FINITE ELEMENT ANALYSIS OF LOW VELOCITY BEHAVIOUR ON FUSED DEPOSITION MODELING PRINTED STAB-RESISTANT BODY ARMOUR DESIGN FEATURES

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Article History: Received 6 August 2017; Revised 19 October 2017; Accepted 20 December 2017

ABSTRACT: Body armour is mainly worn to protect the human torso from attacks caused by weapons or projectiles. Despite a number of modern body armours have been developed, historical issue continue to exist and challenge the current protective solutions. However, additive manufacturing (AM) technology yet to be explored widely in attempt to address these issues. This research therefore investigates the feasibility of using AM system, specifically fused deposition modelling (FDM) process to manufacture textile geometrical models, which can be used for the development of novel user fit stab-resistant body armour. This study analyses the design features that could potentially influence the stab protection performance of FDM printed textile featuring an imbricated layout. This paper presents a finite element analysis to investigate the deformation distributed in the imbricated scale-like assemblies due to the knife blade penetrated through the overlapping scales vary with different scale thicknesses and overlapping angles. The results shows that 4mm model constructed in overlapping angle of 20° absorbed the most energy during the knife blade penetration. A weak region is found in between the overlapping scale of the single layer stab resistant model which could potentially allow the penetration of knife blade to cause injury.

KEYWORDS: *Fused Deposition Modeling; Additive Manufacturing; Low Velocity Impact; Stab Resistance; Body Armour*

1.0 INTRODUCTION

Sharp force injury is a common threat that police officers encountered since they involve in a wide range of duties from general, daily, patrol activities to specific criminal activities such as narcotic investigation and even more activities [1-2]. In United States, data released by the Federal Bureau of Investigation (FBI) has shown the law enforcement officers killed by handgun, rifle and shotgun were occupied the most percentage from 2005-2014 [3]. There are 0.4% of the law enforcement officers killed by knife or other cutting instruments, as compared to other threats [3]. Despite the mortality rate caused by knife or other cutting tools were low, the stab resistant body armour is at least has some practical and commercial experience in current service of the police forces [4].

A number of stab resistant materials are commercially available. The stab resistant body armour can be made from a range of materials, from traditionally foil or mail solutions which are relatively heavy and provide little penetrate resistance, to the modern body armour made of ceramic, polycarbonate or aramid fibres which provide excellent stab protection, but bulky, inflexible and uncomfortable to wear [5]. Therefore, a number of studies have performed to reduce the weight of body armour and improve its flexibility. Although stab resistance of modern armour was undoubtedly improved through implementation of modern standards, but historical issues such as comfort issues causing of thermal stress, poor fitting of armour hinder the body movement of wearers and affect their work performance, etc., continue to exist with many of the current armour protection solutions [6-7].

AM is a layered manufacturing (LM) technique in which the part is built in a layer by layer directly from CAD data. This technology presents an opportunity to design and develop novel solutions for conventional and high-performance textile applications because of their ability in generating geometric complexity and functionality as available from conventional fibre-based textiles [7]. Textile structures realised via AM techniques have received increasing attention since the previous decade. However, this solution yet to be widely explored in an attempt to overcome the body armour issues.

The world's first 3D conformal seamless AM textile garment was designed and manufactured by Bingham using Laser Sintering (LS) system [7]. The applications of AM textiles mostly via LS and 3D printer, especially in the field of fashion design continues to increase. In addition, Johnson et al. (2013) attempted to address the issues that continue to exit with many current protective solutions in the body armour through AM. In their study, LS was adopted to develop stab-resistant test samples for body armour [8]. Browing et al. (2013) studied the structure of composite elasmoid type scales by measuring the mechanical response to blunt and penetrating indentation loading.

In their study, additive manufactured model produced by using Fused Deposition Modelling technique was used only to mimic the feature of fish scale [9]. However, there is no study about the creation of additive manufactured textiles via FDM system for stab-resistant body protective armour with improved comfort ability and reduced weight.

