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Research paper

Impact Resistance of 3D Woven Composites Impacted by Different Impactor Shapes

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Abstract

The aim of this study was to investigate impact resistance of 3D woven composites, impacted by three different impactor shapes. An experimental study was carried out to compare the impact resistance on four types of 3D woven fiberglass composites. Impact resistance test will be performed using standard method ASTM D2444, with a set up initial impact energy is 20 J, velocity of 3.4901 m/s, height of 0.6163m and mass applied is 3.29 kg. Three different impactor shapes which are hemispherical, conical and ogival were used for testing woven fabric composite impact test. Hand lay-up technique was used to fabricate the composites. From results, 4 float Layer-to-layer Interlock (4L) gave the highest impact resistance for all impactor shapes with 6258.0 N for hemispherical impactor, 4000.1 N for conical impactor and 3750.7 N for ogival impactor. Ogival impactor tends to penetrate the woven composite samples better compared to conical and hemispherical impactors.

***Keywords**: Woven composites, Impact resistance, Impactor shapes, Fiberglass, Low-velocity*

1. Introduction

Composite materials are made from combinations of two or more different substances with own characteristics, which then combined produced a superior material used for various applications [1]. Composites materials has developed progressively in a wide range of structural components over conventional materials because of their better properties; such as strength-to-weight ratio, improved fatigue life, high strength and improved corrosion. 3D woven fabric are produced by interlacing of three sets of yarns that are warp yarn, weft yarn and z-yarn [2].

There are many textile structures being used for composites. The structures are woven, knitted, braided and yarns. Among all, woven fabrics are one of the most importance structures used for composites. Woven fabrics are produced by assembling yarns in warp and weft directions. Weft and warp yarns are positioned next to each other depending on the yarn thickness. The position of the yarns should be emphasized as yarn friction contributed to woven fabric resistance against impact of puncture force [3].

Normally, the direction of yarns interlacing for 3D fabric structures are longitudinal (X), cross (Y) and vertical (Z) [4]. During formation of 3D woven fabric, the z-yarn solidify the fabric by interconnecting the warp yarns and weft yarns through the thickness of the fabric [5]. 3D fabrics have developed rapidly to composite manufacturers as it offer better delamination resistance [6, 7]. 3D woven fabric can be produced by 3D and 2D weaving ma chines. Angle interlock and orthogonal weave are examples of 3D woven fabric.

3D angle interlock fabric is good for ballistic resistance. Zhjiang et al [8] stated that 3D angle interlock fabric suitable for applications on ballistic protection because it have high delamination resistance than laminated composite and in-plane modulus. In addition, Vaidya et al [9] studied that 3D angle interlock composite have higher impact resistance due to able to absorb high capacity of energy by the z-direction fibers.

Orthogonal weave is another example 3D woven fabric. Orthogonal weave comprises of three sets of yarns that are warp, weft and stuffer yarns. All these yarns will be bind together by using binder yarn to enhance the structural integrity [10]. This binder yarn helps in improving high modulus, better shear and torsional strength to prevent delamination [11].

Previous study conducted by [12] stated that 3D orthogonal woven composites has a unique energy absorption mechanisms for low-velocity impact and gave the largest spread of damage. In addition, Xiwen Jia et al [13] studied about the ballistic penetration on 3D orthogonal woven composite using conical cylindrical steel projectile. The study concluded that 3D orthogonal woven composite has a good impact resistance as no delamination occurs because of the existence of z-yarns in thickness direction.

In this paper, the impact resistance of 3D woven fabric fiberglass composites when subjected to a drop weight impact loading is studied. This study was carried out for low-velocity impact loading.

2. Methodology

Four types of 3D woven fiberglass fabrics were used for the research. The fabrics are 1-Float Angle Interlock (1A), 3-Float Angle-Layer Interlock (3AL), 9-Float Angle Interlock (9A), and 4-Float Layer-to-Layer Interlock (4L). The cross sectional view of these fabrics are shown in Figure 1, Figure 2, Figure 3 and Figure 4. Epoxy Morcrete BJC39 and hardener HY225 were selected as matrix materials. Fiberglass reacts well with epoxy thus produced a strong and high mechanical performance composites. The properties of Morcrete BJC 39 epoxy resin are shown in Table 1.

