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DESIGN AND ANALYSIS OF FUSED DEPOSITION MODELING TEXTILE GEOMETRICAL FEATURES FOR STAB RESISTANT APPLICATION

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Abstract

Body armour plays a vital role to provide protection to the law enforcement and correctional officers around the world who are significantly working at risk of encountering assault in daily routine. Despite many modern fiber-based soft body armours have been developed, yet a number of historical issues continue to exist and challenge the current protective solutions. In fact, additive manufacturing (AM) presents a great design freedom and advantages in developing customized user fit lightweight product or part, it also reduces the amount of labour costs, operation time and material waste. This research therefore investigates the feasibility of using AM system to manufacture textile geometrical models, which can be used for the development of novel user fit stab–resistant body armour. Prior to the actual experiments, this paper presents the finite element analysis of a planar and five cross-sectional design of textile models that will be additive manufactured with Fused Deposition Modeling (FDM) system utilizing the commonly used materials such as Acrylonitrile Butadiene Styrene (ABS) and Polycarbonate-ABS (PC-ABS) blend. A comparative analysis is performed between both materials. The purpose of this paper is basically to investigate the relationship between the cross-sectional design of textile models and their protective performance against stabbing. Firstly, a planar model and five textile model with different imbricate scale-linked designs were modeled with a CAD software. These models were simulated tested by a test blade using ANSYS software. The specification of test blade was taken from NIJ Standard-0115.00. The comparative result shows that PC-ABS has better performance to resist the knife threat than ABS due to the addition of ABS provides not only other useful properties, yet reduces the limitations of PC and at the same times without removing other superior mechanical properties. The result shows the knife penetration through the planar model was much larger than the imbricate scale-linked design models. The design of model 5 was the most appropriate as compared to other designs, which the maximum total deformation distributed on its cross section area was the lowest. This implies that the design of model 5 can be used in the experiment later and it might contribute high stab resistant towards the knife threat with impact energy of 24 Joules.

Keywords: Additive manufacturing; additive manufactured textile; stab resistant; body armour; finite element analysis

Abstrak

Perisai badan memainkan peranan yang penting untuk memberikan perlindungan untuk pegawai-pegawai penguatkuasaan undang-undang dan pemulihan akhlak di seluruh dunia yang bekerja berisiko dalam menghadapi serangan dalam rutin harian. Walaupun banyak moden berasaskan gentian armours badan lembut telah dikembangkan, namun beberapa isu sejarah terus menwujud dan mencabar penyelesaian perlindungan semasa. Malah, pembuatan bahan tambahan (AM) membentangkan kebebasan reka bentuk yang besar dan kelebihan dalam membangunkan pengguna disesuaikan sesuai produk ringan atau sebahagian, ia juga mengurangkan jumlah kos tenaga kerja, masa operasi dan sisa bahan. Kajian ini oleh itu menyiasat kemungkinan menggunakan sistem AM untuk mengeluarkan tekstil model geometri, yang boleh digunakan untuk pembangunan pengguna novel patut tikaman tahan badan perisai. Sebelum eksperimen sebenar, kertas kerja ini membentangkan analisis terhingga unsur satah dan lima reka bentuk keratan rentas model tekstil yang akan menjadi tambahan yang dihasilkan dengan Terlakur Pemodelan (FDM) sistem yang menggunakan bahan-bahan yang biasa digunakan seperti Akrilonitril Butadiena stirena (ABS) dan polikarbonat-ABS (PC-ABS) gabungan. Analisis perbandingan dilakukan antara kedua-dua bahan. Tujuan kertas kerja ini adalah pada dasarnya untuk mengkaji hubungan antara reka bentuk keratan rentas model tekstil dan prestasi perlindungan mereka terhadap menikam. Pertama, model satah dan model lima tekstil dengan reka bentuk berskala dikaitkan imbricate berbeza telah dimodelkan dengan perisian CAD. Model-model ini telah diuji oleh simulasi pisau ujian menggunakan perisian ANSYS. Spesifikasi ujian bilah diambil dari NIJ Standard-0.115,00. Hasil perbandingan menunjukkan bahawa PC-ABS mempunyai prestasi yang lebih baik untuk menentang ancaman pisau daripada ABS kerana penambahan ABS menyediakan bukan sahaja ciri-ciri berguna lain, namun mengurangkan batasan PC dan pada masa yang sama tanpa membuang lain sifat mekanik unggul. Keputusan menunjukkan penembusan pisau melalui model satah itu jauh lebih besar daripada imbricate model reka bentuk berskala berkaitan. Reka bentuk model 5 adalah yang paling sesuai berbanding dengan reka bentuk yang lain, yang jumlah ubah bentuk maksimum diedarkan di kawasan keratan rentas yang telah yang paling rendah. Ini menunjukkan bahawa reka bentuk model 5 boleh digunakan dalam eksperimen itu kemudian dan ia mungkin menyumbang tikaman tinggi tahan terhadap ancaman pisau dengan tenaga kesan 24 Joule.