This research was therefore performed to investigate the use of Fused Deposition Modelling (FDM) technique in producing additive manufactured textiles geometry using Acrylonitrile Butadiene Styrene (ABS) material for stab resistant body armour. To do this, this study was first conducted in order to aid the development of the research. This study aimed to create an ideal phenomenon to investigate the relationship between the design features of FDM manufactured imbricated scale-like assemblies which could potentially affect their stab protection performance. Therefore, a finite element analysis was performed on stab test of imbricated scale-like assemblies by varying the scale thickness and overlapping angle at knife impact energy level one, as documented in the HOSDB body armour standard [10]. The simulation was performed using ANSYS software. The study investigated the effects of different scale thicknesses and overlapping angles subjected to each imbricated scale-like assemblies. Deformation distributed in the body of every models and the depth of knife blade penetration as a result of impact mechanism into the FDM printed models were analysed. The study has also presented the energy absorption by the target models in order to analyse their stab protective performance. However, the study will not look at assessing the effects of ballistic or blunt trauma such as bruising, but only focus on the prevention of trauma caused by knife penetration.

2.0 METHODOLOGY

In this study, FDM manufactured models were constructed as imbricated scale-like geometry with two different structural parameters such as scale thicknesses (T) and scale overlapping angle (ϴ). The thickness of the scale-like models varies as 4mm, 5mm and 6mm with scale overlapping angle ranging from 10˚, 15˚ to 20˚. The whole model comprised in a total of 10 scales, which were arranged as shown in Figure 1. It has to be noted that simplified model has used in the simulation. Each individual scale was measured with length of 50mm × 50mm. However, the measurement of entire imbricated model was different since each model were applied with different scale thicknesses and variation of overlapping angles.

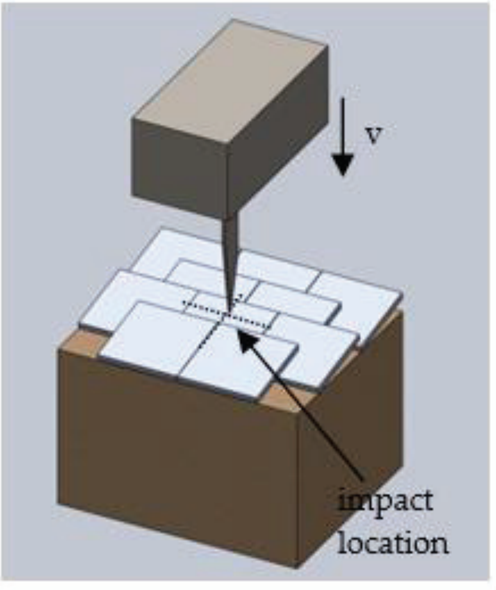


Figure 1: Low velocity impact loading of imbricated scale-like protective system

There were three types of materials used in the simulation. By adhering to the HOSDB body armour international standard [11], B01 type tool steel was used as the material of knife blade, while Roma Plastilina No.1 modelling clay was used for backing material to represent the human body since it has a high coefficient of damping and energy dissipation, low Young's modulus and ease of plastic flow. Acrylonitrile Butadiene Styrene (ABS) was used for the scale-like model, as it is the most commonly used printing material in the FDM system. However, the material was considered anisotropic with mechanical properties as shown in Table 1, since FDM part is produced by stacking layer after layer [12-14].

Table 1: Material Properties of ABS [12]

Properties	Unit	ABS
E_x	MPa	1073
E_y	MPa	1653
E_z	MPa	1391.7
ν_{xy}	–	0.3209
ν_{xz}	–	0.2707
ν_{yz}	–	0.4391
G_{xy}	MPa	369.6
G_{xz}	MPa	540.5
G_{yz}	MPa	554

where E is young's modulus, ν is Poisson's ratio and G is shear stress according to different axis plane. Prior to the simulation, all models were generated by using CAD software and were converted into IGES files, which can be accessed in ANSYS software. The imbricated scale assemblies were designed in the CAD model as shown in Figure 2.