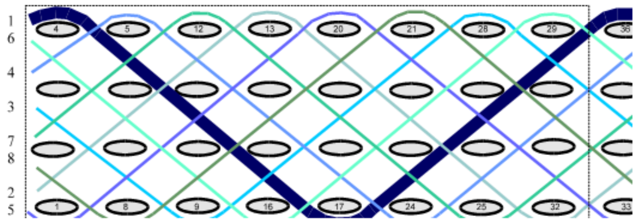

Fig. 1: Non constant crimp 1-float Angle Interlock (1A)

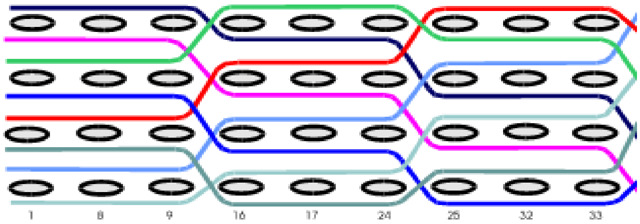

Fig. 2: Non constant crimp of 3-float Angle Layer Interlock (3AL)

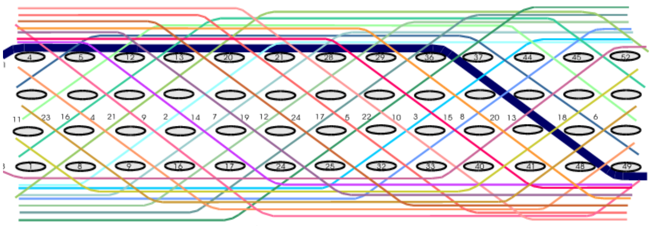

Fig. 3: Non constant crimp of a 9-Float Angle Interlock (9A)

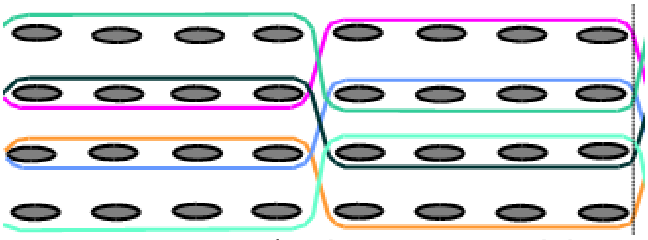

Fig. 4: Non constant crimp of a 4-Float Layer-to-Layer Interlock (4L)

Table 1: Properties of epoxy resin

Properties	Morcrete BJC 39
Density (kg/m^3)	1150
Mixing ratio (epoxy : hardener)	3.7 : 1.3
Compressive Strength (MPa)	75.8
Tensile Strength (MPa)	13.1
Pot life (25°C)	25 – 30 minutes
Cure Time	8 hours
Cure Temperature	Room Temperature

Hand lay-up technique was used to fabricate the composite. All woven fabrics were cut to 80mm x 240mm and placed in the mould. Then resin with hardener (3.7:1.3 ratio) were applied to the woven fabrics, and a roller was used to press the resin well along the fabrics. After that the mould with woven fabrics were placed in the oven for curing process. The temperature was initially set at 30°C, and continually elevated 20°C for every thirty minutes until it reached 100°C. Then the composites samples were further cured at the maximum temperature for another three hours.

3. Impact Testing

Fabric resistance against impact test were measured using Instron Dynatup 9250 HV Tester as shown in Figure 5 (a). Impact resistance test of 3D woven composites were performed allowing to force applied and elongation using method ASTM D2444. This is a drop test where a material or specimen is dropped by an impactor or other type of device until the material ruptures or when the elongation limit is achieved. All tests were conducted with initial impact energy of 20 J, distance between impactor tup to specimen with 0.6163 m, velocity of 3.4901 m/s and mass applied is 3.29 kg. Three types of impactors (12mm diameter) that used were conical, hemispherical, and ogival impactor as illustrates in Figure 6. All samples were cut into 80mm x 80mm to be clamped on top of a round metal block as in Figure 5 (b) that allow the impactor penetrate through it. The force that applied to the composites was measured immediately once the probe penetrated the composite material. All result and data were collected and analyzed.

