Aim and Objectives of Study

The general objective of the study is to conduct an experimental investigation of high velocity impact and low velocity impact subjected to changes in the test specimen layers, thickness, type of bullet and velocity using a Single Stage Gas Gun (SSGG) and an IM10 Drop Weight Impact Tester. The specific objectives of the study are stated as follows:

i. To fabricate the test specimens by using a traditional hand lay-up technique and with the aid of a hot bounder machine and vacuum bagging.
ii. To conduct an experiment of low velocity impact test on two types of GFRP which are Type C and Type E at different impact energy level by using hemispherical cap impactor.
iii. To conduct an experiment of high velocity impact test on GFRP; Type C and Type E at different gas gun pressure and impact velocities.
iv. To analyse the impact load, impact energy, impact resistance, penetration behaviour and the effect of high impact loading toward different layers and velocity between the two types of fibreglass by SSGG, using different types of bullet.
v. To analyse the impact force, impact energy, energy absorbed, damage area, displacement and the effect of a low velocity impact corresponding to different numbers of layers and the impact energy level between two types of fibreglass- Type C-glass/Epoxy 600 g/m^2 and Type E-glass/Epoxy 600 g/m^2- using an IM10 Drop Weight Impact Tester.
vi. To observe the type of failure between the two types of fibreglass using a non-destructive technique.

1.4 Layout of Thesis

This thesis is basically divided into 6 chapters. The first chapter has been discussed here thoroughly. The outlines of the following chapters are as follows:

i. A literature review has been carried out in Chapter 2 in order to study the previous experimental and research studies on low velocity and high velocity impact loading on composite materials. Once the literature review is done, the appropriate methodology for the current research can be decided.
ii. In Chapter 3, the methodology for preparing the test specimens and performing the impact tests is discussed. Also discussed are the methods used in the non-destructive techniques involved in this study.
iii. In Chapter 4, the low velocity results and analysis are presented.
iv. The high velocity results and analysis are discussed in Chapter 5.
v. The study is concluded in Chapter 6. Future recommendations are also proposed in this chapter.

1.5 Scope of Studies

The scope of studies is to investigate the impact of characteristic and resistance behaviour of the two types of Glass Fibre Reinforce Polymer (GFRP); Type C which has a high chemical durability and Type E that has a low electrical conductivity. Low velocity impact and high velocity impact were conducted to study the impact behaviour on the specimens. The differences in thickness, number of layers, impact energy level, bullet types and impact velocity of impactor/projectiles had been used in order to study the effect of the impact event. The damage on the specimens after the impact test were then examined by using a non-destructive method.

REFERENCES

[1] **Stilp, A. J. and Hohler, V.** *Experimental Methods for Terminal Ballistics and Impact Physics. High Velocity Impact Dynamics*, John Wiley and Sons, Inc, 1990.

[2] **Abrate, S.** *Impact on composite structures.* Cambridge, UK : Cambridge University Press, 1998.

[3] **Christopher Wonderly, A.P. and Swanson, S. R.** *Analysis of Impact Response in Composite Plates.* 2003, International Journal Solids Structures 27 (2), pp. 161-170.

[4] **Zhou, G.** *Damage Mechanisms In Composite Laminates Impacted By A Flat-Ended Impactor.* 1995, Composites Science and Technology 54, pp. 267-273.

[5] **Ibekwe, S. I., et al.** *Impact and post impact response of laminated beams at low temperatures.* 2007, Composite Structure, pp. 79:12-7.

[6] **Hawyes, V. J., Curtis, P. T. and Soutis, C.** *Effect of impact on the compressive response of composite laminates.* 2001, Composite Part A-Appl S, pp. 32:1263-70.

[7] **Bond, D. A.** Composites. *MSc Lecture Notes.*

[8] Carbon Fibre. [Online] [Cited: Mac 31, 2012.] http://www.azom.com/details.asp?articleID=962.

[9] **Paget, J.** Composite Materials-An Introduction. [Online] [Cited: February 19, 2012.] http://elitecomposites.co.uk.

[10] **Kalpakjian, S. and Schmid, S. R.** *Manufacturing Engineering and Technology.* Singapore : Prentice Hall Pearson Education South Asia Pte Ltd Publishers, 2006.

[11] Introduction to laser machining of composites (I). [Online] [Cited: December 20, 2012.] http://www.mrl.columbia.edu/ntm/level1/ch05/html/l1c05s03.html.

[12] **Gombos, Z.** *Analysis Of Glass Fibre Mat Structures And Their Impact On The Resin Absorption Process And On The Characteristics Of Composites.* Department of Polymer, 2010.

[13] **Seelenbinder, J.** *Composite heat damage measurement using the handheld Agilent 4100 ExoScan FTIR, Easy, non-destructive analysis of large parts.* Connecticut, USA : Agilent Technologies, 2011.

[14] **Anefaie, K., Abd-Rabou, M. and Bajaba, N.** *Finite Element Modeling of multi-Layer Composite Plates with Internal Delamination.* 2009, Composite Structure, pp. 90(1):21-27.

[15] **Børvik, T.** *An introduction to impact and penetration dynamics.* Norwegian University of Science and Technology, 2003.

[16] **Meyers, M.A.** *Dynamic behavior of materials.* Wiley, New York , 1994.

[17] **Vlot, A. and Gunnink, J. W.** *Fibre metal laminates, an introduction.* Dordrecht, the Netherlands : Kluwer Academic Publishers, 2001.

[18] **Cantwell, W. J. and Morton, J.** *The impact resistance of composite materials-a review.* 1991, Composites, pp. 347–362.

[19] **Harris, C. H., Jr., J. H. Starnes and Shuart, M. J.** *Design and Manufacture of Aerospace Composite Structures, State-of-the Art Assessment.* 2002, Journal of Aircraft, pp. 545-560.

[20] **Freeman, W. T.***The Use of Composites in Aircraft Primary Structure.* 1993, Composites Engineering, pp. Vol. 3, pp. 0961-9526

[21] **Mazumdar, S.K.** *Composites Manufacturing Materials, Product, and Process Engineering.* CRC Press, 2001.

[22] **Pora, J.** *Composite Materials in the Airbus A380, From History to Future.* Airbus, Large Aircraft Division, 2001.

[23] **Niu, M. C.** *Composite Airframe Structures.* Hong Kong : Materials, Conmilit Press Ltd, 2010.

[24] **Laliberté, J. F., et al.***Applications of fibre-metal laminates.* 2004, Polym Composite, pp. 558–567.

[25] **Bradshaw, F. J., Derey, G. and Skley, G. R.** *Impact resistance of carbon reinforced plastics.* RAE TR, 1972.

[26] **Retem, A.** *Residual flexural strength of FRP composite specimens subjected to transverse impact loading.* 1988, SAMPE Journa124, pp. 24:19–25.

[27] **Avery, J.G.** *Design Manual for Impact Damage Tolerant Aircraft Structures.* s.l. : AGARDograph No 238 NATO, 1981.

[28] **Zukas, J. A.** *Impact dynamics.* New York : John Wiley & Sons, 1990.

[29] **Grytten, F.** *Low-Velocity Penetration of Aluminium Plates.* s.l. : Norwegian University of Science and Technology, 2008.

[30] **Backman, M. E. and Goldsmith, W.** *The mechanics of penetration of projectiles into targets.* 1978, Int. J. Eng. Sci, pp. 1–99.

[31] **Zheng, Daihua.** *Low Velocity Impact Analysis of Composite Laminated Plates.* The Graduate Faculty of the University of Akron : Ph.D. Thesis, 2007.

[32] **Yidris, N., et al.** *Crush Simulation of Woven C-Glass/Epoxy Unmanned Ariel Vehicle Fuselage Section.* 2010, International Journal of Mechanical and Material Engineering, pp. 260-267.

[33] **Sultan, M. T. H.** *Impact Damage Characterisation in Composite Laminates.* Department of Mechanical Engineering the University of Sheffield : PhD Thesis, 2011.

[34] **Sultan, M. T. H., et al.** *Impact damage characterisation of composite laminates using a statistical approach.* 2012, Composites Science and Technology 72, pp. 1108-1120.

[35] **Schoeppner, G. A. and Abrate, S.** *Delamination threshold loads for low velocity impact on composite laminates.* 2000, Composite Part A: Applied Science and Manufacturing, pp. 903-915.

[36] **Sultan, M. T. H., et al.** *Impact Damage Detection and Quantification for CFRP Laminates Subjected To Low Velocity Impact Damage - A NDT Approach.* 2011, Journal of Malaysian Society for Non-Destructive Testing (NDT Spectra), pp. 5, 15-20.

[37] **Naik, N. K., Chandra, Y. S. and Meduri, S.** *Damage in woven-fabric composites subjected to low-velocity impact.* 2000, Composite Science and Technology, pp. 60(5), 731-744.

[38] **Rilo, N. F. and Ferreira, L. M. S.** *Experimental study of low-velocity impacts on glass-epoxy laminated composite plates.* Int J Mech Mater Des, 2008.

[39] **Tita, V., Carvalho, J. D. and Vandepitte, D.** *Failure analysis of low velocity impact on thin composite laminates: Experimental and numerical approaches.* 2008, Composite Structures 83, pp. 413–428.

[40] **Grady, D. E. and Winfree, N. A.** *Impact fragmentation of high-velocity compactprojectiles on thin plates: a physical and statistical characterization offragment debris.* 2001, International Journal of Impact Engineering, pp. 26(1–10):249–62.

[41] **Hibbler, R. C.** *Engineering mechanics: statistics.* New York : Macmillan, 1989.

[42] **Sultan, M. T. H., et al.** *Impact damage characterisation of composite laminates using a statistical approach.* 2012, Composites Science and Technology 72, pp. 1108–1120.