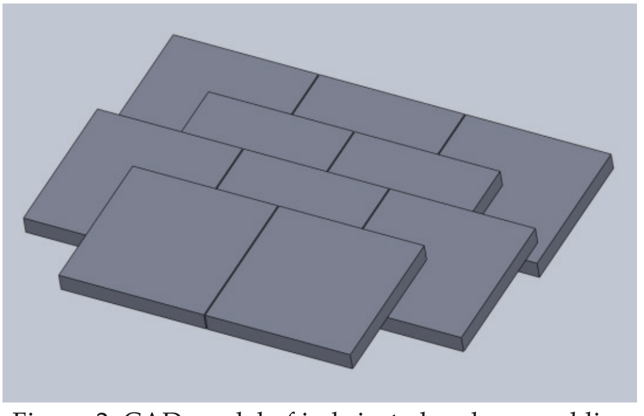


Figure 2: CAD model of imbricated scale assemblies

Explicit dynamic analysis was performed under an environmental temperature of 22°C. The entire geometry was meshed using hexagonal (hex8) and tetrahedral (tet4) elements. The knife blade was modelled as a perfectly rigid body in the simulation since it does not encountered plastic effects during the impact. The knife blade impacted in direction which was normal to (0° angle of incidence) the top surface of centered located scale, as shown in Figure 1, where the blade was dropped vertically in the same direction as gravity. The impact location was considered at both minimum overlapping thickness and maximum overlapping thickness, as shown in Figure 3.

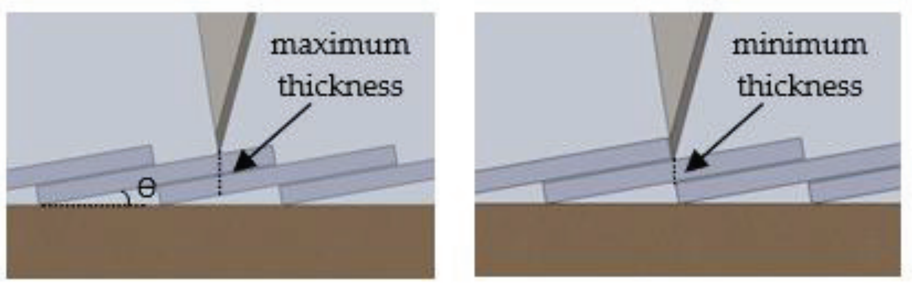


Figure 3: Impact locations

The blade energy which taken from the HOSDB standard was determined at 24J, at a speed of V = 4.11m/s. This speed will be used in the final experimental model with unchanged kinetic energy. However, a speed of V = 130m/s was applied in the simulation in order to reduce computational time. The physics of the phenomenon should not be influenced by such a change in speed since blade energy is constant throughout the experiment [15]. The standard specify only the kinetic energy of blade set, but does not include the speed. Besides, a fixed support boundary condition was applied to the bottom and four side faces of the backing clay, therefore, all degree of freedom are restricted.

3.0 RESULT AND DISCUSSION

Finite element analysis was performed to analyse the stab performance of the imbricated FDM manufactured textile models constructed with different scale thicknesses and overlapping angles. The next section presents the results obtained for the effects of knife penetration through the FDM manufactured scale-like assemblies. The influence of both structural parameters to the imbricated design feature was discussed. Generally, the results showed the damage pattern and depth of knife penetration within a short duration, as well as traced on the variations of energy absorbed by the test models.

3.1 Influence of Scale Thickness and Overlapping Angle

In the simulation, the scale overlapping angle ranging from 10° to 20° were governed in the imbricated scale structure since armour design features characterized within this range was possible to provide the best combination of penetration resistance and flexibility [16]. Table 2 shows the measurements of these geometric features.