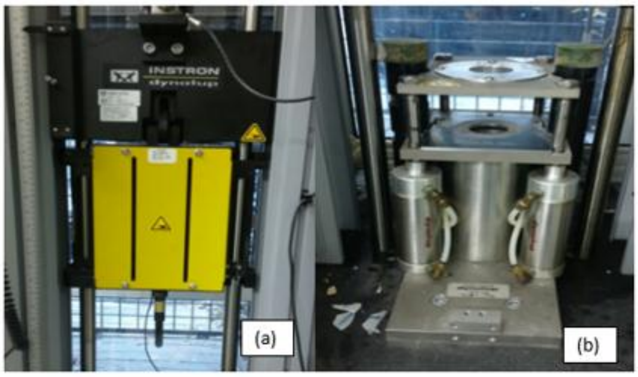

Fig. 5: INSTRON Dynatup 9250 HV (a) and round metal block (b)

Fig. 6: Ogival (A), Hemispherical (B), Conical (C) Conical impactors

4. Results and Discussions

4.1. Peak force versus time

Low-velocity impact response of all woven composites were tested using INSTRON DYNATUP impact test machine with constant initial impact energy, E = 20 J. Energy and load versus time response were plotted in graphs for each woven composites. The energy and load versus time response for 1-Float Angle Interlock (1A), 3-Float Angle-Layer Interlock (3AL), 9-Float Angle Interlock (9A), and 4-Float Layer-to-Layer Interlock (4L) were presented in Figure 7, Figure 8, Figure 9 and Figure 10 respectively.