[43] **Mathivanan, N. Rajesh and Jerald, J.** *Experimental investigation of low-velocity impact characteristics of woven glass fiber epoxy matrix composite laminates of EP3 grade.* 2010, Materials and Design 31, pp. 4553–4560.

[44] **Zhang, Z. Y. and Richardson, M. O. W.** *Low velocity impact induced damage evaluation and its effect on the residual flexural properties of pultruded GRP composites.* 2007, Composite Structure, pp. 81:195–201.

[45] **Santos, M. J., et al.** *Low velocity impact damage evaluation in fiber glass composite plates using PZT sensors.* 2013, Composites: Part B 55, pp. 269–276.

[46] **Sfarra, S., et al.** *Falling weight impacted glass and basalt fibre woven composites inspected using non-destructive techniques.* 2013, Composites: Part B 45, pp. 601–608.

[47] **Russo, P., et al.** *Flexural and impact response of woven glass fiber fabric/polypropylene composites.* 2013, Composites: Part B 54, pp. 415–421.

[48] **Fatt, M. S. Hoo and Sirivolu, D.** *A wave propagation model for the high velocity impact response of a composite sandwich panel.* 2010, International Journal of Impact Engineering 37, pp. 117–130.

[49] **Sabet, A., Fagih, N. and Beheshty, M. H.** *Effect of reinforcement type on high velocity impact response of GRP plates using a sharp tip projectile.* 2011, International Journal of Impact Engineering 38, pp. 715–722.

[50] **Kim, J. K. and Sham, M. L.** *Impact and delamination failure of woven-fabric composites.* 2000, Composite Science Technology, pp. 745–761.

[51] **Mines, R. A. W., Roach, A. M. and Jones, N.** *High velocity perforation behavior of polymer composite laminates.* 1999, International Journal of Impact Engineering, pp. 561–588.

[52] **Babu, M. Ganesh, Velmurugan, R. and Gupta, N.K.** *Energy absorption ans ballistic limit of targets struck by heavy projectile.* 2006, Latin Am J Solids Structures, pp. 21-39.

[53] N**aik, N. K., Shrirao, P. and Reddy, B. C. K.** *Ballistic impact behavior of woven fabric composites: formulation.* 2006, International Journal of Impact Engineering, pp. 1521–1552.

[54] **Sultan, M. T. H., et al.** *High Velocity Impact Damage Analysis for Glass Epoxy – Laminated Plates.* 2012, Advanced Materials Research, pp. 2318-2328.

[55] **Mahfuz, H., et al.** *Investigation of high-velocity impact on integral armor using finite element method.* 2000, International Journal of Impact Engineering 24, pp. 203-217.

[56] **Fujii, K., et al.** *Impact perforation behavior of CFRPs using high-velocity steel sphere.* 2002, International Journal of Impact Engineering 27, pp. 497–508.

[57] **Kim, H., Welch, D. A. and Kedward, K. T.** *Experimental investigation of high velocity ice impacts on woven carbon/epoxy composite panels.* 2003, Composites: Part A 34, pp. 25–41.

[58] **Villanueva, G. R. and Cantwell, W.J.** *The high velocity impact response of composite and FML-reinforced sandwich structures.* 2004, Composites Science and Technology 64, pp. 35–54.

[59] **Beppu, M., et al.** *Damage evaluation of concrete plates by high-velocity impact.* 2008, International Journal of Impact Engineering 35, pp. 1419–1426.

[60] **Sevkat, E., et al.** *A combined experimental and numerical approach to study ballistic impact response of S2-glass fibre/toughened epoxy composite beams.* 2009, Composites Science and Technology 69, pp. 965–982.

[61] **López-Puente, J., et al.** *Analytical modelling of high velocity impacts of cylindrical projectiles on carbon/epoxy laminates.* 2009, Composites: Part A 40, pp. 1223–1230.

[62] **Buitrago, B. L., García-Castillo, S. K. and Barbero, E.** *Experimental analysis of perforation of glass/polyester structures subjected to high-velocity impact.* 2010, Materials Letters 64, pp. 1052–1054.

[63] **Ozsahin, E. and Tolun, S.** *Influence of surface coating on ballistic performance of aluminum plates subjected to high velocity impact loads.* 2010, Materials and Design 31, pp. 1276–1283.

[64] **Buitrago, B. L., et al.** *Modelling of composite sandwich structures with honeycomb core subjected to high-velocity impact.* 2010, Composite Structures 92, pp. 2090–2096.

[65] **Johnson, G. R., Beissel, S. R. and Gerlach, C. A.** *Another approach to a hybrid particle-finite element algorithm for high-velocity impact.* 2011, International Journal of Impact Engineering 38, pp. 397-405.

[66] **Combescure, A., Chuzel-Marmot, Y. and Fabis, J.** *Experimental study of high-velocity impact and fracture of ice.* 2011, International Journal of Solids and Structures 48, pp. 2779–2790.

[67] **Johnson, G. R.** *Numerical algorithms and material models for high-velocity impact computations.* 2011, International Journal of Impact Engineering 38, pp. 456-472.

[68] **Ivañez, I., et al.** *Numerical modelling of foam-cored sandwich plates under high-velocity impact.* 2011, Composite Structures 93, pp. 2392–2399.

[69] **Talib, A.R. Abu, et al.** *Ballistic impact performance of Kevlar-29 and Al2O3 powder/epoxy targets under high velocity impact.* 2012, Materials and Design 35, pp. 12–19.

[70] **Astanin, V.V., et al.** *Characterising failure in textile-reinforced thermoplastic composites by electromagnetic emission measurements under medium and high velocity impact loading.* 2012, International Journal of Impact Engineering 49, pp. 22-30.

[71] **Prakash, A., et al.** *Influence of adhesive thickness on high velocity impact performance of ceramic/metal composite targets.* 2013, International Journal of Adhesion & Adhesives 41, pp. 186–197.

[72] **Jabbar, Abdul, et al.** *Comparison of Mechanical and Ballistic Performance of Composite Laminates Produced From Single-layer and Double-layer Interlocked Woven Structures.* 2013, Wiley Online Library (wileyonlinelibrary.com).

[73] **Othman, A.R. and Hassan, M.H.** *Effect of different construction designs of aramid fabric on the ballistic performances.* 2013, Materials and Design 44, pp. 407–413.

[74] **Ramadhan, A.A., et al.** *High velocity impact response of Kevlar-29/epoxy and 6061-T6 aluminum laminated panels.* 2013, Materials and Design 43, pp. 307–321.

[75] **Grimaldi, A., et al.** *Parametric study of a SPH high velocity impact analysis – A birdstrike windshield application.* 2013, Composite Structures 96, pp. 616–630.

[76] **Mohotti, D., et al.** *Polyurea coated composite aluminium plates subjected to high velocity projectile impact.* 2013, Materials and Design 52, pp. 1–16.

[77] **Wan, H., et al.** *Shielding performances of the designed hybrid laminates impacted by hypervelocity flyer.* 2013, Materials and Design 52, pp. 422–428.

[78] **Khan, D. F., et al.** *Effect of impact force on Ti–10Mo alloy powder compaction by high velocity compaction technique.* 2014, Materials and Design 54, pp. 149–153.

[79] **Sánchez, J. P., et al.** *Experimental analysis of normal and oblique high velocity impacts on carbon/epoxy tape laminates.* 2014, Composites: Part A 60, pp. 24–31.

[80] **Heimbs, S., et al.** *High velocity impact on preloaded composite plates.* 2014, Composite Structures 111, pp. 158–168.

[81] **Nasirzadeh, R. and Sabet, A. R.** *Study of foam density variations in composite sandwich panels under high velocity impact loading.* 2014, International Journal of Impact Engineering 63, pp. 129-139.

[82] **Frederick, E.C. and Hagy, J.L.** *Factors Affecting Peak Vertical Ground Reaction Forces in Running.* 1986, International Journal of Sport Biomechanics, pp. 41 – 49.

[83] Impact (mechanics). [Online] [Cited: December 10, 2013.] http://en.wikipedia.org/wiki/Impact_(mechanics).

[84] **Lu, G. and Tongxi, Y.Y.** *Energy Absorption of Structures and Materials.*Woodhead Publishing, 2003.

[85] **Rattan.** *Strength Of Materials.* Tata McGraw-Hill Education, 2011.

[86] **Jacob, G.C., et al.** *Energy Absorption in Polymer Composite Materials for Automotive Crashworthiness.* 2002, pp. 813-850.

[87] **Farley, G.L.** *Relationship Between Mechanical Property and Energy Absorption Trends for Composite Tubes.* NASA TP-3284, 1992.

[88] **Gupta, N.K., Iqbal, M.A. and Sekhon, G.S.** *Effect of projectile nose shape, impact velocity and target thickness on deformation behavior of aluminum plates.* 2007, International Journal of Solids and Structures 44 , pp. 3411–3439.

[89] **Wingrove, A.L.** *The influence of projectile geometry on adiabatic shear and target failure.* 1973, Metallurgical Transactions, pp. 1829-1833.

[90] **Ipson, T.W. and Recht, R.F.** *Ballistic Perforation by Fragments of Arbitrary Shape.* Denver : University of Colorado, Denver Research Institute, 1977.

[91] **Borvik, T., et al.** *Perforation of 12 mm thick steel plates by 20 mm diameter projectiles with flat, hemispherical and conical noses part II: numerical simulations.* 2002, International Journal of Impact Engineering 27, pp. 37–64.

[92] **Drzal, L. T., Herra-Franko, P. J. and Hoe, H.**. *Fibre-Matrix Interface Tests.* 2000, Comprehensive Composite Materials.

[93] **Liu, D. and Malvern, L.E.** *Matrix cracking in impacted glass/ epoxy plates.* 1987, J. Compos. Mater, pp. 594-609.

