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FINITE ELEMENT ANALYSIS OF ADDITIVE MANUFACTURED TEXTILE FOR STAB RESISTANT APPLICATION

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ABSTRACT

An attempt is made to investigate the feasibility of Fused Deposition Modelling (FDM) using Acrylonitrile Butadiene Styrene (ABS) polymer material reinforced with composite layers to additive manufacture textiles for stab–resistant application. The purpose of this study is to investigate the relationship between the cross-sectional design of textiles and their protective performance. This paper presents finite element analysis of a planar CAD model and five additive manufactured textiles with different overlapped scale-linked design features that were created through a CAD system and simulated by a test blade using ANSYS software. Acrylonitrile Butadiene Styrene (ABS) polymer was applied to all the test samples in simulation testing, whereas, the specification of test blade was taken from NIJ Standard-0115.00. Result shows the knife penetration through the planar model was much larger than the scale-linked textile models. The overlapping feature of textile models had restricted the penetration of knife. However, Model 5 was the most suitable design for stab protection among the textile models and maximum total deformation distributed on its body was the lowest compared to other designs.

Keywords: additive manufactured textile, body armour, stab resistant, finite element analysis.

INTRODUCTION

In the last few decades, Additive Manufacturing (AM) has emerged for producing models and prototype parts, but since its creation, the applications of AM has widely expanded and even used to produce functional parts (Novakova-Marcincinova and Novak-Marcincin, 2012). AM is defined in ASTM (ASTM F2792-12a, 2012) standard as a process of joining materials to build objects in a layer by layer directly from 3D model data, unlike subtractive manufacturing technologies which build objects by removing of materials from a bulk solid to form a desired shape. AM offers the designers and engineers in the realization of their ideas into three dimensional models. This technology allows the creation of complex shapes, yet reduces the amount of production costs, operation time and the frequency of human intervention as compared to the traditional manufacturing processes (Cooper, 2001).

Body armour with stab protection is typically manufactured from aramid-based fibres such as Kelvar. Body armour is capable to provide protection against significant levels of impact energy, but continuous historical issues are unable to be addressed thoroughly (Johnson *et al*., 2012). However, additive manufactured textiles present 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.

This research has come from an interest to investigate the use of additive manufactured textiles with a Fused Deposition Modelling (FDM) machine using Acrylonitrile Butadiene Styrene (ABS) polymer material. The manufactured textiles will then be reinforced with composite layers for a light weight stab resistant body armour. Therefore, this study was conducted to aid the development of the research. This study aims to create an ideal phenomenon to investigate the relationship between the cross-sectional design of additive manufactured textiles and their protective performance. In this study, a planar CAD model was created and five articulated textile models with different scale link were design. Besides, the test blade was also generated into a CAD model and its specification was taken from NIJ Standard-0115.00. Both planar model and articulated textile models are then impact simulated with the test blade to investigate their protective performance. Finite element analysis (FEA) was performed with the aid of ANSYS software.

LITERATURE REVIEW

Body protective armour

Military, law enforcement and correctional officers around the world significantly work at risk of encountering an assault every day. As part of personal protective equipment, body armour plays a vital role to resist these professionals from a life threatening injury. Outfitting a police officer with body armour more than triple the likelihood that they will survive from a fatal shooting (LaTourrette, 2010).

Technical complexity in both design and manufacture of armour continues to increase, while the requirement of armour is getting greater as human evolve (Johnson *et al*., 2013). However, human body armour continues to be driven by two main objectives, which are to maximize battlefield survivability and mobility. These objectives can be achieved by maximizing energy absorption and dissipation, maximizing freedom of movement, while minimize deformations and penetration of body armour (Arciszewski and Cornell, 2006).

In general, there is always a need to keep a balance between body protection and mobility in designing armour (LaTourrette, 2010). In order to protect from sustaining a sharp force injury caused by a bladed threat, stab-resistant body armour must adhere to strict performance and test requirements (Johnson *et al.*, 2012). Therefore, the UK and the US government departments have developed a series of closely related standards for stab-resistant body armour test specification - with a maximum permissible knife penetration of 7 mm for all levels and both are closely similar, as stated in a) and b):

UK	Home Office Scientific Development Branch (HOSDB) Body Armour Standards for UK Police (2007) Part 3: Knife and Spike Resistance - Publication No. 39/07/C (Croft and Longhurst, 2007).
US	Stab Resistance of Personal Body Armor National Institute of Justice (NIJ) Standard - 0115.00 (National Institute of Justice, 2000).

Additive manufactured textiles

During the previous decade, textile structures realised by AM techniques have received increasing attention. According to (Bingham *et al.* 2007), the application of AM can enable the manufacture of fully finished customised items of clothing, new high-tech smart textiles capable of executing specifically designated tasks, components that transition from solid to textile, such as optimised footwear, and the potential to give textiles added functionality through design. This is illustrated in Figure-1, which is the world's first 3D conformal seamless AM textile garment designed and manufactured using a Laser Sintering (LS) system.