Kata kunci: Pembuatan tambahan; pembuatan tambahan tekstil; tikaman tahan; perisai badan; analisis unsur terhingga

1.0 INTRODUCTION

In the last few decades, Additive Manufacturing (AM) has emerged for producing models and prototype parts. Now, AM has widely expanded and used to produce functional end-used parts [1]. AM is defined in ASTM 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 [2]. Nowadays, the applications of AM process have significantly increase to various fields, such as medical, automotive, aerospace, textile, electrical appliances, foot-ware design, architectural interior design, furniture design, etc. Most of these industries begin to use AM process to develop tooling and functional end-use products, yet not only produce prototyping models because this process is capable to provide improvement in speed, part accuracy, and material properties, as well as reductions in machine and operating costs [3-4].

Body armour is mainly worn to protect the human torso from attacks caused by weapons or projectiles. The body armour is typically designed for two major purposes, which include ballistic resistant and stab resistant [5]. Ballistic resistant body armour can be used to protect against handgun and rifle ammunition threats, whereas stab resistant body armour can be used to protect the torso against slash and stab threats [6-7]. Modern armour can be also made for both knives and bullets threats. however, such combination of armour is necessarily heavier and less flexible than single purpose armour. Therefore, accurate and relevant risk assessments are important to predict the type of threats which will be encountered by the wearers for their routine works and select armour that provides appropriate protection against specific threats [8]. In the Unite State (US), body armours are designed to provide protection from fragmentation and ballistics threats for military purpose. Urban conflict is also required the protective armour with additional stab resistant capabilities due to the increasing relevance of close-quarters [9]. The applicable scientific work exits on stab resistant armour is indeed relatively little as compared to ballistic armour. However, the uses of stab resistant armour are significant in Europe and other countries where restrictions on gun ownership. Nowadays, body armour is typically manufactured from materials such as nylon, fiberglass, Kelvar and many other synthetic fibers [10]. Body armour is capable to provide protection against significant levels of impact energy, but continuous historical issues are unable to be addressed thoroughly [11]. However, additive manufacturing 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.

This research has therefore comes from an interest to investigate the use of additive manufactured textiles geometry with using Fused Deposition Modelling (FDM) machine using Acrylonitrile Butadiene Styrene (ABS) and Polycarbonate-ABS (PC-ABS) material. The manufactured textile will then be reinforced with composite layers for a sample of light weight stab resistant body armour. However, the research is not going to 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. Thereby, a study was first conducted in order 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 sample and their stab resistant behavior. To do this, finite element simulation was performed with the aid of ANSYS software. Firstly, a planar CAD model was created and five articulated textile models with different scale link were designed. Besides, a test blade was also generated into a CAD model which its specification was taken from NIJ Standard-0115.00. Comparative study was performed to analyse on the effect of using both FDM materials, at the same time both planar and articulated textile models were impact simulated with the test blade to investigate their protective performance for stab defence.

2.0 BACKGROUND

2.1 Body Protective Armour

Military, law enforcement and correctional officers around the world significantly work at risk of encountering an assault in daily duties routine. Therefore, body armour must be worn to be effective to protect these professionals from life threatening injuries. Body armour can provide protection against a multitude penetrative threat, for example, battlefield threats, such as shell fragments and high-velocity bullets, and threats to law enforcement personnel, such as handgun bullets and knives [12]. Depending on the types of threats, different types of body armour may be worn.

Knife attacks is the most 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 [13-14]. However, outfitting a police officer with body armour is more than triples the likelihood that the police officer will survive from a fatal shooting [15]. Basically, there are two types of stab threats, including puncture and cut. Penetration by instruments with sharp tips, but without cutting edge is referred as puncture, however, cut refers to the contact with knives with a continuous cutting edge. Knife or cut threats are obviously more difficult to stop as compared to puncture due to the long cutting edge presents a continuous source of damage initiation during the stab event [16].