[94] **Richardson, M.O.W. and Wisheart, M.J.** *Review of low-velocity impact properties of composite materials.* 1996, Composites Purr A 27A, pp. 1123–1131.

[95] **Hawthorne, K.** What Is Woven Roving Fiberglass. [Online] [Cited: Mac 20, 2013.] http://www.ehow.com/facts_7767993_woven-roving-fiberglass.html.

[96] **Al-Hasani, E. S.** *Study of Tensile Strength and Hardness Property for Epoxy Reinforced With Glass Fiber Layers.* 2007, Eng. & Technology.

[97] **Avila, A. F. and Morais, D. T. S.** *A Multiscale Investigation Based On Variance Analysis For Hand Lay-Up Composite Manufacturing.* 2005, Composites Science and Technology 65, pp. 827–838.

[98] **Campbell, F.C.** *Manufacturing Technology for Aerospace Structural Materials.* s.l. : Elsevier Ltd, 2006.

[99] **Mazumdar, S. K.** *Composites Manufacturing Materials, Product, and Process Engineering.* s.l. : CRC Press, 2001.

[100] **Pora, J.** *Composite Materials in the Airbus A380,From History to Future.* Airbus, Large Aircraft Division, 2001.

[101] *Epoxy Resin/ Hardener Zeepoxy HL002 TA/B.* Shah Alam, Selangor : My East Sdn Bhd.

[102] **Boeing.** *Advanced composite compression tests BSS 7260. In Boeing Specification Support Standard BSS 7260.* Washington : Boeing Spec Support std.

[103] *Standard Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer Matrix Composite to a Drop-Weight Impact Event.* 2005, ASTM International.

[104] Imatek. [Online] [Cited: July 15, 2014.] http://www.imatek.co.uk/downloads/product-brief-im10t.pdf.

[105] **UMP.** *Operation Manual- One (01) Unit Single Stage Compressed.* Pekan, Pahang, Malaysia : University Malaysia Pahang.

[106] Boeing 787 Official Home Page. [Online] [Cited: December 18, 2012.] http://www.boeing.com/commercial/787family.

APPENDICES

Appendix A

Procedure for Using Single Stage Compressed Gas Gun

1. The main valve on the helium gas tank was turned on. The reading on the main meter displays the content of helium gas in the tank unit. The pressure in the helium gas tank is ensured to be sufficient before conducting the project. (Pressure depends on the needs of the specific project to be conducted)

2. The switch of the compressor unit was turned on. The pressure in the compressor unit is ensured to be sufficient (The compressor will turn off automatically when there is enough pressure). It is ensured that the valve of the compressor is turned on.

3. The second valve was turned on by turning it (in a clockwise direction) until the desired pressure was reached. The reading displayed on the second meter shows the helium gas content that has been dissipated from the helium tank. The valve was turned slowly to prevent the pressure being dissipated being more than the pressure required. The second meter reading was continually observed while turning the valve.

4. The safety valve was turned on (situated on the helium gas pipe) to adjust the pressure in the pressure chamber which depends on the digital pressure gauge. The safety valve is on the helium gas. The valve was turned on (counter clockwise). The digital meter reading was continually monitored while adjusting the pressure.

5. The reading of the digital pressure gauge was ensured to be as needed. If the pressure reading on the digital meter is less, pressure was added using the second valve by turning the valve (in a clockwise direction) until the desired pressure was achieved.

6. Method to disassemble the connector to insert the projectile:
   i. First: the connector system was opened.
   ii. Second: the connector was turned.

7. Projectile has to be inserted according to the procedure as follows:
   i. First: the projectile was inserted into the tube/barrel hole.
   ii. Second: the projectile was inserted in the tube/barrel hole until it surpassed the connector using the metal object provided.
   iii. Third: the metal object was taken out after inserting the projectile.

iv. Fourth: The connector systems were re-assembled.

8. Method to open the Test Section. The correct procedure was ensured as the following step was performed before the specimen was inserted into the test section:
   i. First: the PVC Plate lock was opened.
   ii. Second: the PVC Plate was lifted up.
   iii. Third: the PVC Plate was hooked using the lock provided.
   iv. Fourth: the PVC plate was locked after the specimen had been inserted.

9. The trigger button unit was pressed to launch the projectile towards the specimen. Before the experiment was conducted, the user was located in the safe distance position.

Procedure of the Ballistic Data Acquisition System Hardware and Software

Test setup of the ballistic data acquisition system:
1. The tensioning bolt was loosened by turning the bolt counter-clockwise.
2. The force sensor housing was pulled back.
3. The force transducer housing was pulled back to its initial position. By doing this, the impact cap and force sensor button should be separated from each other.
4. The specimen clamping nuts were loosened to open the specimen clamping section which is the section between the specimen clamping back plate and the specimen clamping plate.
5. The previous specimen was removed if it was still in the specimen clamping section.
6. Step 5 was skipped if there was no previous specimen.
7. The specimen was inserted into the specimen clamping section.
8. The height of the specimen was adjusted through the specimen height adjustment hole.
9. The specimen clamping nuts were tightened to secure the specimen in the plate.
10. A check was made to see if the force transferring wing nuts were loose.
11. The force transferring wing nuts were tightened lightly to secure the wing nuts to the force transferring plate.
12. The movement of the shaft was checked. The shaft should move back and forth freely when the impact area is tapped slightly, which indicates minimal friction of the shaft and guide bearing.
13. If the movement of the shaft was restricted, the cable tensioner was tightened or loosened while checking the shaft movement.
14. The tensioning bolt was turned clockwise to push the force sensor forward to make the force sensor button and the impact cap touch each other. The touching of the two is indicated when the tensioning clip has touched the holding barrier and the tensioning clip is distorted slightly. When this has been reached, the bolt was turned approximately another quarter turn to maximise the touching of the force sensor button and the impact cap.
15. Once the sensor had been set and was ready to test, it was necessary to stay away from sensor.

16. Steps 1 to 14were repeated to test another specimen.

Running the Software

1. Key in the pressure value (in bar) in the text editor which must be equal to the pressure value of the pressure chamber that was displayed on the digital pressure gauge. The pressure value must be between 1 to 60 bar. Then press the insert button.

2. Key in the mass (in gram) value of the bullet. Make sure the mass of the bullet is determined beforehand. This is very important in order to get an accurate calculation. The mass value must be in between 1 to 25 gram. Then press the insert button.

3. Key in the range value (in cm) from the muzzle to the specimen surface. Make sure the range of the bullet is determined beforehand. This is very important in order to get an accurate calculation. The value must be in between 1 to 25 cm. Then press the insert button.

4. Choose the accurate shape of the bullet on the window by clicking one of the three possible shapes of the bullet.

5. To start running the software, make sure:
   i. The load cell cable is connected properly with the load cell and the BSC01 unit.
   ii. The connection of low noise from the BSC01 unit to the ADQ108 is properly connected.
   iii. The connection of the USB cable from the ADQ108 to the PC is properly connected.
   iv. The power of the BSC01 is on.
   v. The power of the ADQ108 is on.

Click on the START button to start recording data from the load cell (start the experiment). After clicking on the START button, wait a while until the ready light of the ADQ108 is energised before starting to fire (shoot) the bullet to the specimen. The ready light indicates that the ADQ108 is ready to receive high speed data. The waiting time is about 5-10 seconds. After the ready light is ON, always monitor the ready light. Make sure the light is still ON when starting to shoot the bullet. If the ready light is OFF suddenly, caused by any unknown reason, wait a while until the software displays the noise chart and the RESTART button appears. If this problem happens, re-start the process from the beginning (points 1 to 5). To re-start the process, click on the RESTART button on the window.

6. If nothing happens and the ready light is still ON, start to shoot the bullet. After the bullet is shot and has made direct contact with the specimen, the ready light of the ADQ108 will be OFF suddenly along with the impact occurring. Wait awhile until the software displays the current impact chart (Force against Time) and the information text displayed is “Done” on the window.

After the software records the data from the AD108, the raw data in decimal numbers will be converted to volts and then converted to force according to the calibration value from the factory and the gain factor of the signal conditioning. The force data recorded will be plotted by the software in Force (Newton) against Time (ns) and displayed on the window. The software also calculates the maximum impact force on the specimen and displays this on the window. The speed of the bullet is approximated by using a 5^{th} order polynomial of curve fitting method from the calibration data using a high speed camera. The approximation speed is displayed on the window.

7. Save the data file (*.mat) using the SAVE button. Replace the name of the file first before clicking on the SAVE button.

To place the file into a specific folder, click on the *Folder select* button at the left side of the SAVE button. The *Save Workplace As* window will appear. Key in the new file name in the file name textbox and then click the *Save* button. The new file name will appear in the file name textbox of the software window.
Then press the SAVE button on the window to save the data as a new file name. Please wait awhile until the Save information text displays “Data Saved”. The saving of data will need some time to finish.

8. There are several graph options already given by the software and displayed on the window.
   i. Graph Volt-Time. This option will display data in Volts against Time (ns) on the chart of the software. Click on the Graph Volt-Time button and the graph will automatically display the chart.
   ii. Graph Force-Time. This option will display data Force (Newton) against Time (ns) on the chart of the software. Click on the Graph Force-Time button and the graph will automatically display the chart.
   iii. Impulse Calculation. This option will calculate the integration impulse from force multiplied by time at the specified time range. Click on the Impulse Calc button then the software will display the graph Force against Time on the chart. The user needs to select the starting time and the stop time of the impulse time range by clicking the point on the data graph using the mouse cursor. The mouse cursor will appear on the chart once the mouse pointer is placed on the chart. The user just needs two points only at the first stage of this process.