Table 2: Structural parameters of imbricated scale-like model and degree of overlap

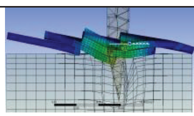
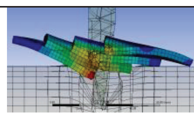
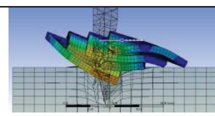
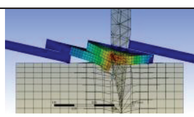
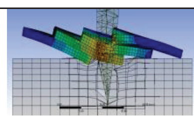
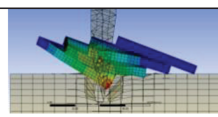
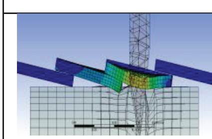
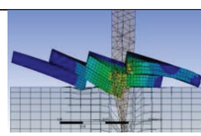
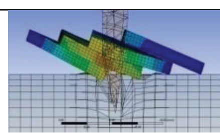
T, mm	θ	min T, mm	max T, mm	h, mm	L, mm	d, mm	K_d
4	10	4.06	8.53	12.62	50	24.98	0.410
	15	8.70	13.25	16.80	50	16.42	0.328
	20	13.62	13.62	20.86	50	12.09	0.242
5	10	5.08	10.56	13.61	50	30.70	0.614
	15	10.76	16.36	17.77	50	20.15	0.403
	20	16.82	16.82	21.8	50	14.84	0.297
6	10	6.09	12.59	14.59	50	36.30	0.726
	15	10.80	12.84	18.74	50	23.89	0.478
	20	13.90	20.00	22.74	50	17.58	0.352

The minimum (min T) and maximum (max T) scale overlapping thickness, total height (h) of thickness and exposed scale length (d) were changed with different scale thicknesses and overlapping angle (θ) of individual scale element. From here, the degree of scale overlap, which is also known as imbrication factor, K_d also can be determined by d/L [7]. By considering the degree of scale overlap (K_d), armour can be classified according to their potential level of protection. Armour featuring a higher level of scale overlap when the value of imbrication factor is returned close to zero and it could be considered as heavily armour, whereas when the value of imbrication factor is returned close to one, a low level of scale overlap is presented and such armour is considered lightly in weight [7]. Based on Table 2, K_d value of the model increases with larger scale thickness. However, the K_d value of the model decreases as the overlapping angle increases. 4mm scale overlapped at angle 20° gained the lowest K_d value as compared to the other scale thicknesses at the same scale overlapping level. It can be considered as the heaviest among all scales assembly due to its arrangement were much compact and cumbersome. This can be referred to Table 3. However, 6mm scales with overlapping angle at 10° has the lowest level of scale overlap as its K_d value was the most returned close to one, thus it was the lightest weight among all these model. Besides, the overall height of the model was increased as the individual scale thickness increased at the similar scale overlapping angle.

3.2 Damage Pattern and Knife Penetration

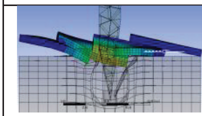
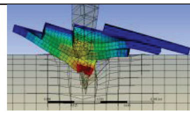
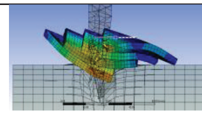
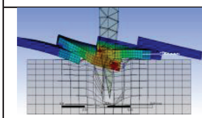
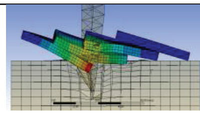
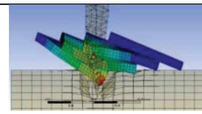
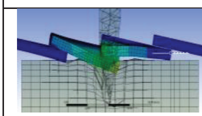
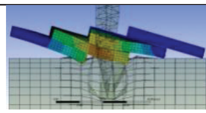
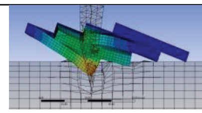
The knife blade was impact simulated respectively onto the region of minimum and maximum scale overlapping thicknesses of the imbricated scale-like assemblies. Table 3 and Table 4 show the deformation distributed at both of these regions of each assembly with different scale thicknesses and overlapping angles. Deformation mode of every models behaved in different ways, although the simulations were conducted under the similar environment and boundary condition.