Figure-1. 3D conformal AM textile garment (Bingham *et al*. 2007).

Later, 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. The applications of AM textiles mostly via LS and 3D printer, especially in the field of fashion design continues to increase. However, there is no study about the generation of additive manufactured textiles via FDM machine reinforced with composite layers for stab-resistant body protective armour. Therefore, this study has been initiated in order to find out a novel and an enhanced solution for the protective body armour.

Finite element analysis

Finite element analysis (FEA) is required in the design process to present an ideal phenomenon for real case situation so that part performance can be predicted and the number of prototypes necessary in real tests can be reduced (Arriaga *et al*., 2010). FEA using explicit dynamics able to help gain insight into virtually any events that can be simulated, includes any short-duration events, complex or changing-body interactions (ANSYS, Inc., 2011). The applications include the drop-test, impact and penetration analyses, explosive loading and forming, blast-structure interactions, etc. In this study, explicit dynamics simulation was performed to understand the relationship between the cross section design of textile models and their protective performance against stab threats prior to the real experiment.

METHODOLOGY

In this study, two types of CAD models were generated and simulated under environment temperature of 22˚C using ANSYS. A planar CAD model was created to a dimension of 80 × 80 mm with thickness of 5.6mm. The planar model was impact simulated to a centrally located stab zone identified on its top faces, as shown in Figure-2.

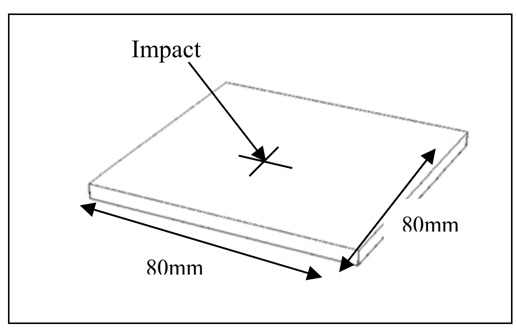
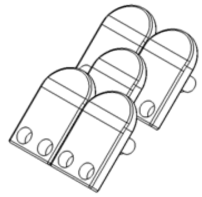
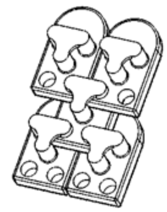
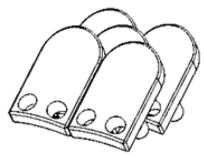
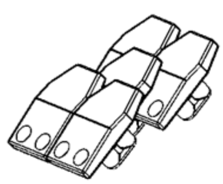
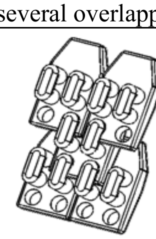
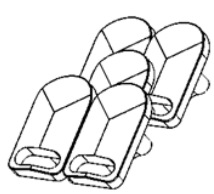
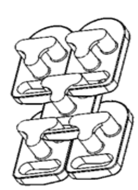


Figure-2. Central impact zone located on planar model.

Five textile CAD models were created individually into articulated which featuring different scale link designs, as illustrated in Table-1. Every scales were overlapped and imbricated like fish scales. These textile models were designed to a dimension of 85 × 88 mm and featured a minimum material thickness of 5.6 mm at its thinnest area for stab testing, as shown in Figure-3.

Table-1. Design concept of additive manufactured textile models.

Model 1		
This textile-like articulated model was designed with fish scale-like geometry attached with tripod-like support. Scales were assembled to each other and overlapped in row by row to form a sheet.		
Model 2		
Fish scale-like geometry was designed into curve and supported by a pair of cylinders positioned in parallel. Scales were arranged into row by row and assembled by inserting each cylinder into desire circular hole.		
Model 3		
Articulated textile model was created with dragon scale-like pattern which is shaped much like a heater shield. Its support was designed like a pull handle with different dimensions for both ends. Two supports were arranged outwardly from centre region of the scale in opposite direction. Dragon scales were assembled into several overlapping rows.		
Model 4		
Scale was designed with semi-hexagon shape at tail region and with two slanting surface positioned in opposite direction. The support was also created like a pull handle, but with two identical cylinders. Two supports were positioned in parallel on the bottom of each scale. All the scales were articulated in an orderly manner to form several overlapping row.		
Model 5		
This model was designed as fish scale shape which similar as in Model 1. However, its surface was made as pyramid shape and the cavity was created as straight slot rather than circular hole. Every supports were articulated with straight slots to form a desire number of overlapping rows.		

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NIJ standardized test blade was created and mated with the planar model and each textile model by using SolidWorks. The entire CAD file was then converted into IGS file, which can be used in ANSYS software.