After clicking two points on the graph (start and stop time points), the software will automatically zoom and focus the graph only at that specified time.

In the second process, the user needs to specify in more detail the two points (start and stop points) of the impulse calculation. This process is the same as the first process. The user needs to click two points on the graph using the mouse cursor. After that the software will calculate the impulse or area underneath the curve.

Important: this process will need much time and memory to finish. Make sure that there is no other application running on the computer than Matlab. Wait until the process is finished.

After the process is finished, the software will display a graph in different figures with the red colour underneath the curve and Impulse Value also displayed at the top of the graph as shown in the figure below.

i. Impact Energy. This option will calculate the Kinetic Energy of the bullet based on the mass and speed of the bullet and also the energy absorbed by the specimen. The absorbed energy is calculated from the maximum force and travelling range of the bullet from the muzzle. The result is displayed on the window. The unit of energy is the Joule.
ii. Use Filter. This option is used when the user needs to remove specified noise from the recorded data. The filter that is provided by the software is a second order low pass filter. To start filtering the data, the user needs to click the option box Use Filter. Then the frequency textbox and Filter button will appear. Key in the cut off frequency of the low pass filter in Hertz then click the filter button. The software will then calculate a bode plot of the filter and display plotted filtered data on the chart.

9. If the user wants to start another experiment, the user can start it directly using the opened software window without having to close the software by clicking on the RESTART button and following steps 1 to 8.

10. If the user wants to exit from the software, the user can click on the EXIT button. Then the EXIT window will appear. The user can choose Yes to exit from the software, and No or Cancel if wanting to stay in the software.

APPENDIX B

Table 1: Results of Energy Absorbed (E_a) and Maximum Force (F_{max}) for 6 mm E-glass/Epoxy 600 g/m^2

Bullet type		6 bar				12 bar				18 bar			
		T1	T2	T3	Average	T1	T2	T3	Average	T1	T2	T3	Average
Blunt	E_a	30.603	42.288	30.864	34.5850	53.938	40.84	48.895	47.8910	60.68	60.706	74.014	65.1333
	F_{max}	182.16	251.71	183.71	205.8600	321.06	243.09	291.04	285.0633	361.19	361.35	440.56	387.7000
Hemi-spherical	E_a	26.044	30.316	28.224	28.1947	43.03	47.571	41.318	43.9730	46.905	69.614	71.104	62.5410
	F_{max}	155.02	180.45	168.48	167.9833	256.13	283.16	245.94	261.7433	279.19	414.37	423.24	372.2667
Conical	E_a	28.872	29.473	21.568	26.6377	39.315	25.617	54.195	39.7090	72.693	38.873	46.179	52.5817
	F_{max}	171.86	175.43	128.38	158.5567	234.02	152.48	322.59	236.3633	432.7	231.39	274.88	312.9900

Table 2: Results of Energy Absorbed (E_a) and Maximum Force (F_{max}) for 6 mm C-glass/Epoxy 600 g/m^2

Bullet type		6 bar				12 bar				18 bar			
		T1	T2	T3	Average	T1	T2	T3	Average	T1	T2	T3	Average
Blunt	E_a	21.6871	42.2453	37.2019	33.7114	33.7058	63.022	42.081	46.2696	65.6846	60.5522	60.88	62.3723
	F_{max}	129.09	251.46	221.44	200.6633	200.63	375.13	250.48	275.4133	390.98	360.43	362.38	371.2633
Hemi-spherical	E_a	23.9	34.4635	32.1686	30.1774	43.245	45.081	37.721	42.0157	59.603	56.851	65.352	60.6020
	F_{max}	142.26	205.14	191.48	179.6267	257.41	268.34	224.53	250.0933	354.78	338.4	389	360.7267
Conical	E_a	21.3259	24.6439	22.0147	22.6615	37.251	37.737	46.138	40.3753	59.3964	40.1654	50.665	50.0756
	F_{max}	126.94	146.69	131.04	134.8900	221.73	224.63	274.62	240.3267	353.55	239.08	301.58	298.0700

Table 3: Results of Energy Absorbed (E_a) and Maximum Force (F_{max}) for 8 mm E-glass/Epoxy 600 g/m^2

Bullet type		10 bar				20 bar				30 bar			
		T1	T2	T3	Average	T1	T2	T3	Average	T1	T2	T3	Average
Blunt	E_a	31.965	46.509	46.047	41.5070	48.124	50.371	49.586	49.3603	48.997	55.531	88.968	64.4987
	F_{max}	192.56	276.84	274.09	247.8300	289.9	303.44	298.71	297.3500	295.17	334.52	535.95	388.5467
Hemi-spherical	E_a	44.305	28.725	36.06	36.3633	48.922	30.696	44.022	41.2133	60.401	56.806	63.251	60.1527
	F_{max}	266.9	173.04	217.23	219.0567	294.71	184.91	265.19	248.2700	363.86	342.2	381.03	362.3633
Conical	E_a	35.238	31.864	28.796	31.9660	46.013	49.723	30.591	42.1090	57.93	48.065	58.434	54.8097
	F_{max}	212.28	191.95	173.47	192.5667	277.18	299.54	184.28	253.6667	348.97	289.55	352.01	330.1767

Table 4: Results of Energy Absorbed (E_a) and Maximum Force (F_{max}) for 8 mm C-glass/Epoxy 600 g/m^2

Bullet type		10 bar				20 bar				30 bar			
		T1	T2	T3	Average	T1	T2	T3	Average	T1	T2	T3	Average
Blunt	E_a	44.909	43.424	42.802	43.7117	49.516	53.927	66.117	56.5200	81.13	82.067	84.193	82.4633
	F_{max}	270.53	261.59	257.85	263.3233	294.74	324.86	398.29	339.2967	488.73	494.38	507.19	496.7667
Hemi-spherical	E_a	42.088	55.242	20.757	39.3623	41.776	65.28	46.444	51.1667	72.141	75.002	67.789	71.6440
	F_{max}	253.54	332.78	125.04	237.1200	251.66	393.25	279.78	308.2300	429.41	451.82	408.37	429.8667
Conical	E_a	44.989	33.638	36.445	38.3573	54.198	45.46	44.266	47.9747	62.352	62.426	73.535	66.1043
	F_{max}	271.02	202.64	219.55	231.0700	326.5	273.86	266.66	289.0067	375.61	376.06	442.98	398.2167

Table 5: Results of Energy Absorbed (E_a) and Maximum Force (F_{max}) for 10 mm E-glass/Epoxy 600 g/m^2

Bullet type		15 bar				30 bar				45 bar			
		T1	T2	T3	Average	T1	T2	T3	Average	T1	T2	T3	Average
Blunt	E_a	55.698	63.715	28.644	49.3523	40.312	67.427	51.829	53.1893	69.544	74.174	72.455	72.0577
	F_{max}	339.62	388.51	174.66	300.9300	245.8	411.14	316.03	324.3233	424.05	452.28	441.8	439.3767
Hemi-spherical	E_a	43.669	37.457	41.642	40.9227	48.006	38.338	72.003	52.7823	76.773	65.734	73.426	71.9777
	F_{max}	266.28	228.4	253.91	249.5300	292.72	233.77	439.04	321.8433	468.13	400.82	447.72	438.8900
Conical	E_a	38.836	33.094	35.785	35.9050	48.563	52.03	37.222	45.9383	68.37	74.789	30.009	57.7227
	F_{max}	236.8	201.79	218.2	218.9300	296.12	317.256	226.96	280.1120	416.89	456.03	182.98	351.9667

Table 6: Results of Energy Absorbed (E_a) and Maximum Force (F_{max}) for 10 mm C-glass/Epoxy 600 g/m^2

Bullet type		15 bar				30 bar				45 bar			
		T1	T2	T3	Average	T1	T2	T3	Average	T1	T2	T3	Average
Blunt	E_a	36.395	59.051	55.94	50.4620	55.281	53.617	59.919	56.2723	85.648	87.205	79.106	83.9863
	F_{max}	221.92	360.07	341.1	307.6967	337.08	326.93	365.36	343.1233	522.24	531.74	482.35	512.1100
Hemi-spherical	E_a	35.894	47.46	47.399	43.5843	28.043	64.253	58.667	50.3210	77.253	82.407	40.677	66.7790
	F_{max}	218.87	289.39	289.02	265.7600	170.99	391.79	357.72	306.8333	471.05	502.48	248.03	407.1867
Conical	E_a	49.854	26.539	46.702	41.0317	58.78	42.2	30.453	43.8110	50.499	65.666	65.661	60.6087
	F_{max}	303.99	161.82	277.99	247.9333	358.41	257.31	185.69	267.1367	307.92	400.4	400.37	369.5633

Table 7: Results of Energy Absorbed (E_a) and Maximum Force (F_{max}) for 12 mm E-glass/Epoxy 600 g/m^2

Bullet type		20 bar				40 bar				60 bar			
		T1	T2	T3	Average	T1	T2	T3	Average	T1	T2	T3	Average
Blunt	E_a	32.574	59.503	35.744	42.6070	59.226	60.557	52.127	57.3033	63.834	64.495	79.854	69.3943
	F_{max}	201.07	367.3	220.64	263.0033	365.6	373.81	321.77	353.7267	394.04	398.12	492.92	428.3600
Hemi-spherical	E_a	56.426	35.576	33.406	41.8027	53.498	55.427	59.046	55.9903	62.723	65.796	66.435	64.9847
	F_{max}	348.31	219.61	206.21	258.0433	330.24	342.14	364.48	345.6200	387.18	406.15	410.09	401.1400
Conical	E_a	31.776	48.1	27.8186	35.8982	50.588	48.061	45.537	48.0620	64.817	66.877	59.819	63.8377
	F_{max}	196.15	296.91	171.72	221.5933	312.27	296.67	281.09	296.6767	400.1	412.82	369.25	394.0567