Table 3: Deformation contour at minimum scale overlapping thickness

4mm model		
		
ϴ =10°	ϴ =15°	ϴ =20°
5mm model		
		
ϴ =10°	ϴ =15°	ϴ =20°
6mm model		
		
ϴ =10°	ϴ =15°	ϴ =20°

By referring to Tables 3 and 4, imbricated scale-like assembly with overlapping angle of 20° was highly distorted and bottom scale elements were forced into the backing clay as a result of the knife penetration. However, larger scale thickness overlapped at this angle was also distorted but not forced deeply into the backing clay. The maximum deformation was mainly distributed at the scale elements, which located at bottom of the whole model.

Table 4: Deformation contour at maximum scale overlapping thickness

4mm model		
		
Θ =10°	Θ =15°	Θ =20°
5mm model		
		
Θ =10°	Θ =15°	Θ =20°
6mm model		
		
Θ =10°	Θ =15°	Θ =20°

The depth of knife penetration underneath the target models was traced respectively at both minimum and maximum scale overlapping thicknesses, as shown in Figures 3 and 4.

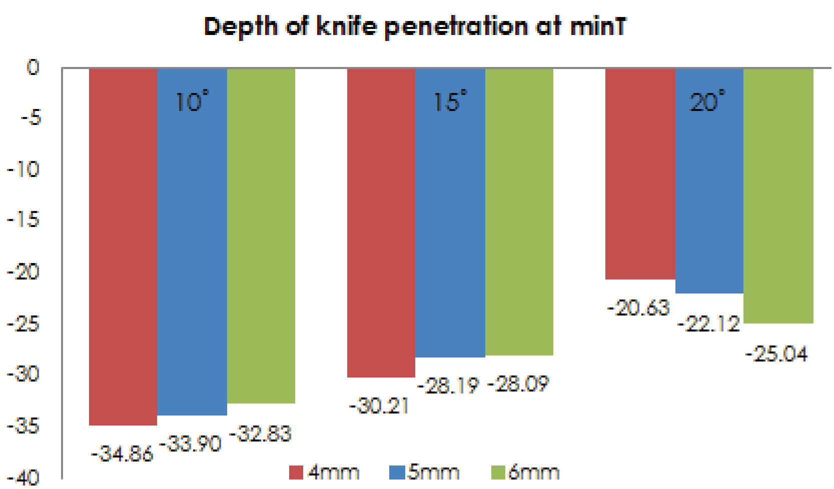


Figure 3: Depth of knife blade penetrated at the minimum scale overlapping thickness

The lowest depth of knife blade penetration at the minimum scale overlapping thickness was found in the assembly built with 4mm thickness and overlapping angle of 20°. This can be identified through the previous deformation contour documented in Table 3.