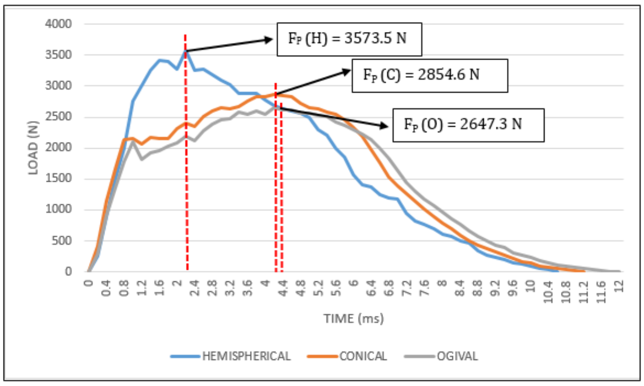

Fig. 7: Peak force over time for all impactor shapes impacted on 1A composite

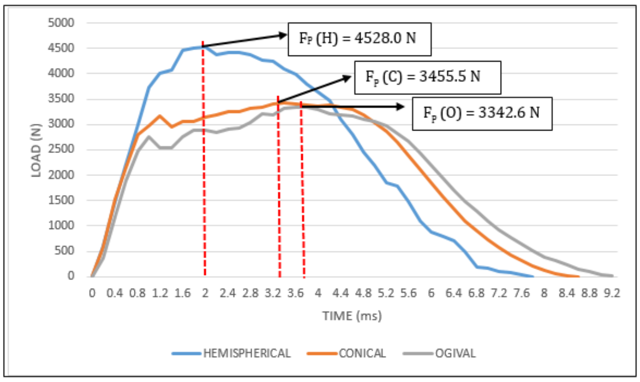

Fig. 8: Peak force over time for all impactor shapes impacted on 3AL composite

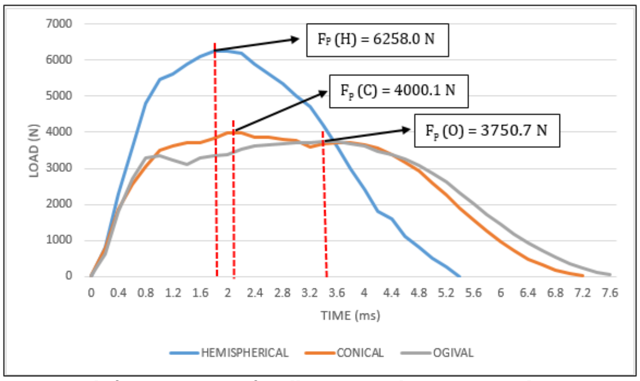

Fig. 9: Peak force over time for all impactor shapes impacted on 4L composite

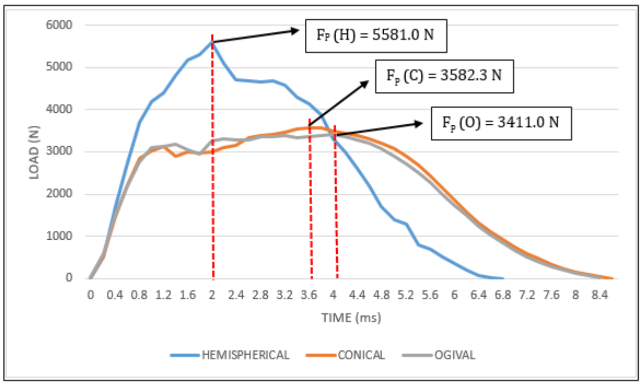

Fig. 10: Peak force over time for all impactor shapes impacted on 9A composite

All 3D woven fabric composites were tested for their impact properties. The experimental peak force over time for all impactor shapes of 3D angle interlock and stitched satin woven composites were obtained and summarize in Table 2.

Table 2: Peak Force values for all 3D woven composites

Fabric	Peak Force (N)		
	Hemispherical	Conical	Ogival
1A	3573.5 N	2854.6 N	2647.3 N
3AL	4528.0 N	3455.5 N	3342.6 N
4L	6258.0 N	4000.1 N	3750.7 N
9A	5581.0 N	3582.3 N	3411.0 N
SS	4141.0 N	3107.8 N	2967.7 N

From the graphs, 4-float Layer-to-layer (4L) woven composite exhibits the strongest compared to others. Weave structure is the main factor that makes the strength of each type of fabric differ. Each layer of 4L woven fabric were bind to each other either above or below it. In addition, float length over depth also increase the impact resistance of the woven fabric. Larger value of float length over depth will increase the impact resistance as it has low crimp percentage. 4L produced the highest ratio of float length over depth with 4. These factor will increase the delamination resistance of the structure itself. Effective resin adhesion in between all layers also contributes to the high impact resistance of 4L woven fabric composite.

9-float Angle Interlock (9A) woven fabric composite also have a good impact resistant when impacted by all three types of impactor shapes. This was due to the longer float at the surface and bottom layer of the fabric. Longer float of an end that passes through 9 picks will produce a low crimp woven fabric. Low crimp percentage leads to a stronger fabric strength as the interlacing of warp and weft is smaller. This longer float at the surface and bottom layer helps in increasing the extension or compression of the composite before it ruptures.

3-float Angle Layer Interlock (3AL) impact performance was in the middle between all five types of woven fabrics. This type of fabric is quite similar to 9A but the end passes through only 3 picks from one layer to another layer until to the bottom layer. Less float length will result in a high crimp percentage. Thus, strength of the woven fabric will decrease. Greater yarn interlacement of 3AL woven composite made it poor adhesion to epoxy resin. As a result, the production of composite will be quite brittle and poor mechanical strength.

1-float Angle Interlock shows the weakest impact resistance performance compared to other woven fabric composite. This was due to the compact structure of the fabric which will resulted to poor mechanical fabric strength. In addition, only one float length produced as the z-yarn passes through every single weft yarn from top to bottom layer. This situation will increase the fabric crimp percentage that leads to poor impact strength of the fabric.

4.2. Impactor Shapes

This section discusses about the effect of impactor shapes to woven structure. Three types of impactor shapes, which are hemispherical, conical and ogival were used in this research. Different impactor shapes will produce different damage areas, damage mechanisms and contact duration in composite. These will resulted in changing material residual properties according to impactor shape as supported by (Mitrevski, Marshall, Thomson, Jones, & Whittingham, 2005). The comparison force and contact duration range between each type of woven composite with different impactor shapes were presented in the following section.

4.2.1 Hemispherical Impactor Shape

Figure 11 shows the peak force over time (in miliseconds) needed by hemispherical impactor to penetrate all samples. From the graph, 4L exhibit the strongest composite with average force 6250.0 N followed by 9A with average force 5581.0 N, 3AL with average force 4528.0 N, SS with average force 4117.0 N and 1A exhibit the weakest with average force 3800.0 N. Based from the graph, different float length can affect the strength of fabric. The contact time range of hemispherical impactor for all woven composites when reached peak force were in between 1.8 ms to 2.2 ms as marked by red dotted line below. This was due to larger impactor surface damage that made it unable to penetrate the woven composite.