Table 8: Results of Energy Absorbed (E_a) and Maximum Force (F_{max}) for 12 mm C-glass/Epoxy 600 g/m^2

Bullet type		20 bar				40 bar				60 bar			
		T1	T2	T3	Average	T1	T2	T3	Average	T1	T2	T3	Average
Blunt	E_a	38.944	58.219	50.119	49.0940	35.3371	73.3455	67.296	58.6595	68.741	76.083	92.224	79.0160
	F_{max}	240.4	359.38	309.37	303.0500	218.13	452.75	415.4	362.0933	424.33	469.65	569.29	487.7567
Hemi-spherical	E_a	48.6502	43.7756	41.161	44.5289	44.444	65.971	53.549	54.6547	73.116	45.279	81.883	66.7593
	F_{max}	300.31	270.22	254.08	274.8700	274.34	407.23	330.55	337.3733	451.33	279.5	505.45	412.0933
Conical	E_a	45.704	41.703	42.6	43.3357	50.9409	68.967	36.3172	52.0750	53.997	57.965	72.706	61.5560
	F_{max}	282.13	257.43	262.96	267.5067	314.45	425.72	224.18	321.4500	409.11	357.81	448.8	405.2400

APPENDIX C
PICTURE OF SPECIMENS OF HIGH VELOCITY IMPACT

High velocity impact test specimens after the impact event have been dyed using dye-penetrant. The red mark is the area that has been damaged by the impact event.

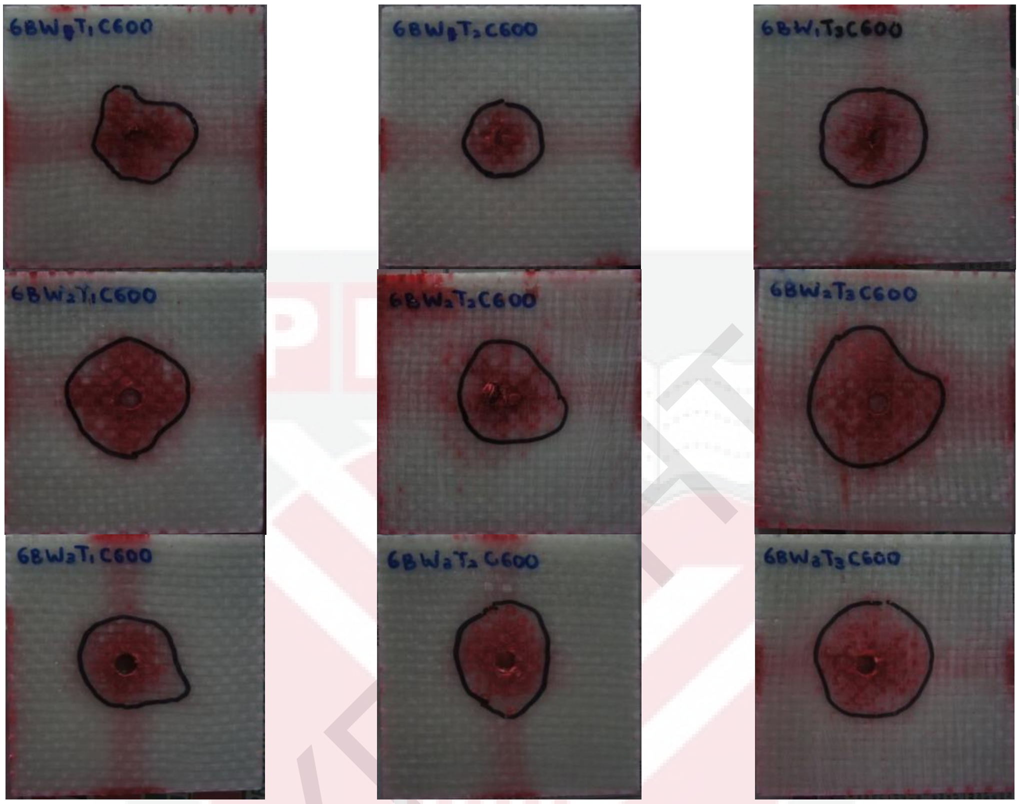

Figure 1: 6mm specimens struck with a blunt bullet at 6 bar, 12 bar and 18 bar of pressure

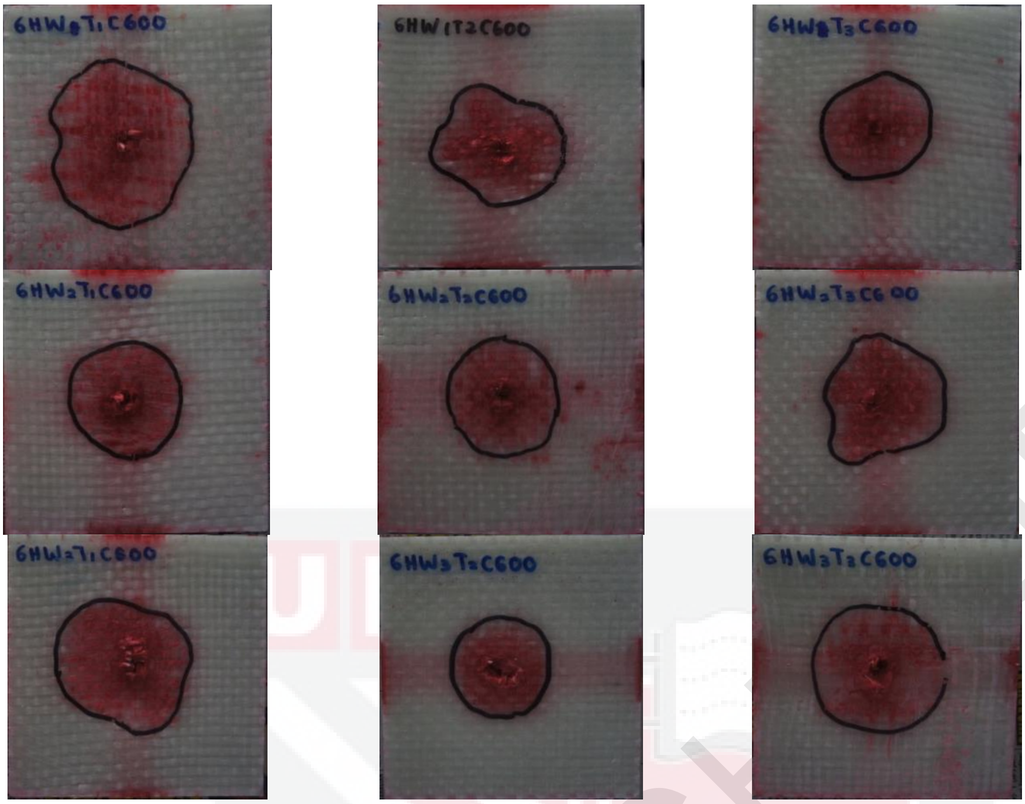

Figure 2: 6mm specimens struck with a hemispherical bullet at 6 bar, 12 bar and 18 bar of pressure

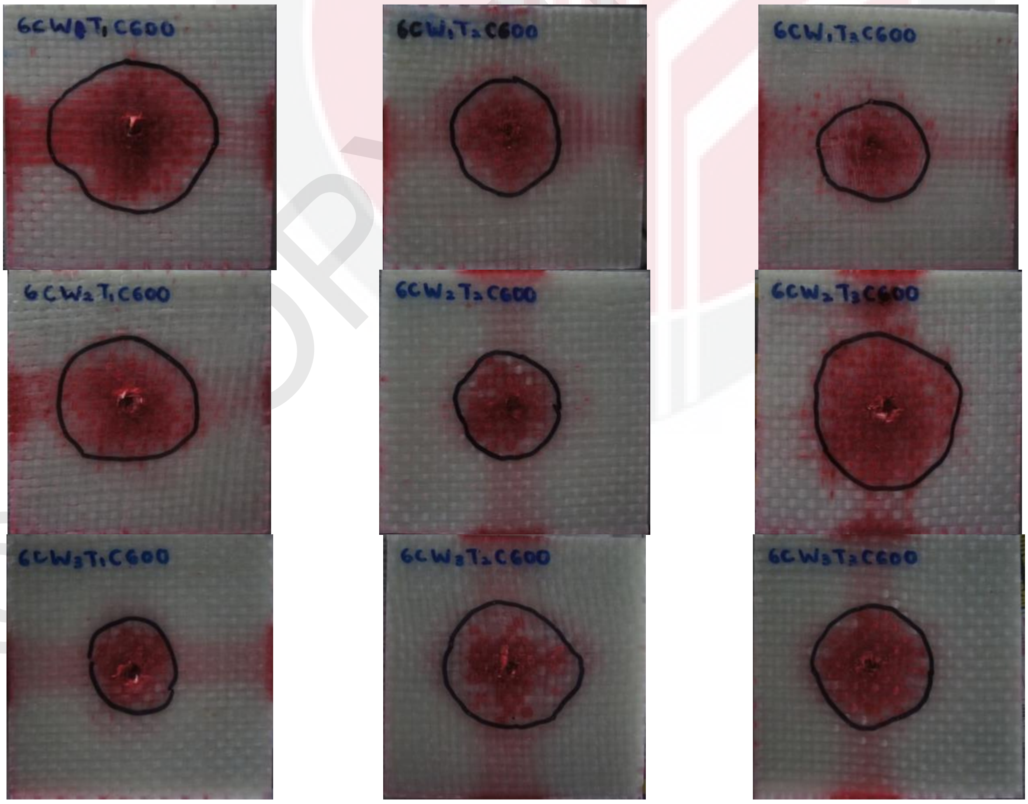

Figure 3: 6mm specimens struck with a conical bullet at 6 bar, 12 bar and 18 bar of pressure