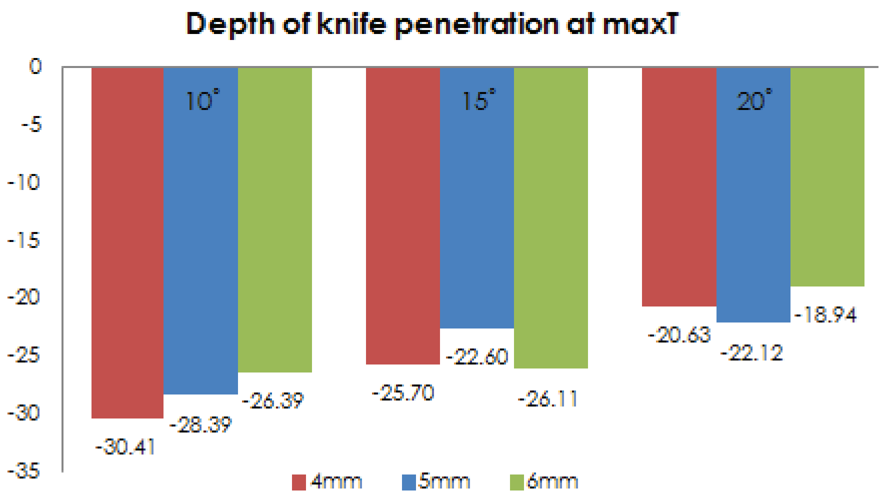


Figure 4: Depth of knife blade penetrated at the maximum scale overlapping thickness

The neighbour scale located at above and bottom of the target scale were highly resisted the penetration of knife through the target model. However, depth of the knife blade penetrated at both minimum and maximum scale overlapping thicknesses of 4mm model with overlapping angle of 10° was the highest as compared to other models. Depth of the knife blade penetrated at maximum scale overlapping thickness in the 6mm model overlapping at angle of 20° was the lowest.

3.3 Energy absorption

Impact damage in the imbricated scale-like assemblies caused by the loss of kinetic energy of the knife blade during penetration. The energy absorption by the target models can be analysed by using the formula,

$$E = \frac{1}{2}m(v_i^2 - v_f^2) \quad (1)$$

where E is the energy absorbed by the target model during knife impact, m is the mass of the knife, v_i and v_f is referred to the initial and final velocity of the knife penetration [16]. The impact performance of target models can be characterised by such penetration mechanism. Figure 5 and 6 show the variations of energy absorption by the target models at the region of minimum and maximum scale overlapping thickness. It can be noticed that there was an increase in the energy absorption by the FDM manufactured scale-like assemblies with different scale thicknesses and overlapping angles.

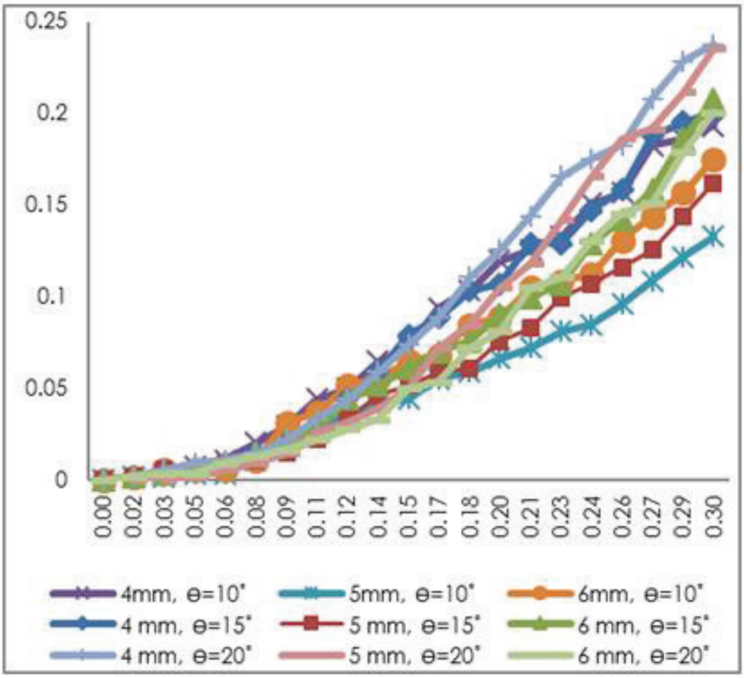


Figure 5: Absorbed energy/time at minimum scale overlapping thickness

Based on Figure 5, the most less energy was absorbed by the model constructed with 5mm scale thickness at lowest overlapping angle since the knife impacted directly through the single layer thickness of 5.08mm without any restriction. Although the minimum scale overlapping thickness of the 4mm scale model overlapped at this angle was lower than the one in 5mm, but a restriction was provided by the neighbour scale which located under it as the knife blade penetrated through it. The 4mm model imbricated at angle of 20° absorbed the most energy since three layers were formed due to the smaller thickness at this angle. Although the thickness of 6mm model overlapped at angle of 20˚ was higher than 4mm model, however, there was only two layers formed.