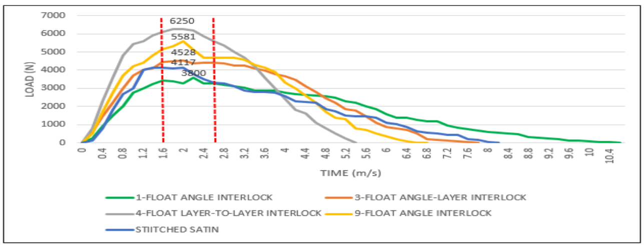

Fig 11: Peak force needed by hemispherical impactor to penetrate all samples

4.2.2 Conical Impactor Shape

Peak force over time (in miliseconds) impacted by conical impactor on all samples were illustrates in Figure 12 below. 4L reached its peak force with 3985.4 N and 1A exhibit the lowest with average force 2854.6 N. 1A, 3AL, 9A and SS reached their peak force in between 3.7 ms to 4.6 ms of contact time as marked by red dotted line except for 4L which reached its peak force at 2.2 ms as marked by purple dotted line. Conical impactor tends to have longer contact time compared to hemispherical impactor as it has smaller impactor surface area. This situation will make the impactor can slightly penetrate several layer of the composite.

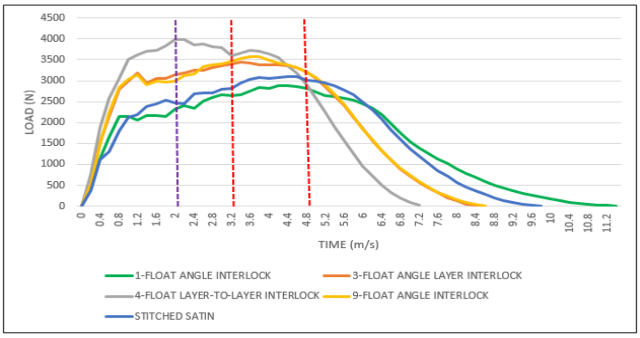

Fig 12: Peak force needed by conical impactor to penetrate all samples

4.2.3 Ogival Impactor Shape

Figure 13 presents the peak force over time (in miliseconds) impacted by ogival impactor on all samples. It can be seen that 4L exhibit the highest with average force 3750.7 N, followed by 9A with average force 3411.0 N, 3AL with average force 3342.6 N, SS with average force 2967.7 N and 1A with average force 2647.3 N. From the red dotted line below, all five woven composites reached their peak force at contact time between 3.6 ms to 4.6 ms.

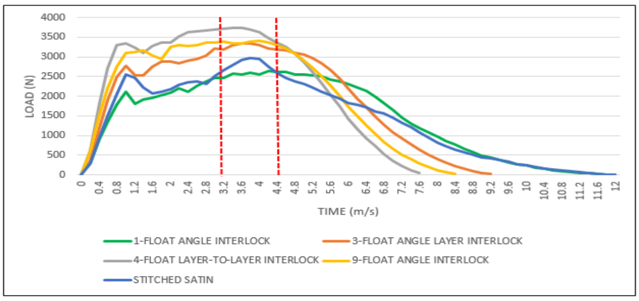

Fig 13: Peak force needed by ogival impactor to penetrate all samples

4.3 Summary of Impactor Shape

Typical force-time graph produced by hemispherical, conical and ogival impactors at initial impact energy of 20 J are shown in Figure 11, Figure 12 and Figure 13. It can be seen that 4L woven composite consistently gave the highest value of peak force, followed by 9A, 3AL, SS and 1A. The force-time graph consists characteristics distinguished by impactor shape used to impact the composites. Larger surface area of hemispherical impactor tup make it difficult to penetrate the composite thus higher force needed. In contrast with ogival impactor, smaller surface area need lower force to penetrate as more pressure exerted to the composites.

Hemispherical impactor produced the largest peak force and shortest contact time whereas ogival impactor produced the lowest peak force and longest contact time as shown in Figure 11 and Figure 13 respectively which quite similar with (Kim & Goo, 1997)'s research on modelling results and the expected trend. The lowest peak force by ogival impactor is caused by the sharp shape of the impactor. A sharp impactor needed a smaller force to penetrate the composites as it had smaller area thus more pressure was exerted to the object. According to the formula of pressure law, F = PA where F was the force, P was the pressure and A was the surface area. Hence, sharp probe that have smaller surface tend to penetrate easily through the composites. Penetration results created by ogival impactor in friction between the impactor and composite will increases the contact time.