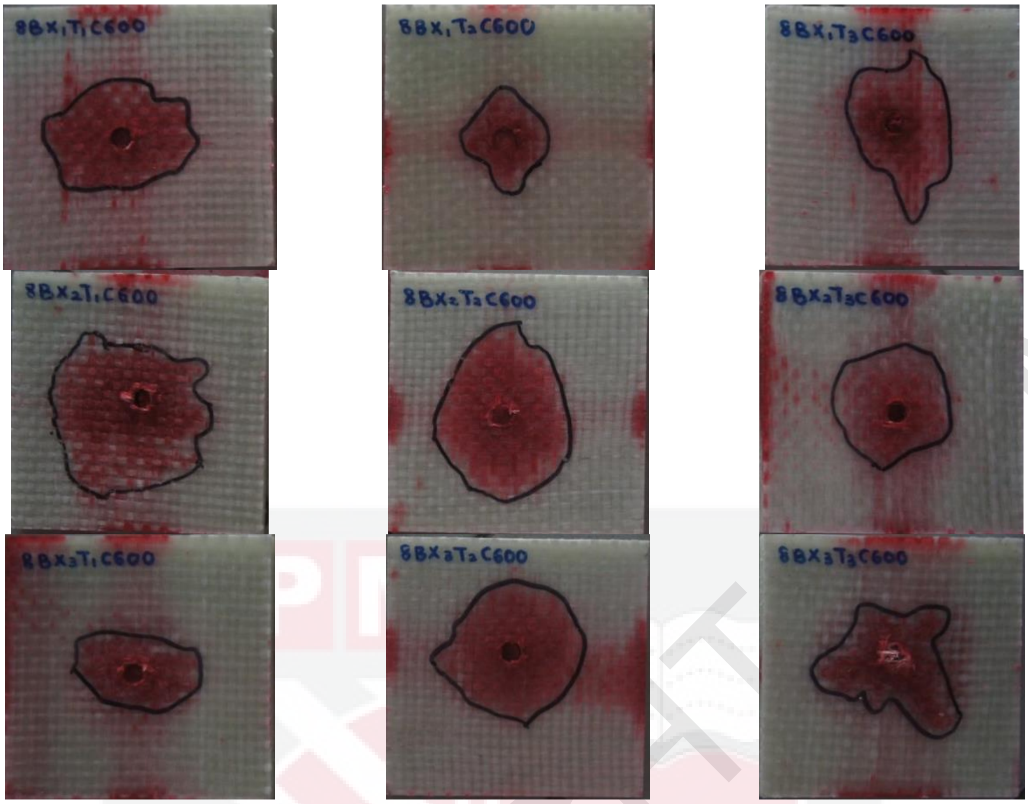

Figure 4: 8mm specimens struck with a blunt bullet at 10 bar, 20 bar and 30 bar of pressure

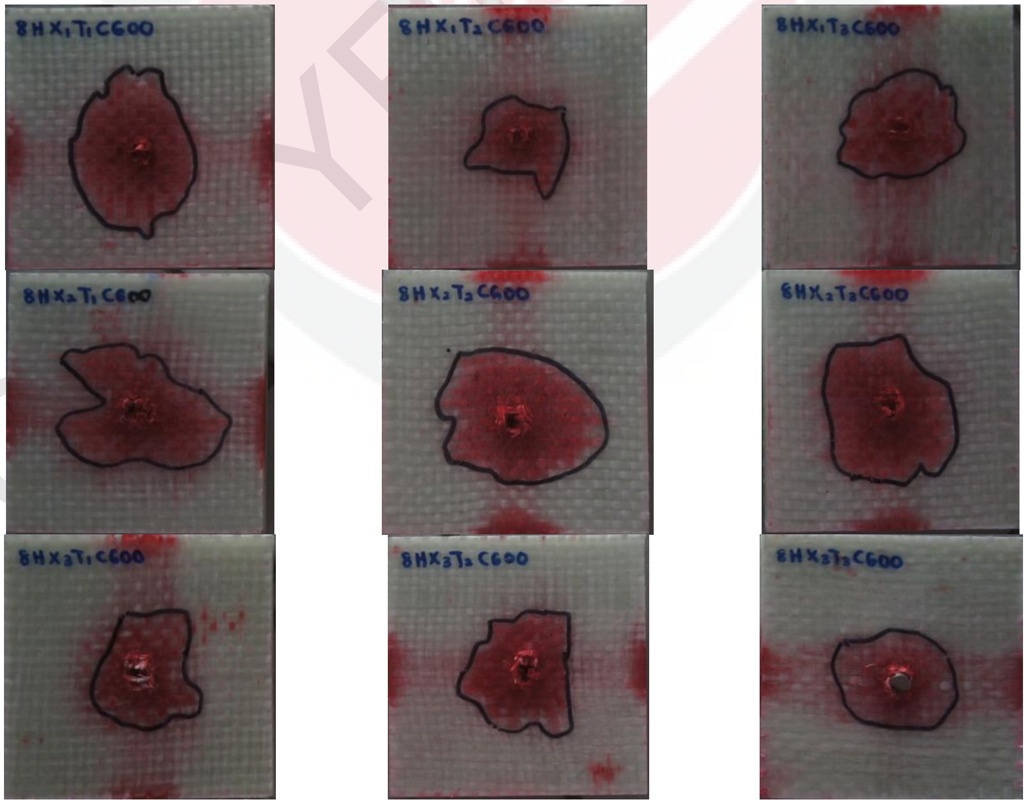

Figure 5: 8mm specimens struck with a hemispherical bullet at 10 bar, 20 bar and 30 bar of pressure

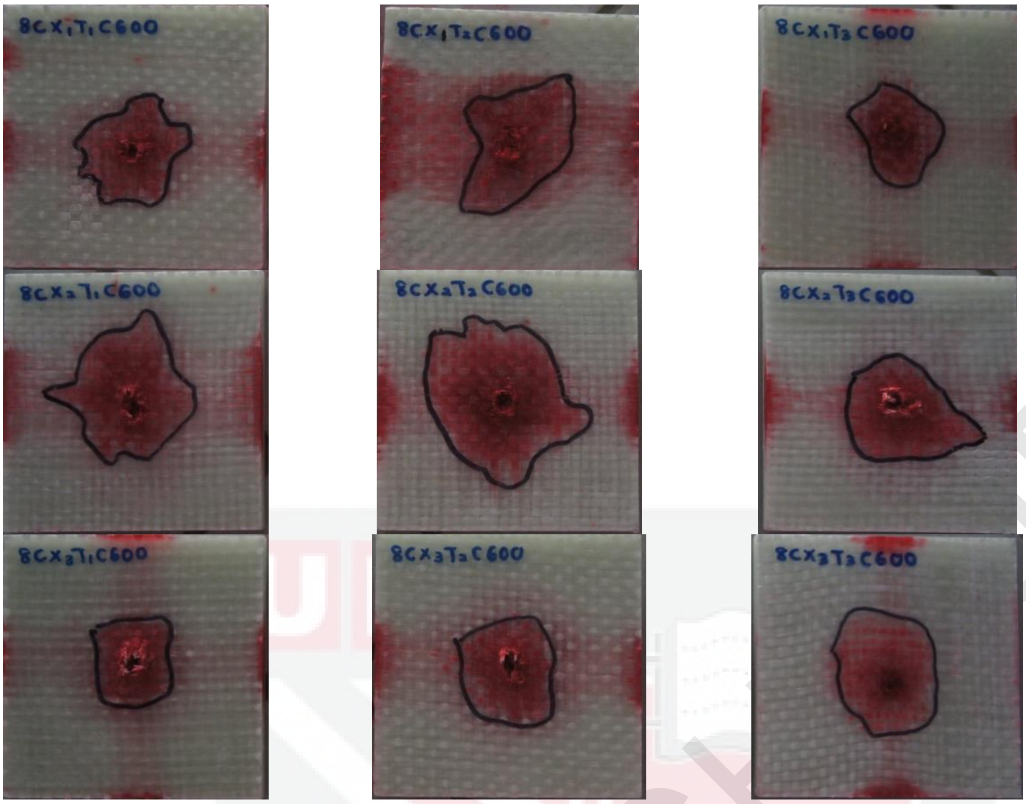

Figure 6: 8mm specimens struck with a conical bullet at 10 bar, 20 bar and 30 bar of pressure