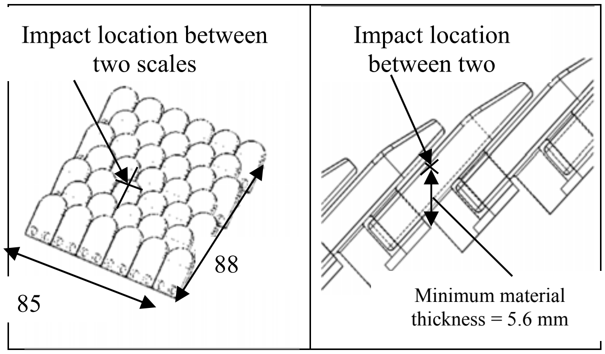

Figure-3. Overlapped scale-linked textile model strike location (L) and section view showing minimum material thickness (R).

FEA was generally focused on only protection against low energy threats with a knife resistance (KR) level one impact energy of 24 Joules. Explicit dynamics FEA was conducted by applying a constant impact force (F) of 242 N to the knife blade which is in the same direction as gravity in order to investigate stab resistant performance of the planar model and each textile model. This condition was illustrated as in Figure-4. The test blade was dropped on the center point of all sample models. This study mainly presents the total deformation distributed in both planar and textile models.

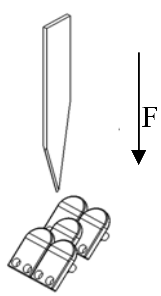

Figure-4. Drop impact test model.

Material used

Two types of material were applied respectively on both knife and all the models. B01 type tool steel was used for the knife blade in accordance with NIJ Standard-0115.00, whereas ABS polymer was used for both planar and textile models. ABS polymer was applied in this study since it is commonly used in FDM as a printing material. In FDM, a heated nozzle extrudes ABS and deposits it into a layer by layer to produce a desired product (McCullough and Yadavalli, 2013). Table-2 shows the material properties of ABS.

Table-2. Material properties of ABS (Materialise, 2013).

Material properties	Value	Unit
Density	1050	kg/m^3
Izod Impact strength, notched, 23˚C	107	J/m
Izod Impact strength, unotched, 23˚C	214	J/m
Young's Modulus	1627	MPa
Flexural Modulus	1834	MPa
Elongation at Break	6	%

RESULT AND DISCUSSIONS

FEA was performed to study on the total deformation distributed in the planar model and each articulated textile models. Under the similar environment and input parameters, deformation of planar model and all the scale-linked textile models behave in different ways. Table-3 shows respective simulation results obtained for planar in sectional and top view and each textile model in sectional view.

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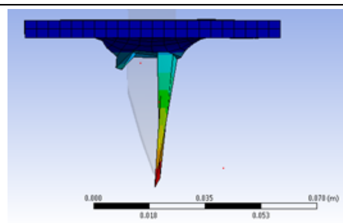
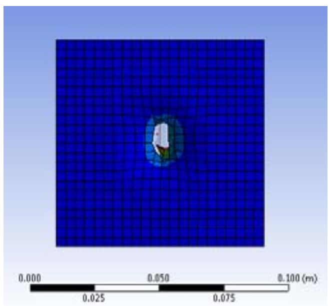
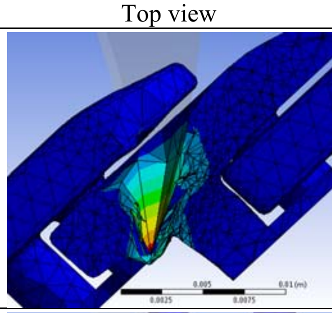
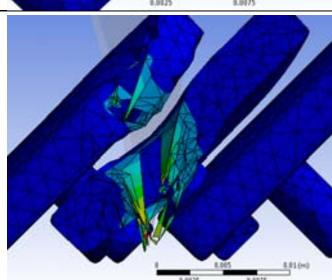
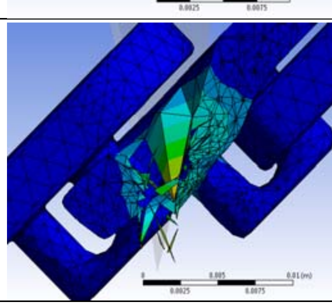
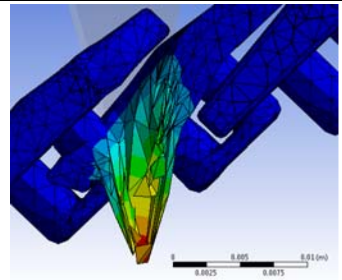
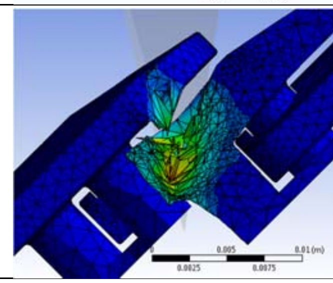
Table-3. Explicit dynamics analysis of planar and five textile models.