4.4 Damage Mechanisms

The front surface damage impacted at initial impact energy of 20 J by all hemispherical, conical and ogival impactors were shown in Figure 14 below. It can be clearly seen that there are differences for front surface damage patterns of the composites where hemispherical impactor produced a larger damage area with matrix cracking. However, hemispherical impactor does not penetrate the composite compared to conical and ogival impactors. Ogival impactor tends to penetrate the composite and matrix cracking can be observed around the penetrated hole which caused by fiber breakage. Penetration also can be seen by the conical impactor but in less damage area and mechanisms compared to ogival impactor. Hemispherical impactor produced larger area of matrix cracking than conical impactor. For back surface damage in Figure 15, ogival impactor fully penetrated the composites induced fiber breakage, whereas conical impactor produced slight penetration and indentation. Hemispherical impactor tends to penetrate certain 3D woven composite depends on the structure. The ogival impactor produced the most extensive back surface damage with hemispherical impactor the least. All these results leads to a conclusion that back surface damage area were depends on the impactor shape after specific initial impact energy is reached.

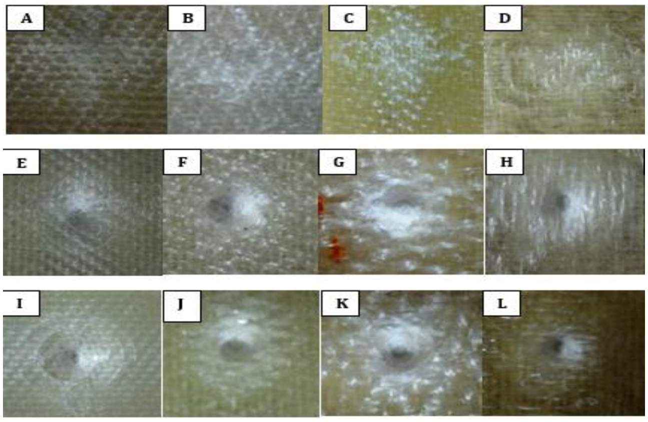

Fig 14: Front Surface Damage on Composites; (A) hemispherical 1A, (B) hemispherical 3AL, (C) hemispherical 4L, (D) hemispherical 9A, (E) conical 1A, (F) conical 3AL, (G) conical 4L, (H) conical 9A, (I) ogival 1A, (J) ogival 3AL, (K) ogival 4L, (L) ogival 9A

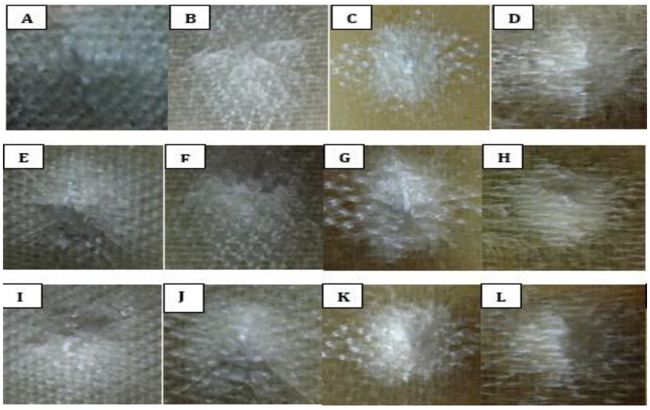

Fig 15: Back Surface Damage on Composites; (A) hemispherical 1A, (B) hemispherical 3AL, (C) hemispherical 4L, (D) hemispherical 9A, (E) conical 1A, (F) conical 3AL, (G) conical 4L, (H) conical 9A, (I) ogival 1A, (J) ogival 3AL, (K) ogival 4L, (L) ogival 9A

5. Conclusion

The research studied on the impact resistance strength of four different types of 3D woven composites. The research concluded that 4L woven composite gave the highest impact resistance compared to others. This happened due to each layer of 4L woven fabric were bind to each other either above or below it. The research also found that the force needed to break the composites using sharp impactor was slightly lower compared to blunt impactor. This was due to the smaller area of sharp impactor thus the pressure was greater to penetrate woven composites.

Acknowledgement

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