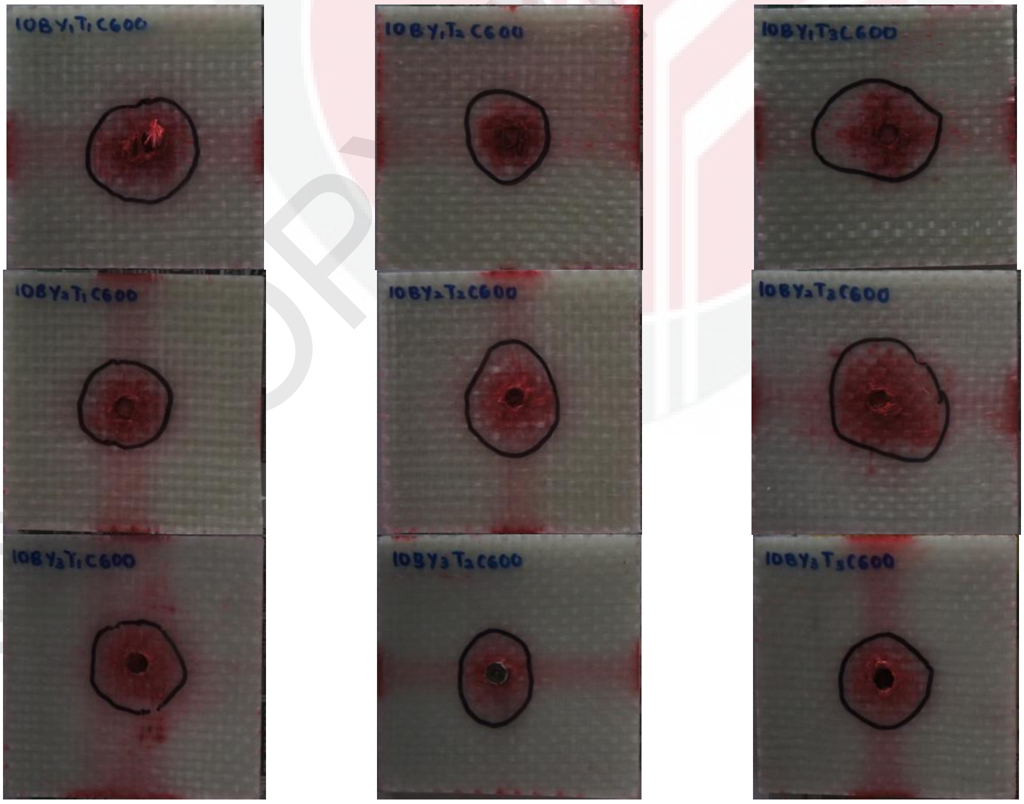

Figure 7: 10mm specimens struck with a blunt bullet at 15 bar,30 bar and 45 bar of pressure

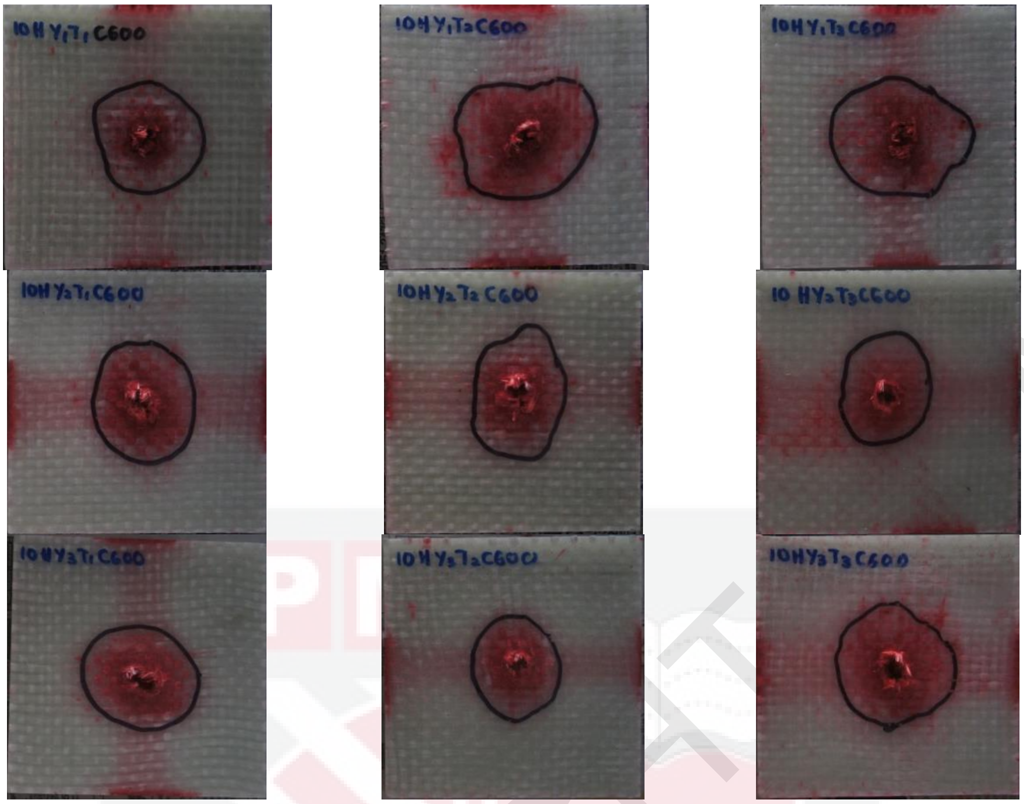

Figure 8: 10mm specimens struck with a hemispherical bullet at 15 bar,30 bar and 45 bar of pressure

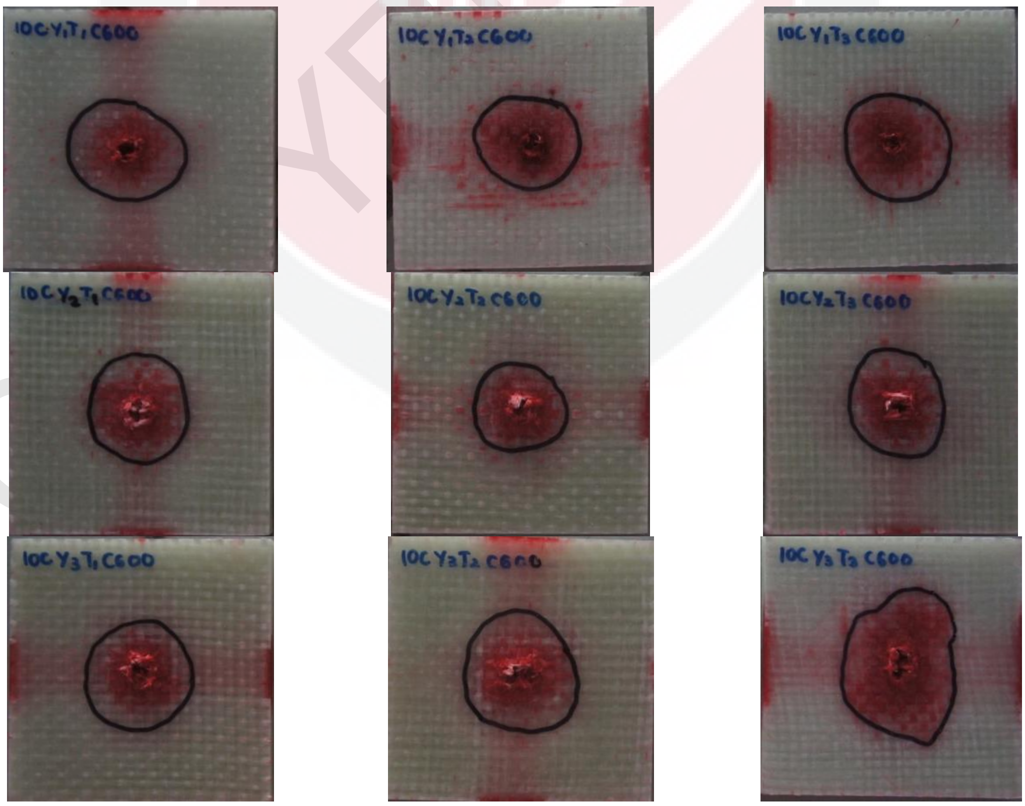

Figure 9: 10mm specimens struck with a conical bullet at 15 bar,30 bar and 45 bar of pressure

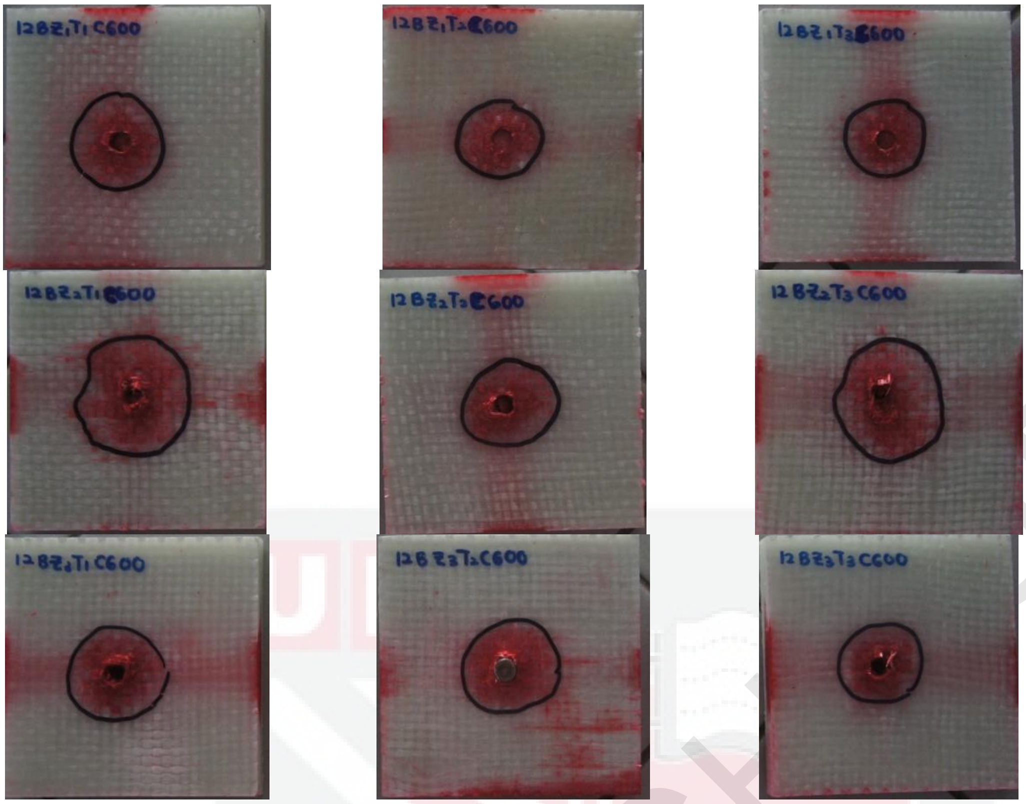

Figure 10: 12mm specimens struck with a blunt bullet at 20 bar,40 bar and 60 bar of pressure