Model	Total Deformation
Planar Model	 Sectional view  Top view
Model 1	
Model 2	
Model 3	
Model 4	
Model 5	

Damage pattern and knife penetration

For the planar model, creation of damaged hole occurred at the center of the sample due to the knife dropped by a force of 242 N. The knife was directly penetrated through the body of planar model without any restriction. Deformation was largely distributed at surrounding of the hole with a maximum value of 4.9823e-002 m. This situation was different with the results obtained from articulated textile models since the overlapped scales of each textile model had formed a resistance towards the stab threats to offer better protections. However, deformation and knife penetration in each textile model was also different from each other due to the design feature of the textile models.

Based on the results obtained from textile models as shown in Table-2, total deformation occured in Model 4 was the highest among all the textile models. Textile surface of this model was designed with a slope pattern allowed the knife to stab much deeper through the its minimum material thickness and distort largely the textile body with a maximum total deformation of 1.1794e-002 m. Model 2 which designed with a curve surface has a relatively large deformation of geometry against the knife threat. Deformation was not only occurred at the individual stabbed scale but also influenced the neighbor scales overlapped on it, as shown in Figure-5. Maximum total deformation distributed on this model was 8.6315e-003 m.

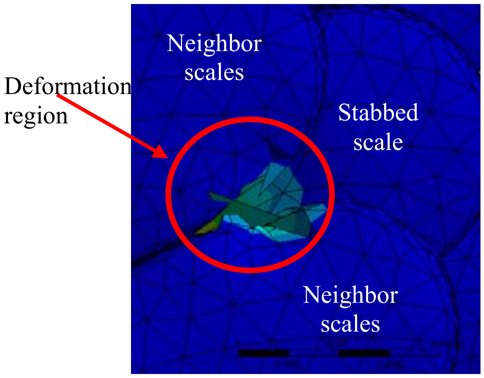


Figure-5. Deformation region in Model 2.

For Model 1, the knife blade had only slightly penetrated through the body thickness, but had distorted the center area of textile body with maximum total deformation distributed of 7.0037e-003 m. The design of this model was acceptable since its protection against knife threat was better compared to others. However, improvement is required to reduce the deformation occured on it. The maximum total deformation distributed on Model 3 was a little higher than Model 1, but the knife blade was puntured deeper through Model 3 and caused its cross section body to crack. In Model 5, maximum total deformation distributed on the textile body was relatively low, which was only 3.8141e-003 m. The test blade was only slightly puntured across the textile body. The textile surface of this model which was designed with pyramid feature enables the textile body to withstand knife penetration and to reduce deformation of the textile body. The neighbor scales were slightly affected in the punture event and they had helped to resist the knife from penetrating deeper across the the thinnest region of textile model.

CONCLUSIONS

This study was conducted in order to aid the development of stab-resistant additive manufactured textiles through FDM system. A planar CAD model and five scale-linked textile models were generated and simulated with the aid of ANSYS to determine their protective performance in terms of total deformation. Based on the results obtained from the finite element analysis, the planar model was significantly penetrated by the test blade with a maximum total deformation of 4.9823e-002 m compared to the five textile models. Injury will happen if this is applied in a real situation. This therefore highlighted the benefits of applying the scale-linked textiles in protecting a wearer. Despite penetration of knife had occurred in the scale-linked textile models, it was still likely to protect the wearer from injury due to their cross section design of body as compared with the planar model. However, different design geometry of scale-linked textile models shows different protective performance.

Based on the simulation results of the scale-linked textile models, Model 4 was highly deformed by the test blade with the highest maximum total deformation of 1.1794e-002 m. This was due to its textile surface which was designed with a slope pattern, had created a situation where it allowed the textile body largely deformed when knife penetrated through it. The deformation on Model 1 was acceptable since penetration of knife was not large, but improvement might be needed to reduce the deformation. However, maximum total deformation distributed on the body of Model 5 was the lowest, which was only 3.8141e-003 m, even though its neighbor scale were also affected. Due to the pyramid-liked feature of individual scale and the restriction from neighbor scales, the test blade was only slightly penetrated across the thinnest region of Model 5 as compared to the knife penetration of other textile models. Therefore, this model was found to be the most safe and was the appropriate scale-linked textile model design.

Other than the design geometry of textiles, methods of enhancing the protective performance of the ABS textile sample with carbon fibre composite material to improve comfort ability and weight lighter for stab resistant body armour are currently being explored to offer better protective solutions in order to give a promising outlook for the future.

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