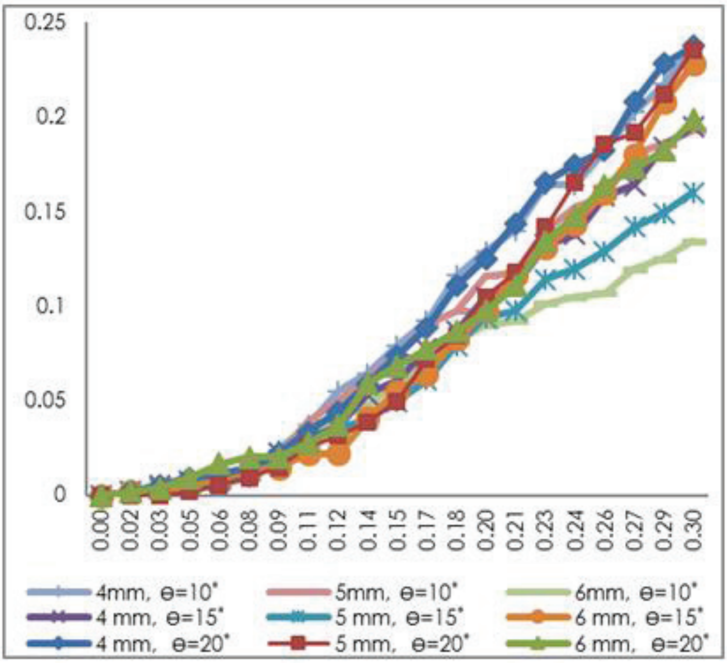


Figure 6: Absorbed energy/time at maximum scale overlapping thickness

By referring Figure 6, the total energy absorbed by 4mm model overlapped with angle of 20˚ was slightly higher than the 4mm model overlapping at angle of 10˚. This happened due to the velocity of knife penetration in the 4mm model overlapping at angle of 10˚ was highly restricted by the backing clay, instead of the body of the model. However, the least energy absorption happened in 6mm model overlapped with angle of 10˚, since the area where restricted the knife penetration was at the centred scales but not influence the neighbour scales.

4.0 CONCLUSION

This study was conducted in order to aid the future design and development of stab-resistant additive manufactured textiles geometry through the FDM system. This paper presents a finite element simulation using ANSYS to analyse the stab resistance behaviour of FDM manufactured imbricated scale-like model. The study explored the geometric characteristics such as overlapping scale angle and scale thickness to govern in the design feature of a scale-like assembly. Result obtained has showed the scale-like assemblies energy absorption by the imbricated scale-like model constructed with 4mm scale thickness and overlapping angle at 20˚ was the highest as compared to others in this study. Although this model was the heaviest as compared to other models in this study due to it has the largest value of imbricated factor, however, this scale overlapping angle still was in the reasonable range. Thus, it can provide higher stab resistance protection and flexibility. In order to design the stab resistant body armour, the scale thickness and overlapping scale angle are the influence factors to the performance of the body armour. However, the weakness region in the arrangement of single layer stab resistance has to be noted, where the location between scales could potentially allow the penetration of knife blade and cause injury. Therefore, further design of single layer stab resistant body armour should avoid from such arrangement. Other geometric characteristics such as total scale length of individual scale and distance between scales also have to be considered in order to maximise the level of protection and flexibility. In addition, the methods of enhancing the protective performance of the textile sample with carbon fibre composite material to improve the strength of FDM material for stab resistant body armour are currently being explored to offer better protection solutions in order to give a promising outlook for the future.

ACKNOWLEDGMENTS

We are thankful to all those who have assisted in this study and gratefully acknowledge UTeM for providing a high quality learning platform and financial support.

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