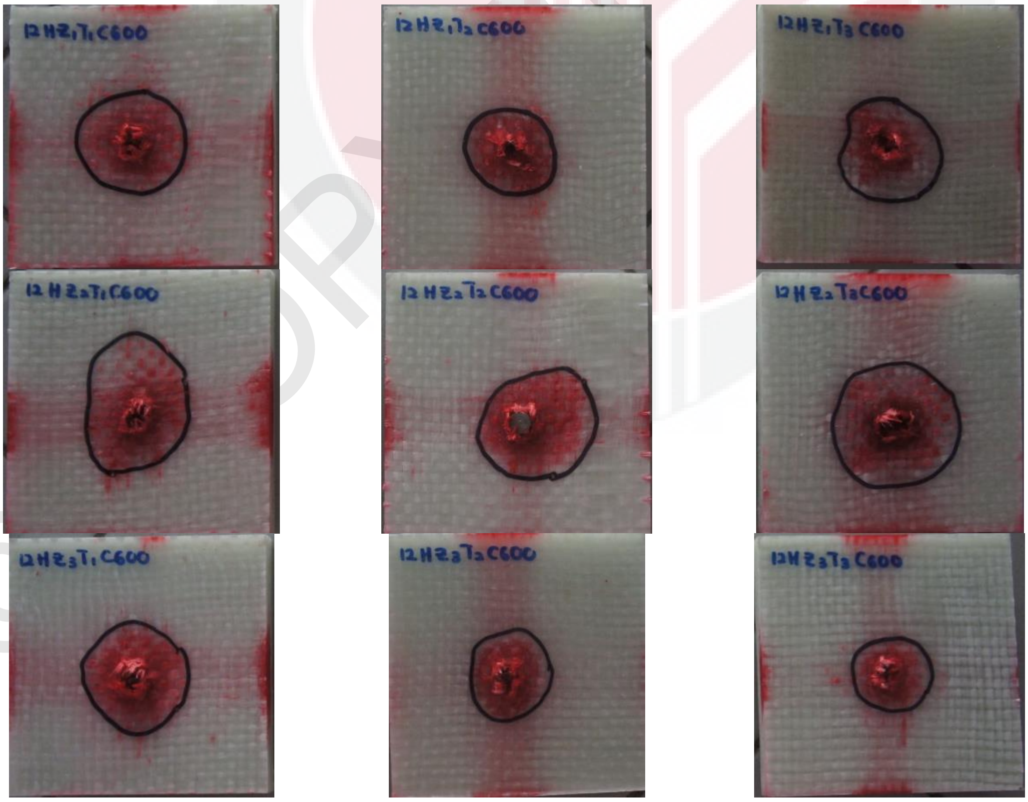

Figure 11: 12mm specimens struck with a hemispherical bullet at 20 bar,40 bar and 60 bar of pressure

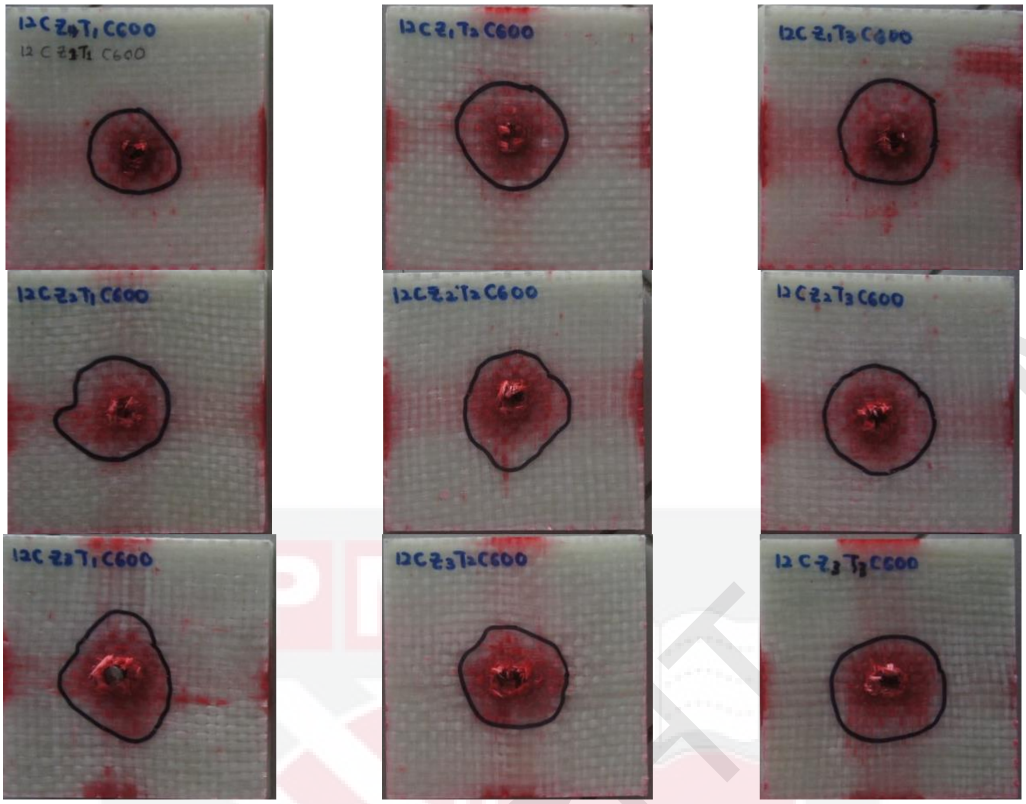

Figure 12: 12mm specimens struck with a conical bullet at 20 bar,40 bar and 60 bar of pressure

BIODATA OF THE STUDENT

The student was born at Tampin, Negeri Sembilan. She obtained her secondary education in Sekolah Menengah Kebangsaan Tampin, Negeri Sembilan which is now known as Sekolah Menengah Tuanku Syed Idrus, Tampin, Negeri Sembilan. She sat for her SPM examination in 2006 which qualified her to pursue her higher education in the Matriculation College of Pahang (KMPh). In 2008, she got a certificate for the physical science programme from the college. After finishing her study in KMPh, she got an offer to further her study at the University Putra Malaysia (UPM) in the Aerospace Engineering programme. In 2011, she did her industrial training at the Police Air Wing Sungai Besi for about 3 months in aircraft maintenance. She obtained a Bachelor Degree in Aerospace Engineering in April 2012.

The student pursued her postgraduate studies in Master of Science (Aerospace Engineering) at UPM in September 2012. Throughout her master's programme, the author took several courses that would help her while doing her research. All the courses attended were to broaden her knowledge in the field. She obtained a Cumulative Grade Point Average (CGPA) of 3.75. While doing her research, she also works as a part time tutor at UPM, and as a Mathematics and Sciences tuition teacher for secondary school students. During her Master's Programme, she submitted three papers to a conference and three papers to a journal. The details of the paper are given in the list of publications.

LIST OF PUBLICATIONS

Published

1. **N. Razali**, M.T.H. Sultan, S.N.A. Safri, S. Basri, N. Yidris, and F. Mustapha, "*High Velocity Impact Test on Glass Fibre Reinforced Polymer (GFRP) Using a Single Stage Gas Gun (SSGG) – An Experimental Based Approach*", Applied Mechanics and Materials Vol. 564 (2014) pp 376-381.

2. S.N.A. Safri, M.T.H. Sultan, **N. Razali**, S. Basri, A.S.M. Rafie, N. Yidris, F. Mustapha and M.R. Ajir, " *The Effect of Thickness and Bullet Type on Impact Properties of Glass Fibre Reinforced Polymer (GFRP) Using a Single Stage Gas Gun (SSGG)*", Applied Mechanics and Materials Vol. 564 (2014) pp 428-433.

3. **N. Razali,** M.T.H. Sultan, F. Mustapha, N. Yidris and M.R. Ishak, "*Impact Damage on Composite Structures – A Review*" The International Journal of Engineering and Science (IJES), Vol. 3 (2014) Issue 7 pp 08-20,

4. **N. Razali** and M.T.H. Sultan, "*A Novel Approach for Detecting, Localising and Characterising Damages in Glass Fibre Reinforced Polymer (GFRP) using the Drop Weight Impact Tester*", International Journal of Research in Engineering and Technology (IJRET), Vol. 03, (2014), Issue 8, pp 295-306, **Impact factor 2.375**.

5. **N. Razali,** S.S. Sazali and M.T.H. Sultan, "*The Study of Impact Damage on C-Type and E-Type of Fibreglass Subjected to Low Velocity Impact*", The International Journal of Engineering and Science (IJES), (2014), V**o**l. 3, Issue 8, 11-25.

6. **N. Razali**, M.T.H. Sultan and Y. Aminanda, "*The Study of Impact Behaviour of Two Types of Glass Fibre Reinforced Polymer (GFRP) Subjected To Low Velocity Impact*". Advanced Materials Research, (2014), Vol. 1044-1045, 153-157.

Accepted

7. **N. Razali,** S.S. Sazali and M.T.H. Sultan, "*The Study of Damage Area and Non-Destructive Testing On Glass Fibre Reinforce Polymer after Low Velocity Impact Event*". International Conference on Advanced Material Engineering & Technology 2014 (ICAMET 2014).

Submitted

8. **N. Razali, M.T.H. Sultan and F. Cardona**, "*An Experimental Study of Non-Destructive Testing On Glass Fibre Reinforce Polymer after High Velocity Impact Event*", Malaysia, International Journal of Impact Engineering, **Impact factor 2.01**.

9. **N. Razali, M.T.H. Sultan and F. Cardona**, "*Characterization and Damage Detection on E-Glass and C-Glass subjected to High Velocity Impact*", Malaysia, Material Design, **Impact factor 3.171**.