In order to protect from sustaining a sharp force injury caused by a bladed threat, the design of stab-resistant body armour must adhere to strict performance and test requirements. To do this, 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):

a) 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 [17].
b) US: Stab Resistance of Personal Body Armor National Institute of Justice (NIJ) Standard – 0115.00 [7].

Based on both HOSDB and NIJ standards, stab resistant body armour model should be designed to meet one of the three levels of protection principle. For Knife Resistance level one (KR1), armour is used to protects against low energy threats and suitable for low risk patrolling environments for maximum periods of wear. Armour at Knife Resistance level two (KR2) protects against medium energy threats by providing extended wear periods for a general duty body armour. However, armour at level three (KR3) provides short/medium periods of wear in high-risk environments to against high energy threats. For any given protection level, stab test of the armour test sample should be conducted with different velocity, at distinct energy levels and over test conditions. Besides, there are different maximum penetration limit allowable for test sample at each protection levels. These requirements for stab test are documented as in Table 1.

Table 1 Requirements of stab test based on each protection level

Prote-ction level	Energy level	Strike Energy (J)	Maximum Penetrati-on (mm)	Velocity (m/s)	Total Missile Mass (kg)
KR1	E1	24 ±0.5	7	5.0 ±0.05	1.9
	E2 – over test	36 ±0.6	20	6.2 ±0.05	1.9
KR2	E1	33 ±0.6	7	5.9 ±0.05	1.9
	E2 – over test	50 ±0.7	20	7.3 ±0.05	1.9
KR3	E1	43 ±0.6	7	6.7 ±0.05	1.9
	E2 – over test	65 ±0.8	20	8.3 ±0.05	1.9

Technical complexity in both design and manufacture of armour continues to increase, while the requirement of armour is getting greater as human evolve [18]. 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 [19]. In general, there is always a need to keep a balance between body protection and mobility in designing armour.

Furthermore, there are a number of historical issues continue to exist and challenge with many of the current protective solutions [11]. The most significant issue involve physical mobility of wearer. Protective body armour which used to protect the wearer against specific threats should not cause obstruction for the wearer in performing their duties [8]. Heavy design of body armour is never the choice in the development of body armour since it is usually too expensive, too cumbersome, and even restrict the mobility and performance of the wearer. Conversely, light body armour is much more preferable to be developed [19].

In addition, the issue of musculoskeletal and nerve injuries associated with long-term wear of protective body armour continue to impact combat readiness of the wearer [20]. Therefore, design of body armour should keep improving to offer not only superior protection, but limiting adverse impacts of musculoskeletal and nerve injuries. Apart from this, the presence of body armour significantly affects the performance of wearer in conducting their tasks due to increased thermo-physiological loading over a longer working period or in hotter environmental conditions [21]. These issues will never be eliminated, therefore, continuing efforts to improve the performance of body armour are necessary ensure its effectiveness and uses.

2.1 Overview of Additive Manufacturing

There are various types of additive manufacturing (AM) techniques are presently available to deposit materials for creating highly innovative and geometrically complex prototype and even functional assemblies. The more maturely commercialized techniques for manufacturing the products mainly include Stereolithography (SL), Fused Deposition Modelling (FDM), Selective Laser Sintering (SLS), and Three Dimensional Printing (3DP) [4].

In general, SL system is the first and the most widely used rapid prototyping system. SL is a liquid-based process that uses a computer-controlled ultraviolet (UV) laser to cure a photopolymer resin to form a desired shape following a 3D CAD model which had been translated into STL file [22]. While FDM is a process of material extrusion which used to manufacture thermoplastic parts through a heated nozzle to deposit the materials layer by layer [2]. The commonly used materials include Acrylonitrile Butadiene Styrene (ABS), Polycarbonate (PC), PC-ABS blend, polyphenylsulfone (PPSF) and PC-ISO which is frequently used in medical field [22].

Another process is SLS, whereby a carbon dioxide (CO_2) laser is used to heat and selectively fuse the durable thermoplastic powder such as filled and unfilled polyamides (PA), thermoplastic elastomers (TPE), polyether ketone (PAEK) and polystyrene (PS) to build parts in layer by layer [23-24]. Furthermore, 3DP is also considered as a powder-based process in which an ink-jet printing head deposits a liquid binder onto thin layer of powders to print a desired shape in layer by layer manner [25]. The materials that commonly used in this system include plaster power used for making concept design model, starch powder that used to manufacture master pattern for investment cast, and ceramic powder coated with resin which used for making sand casting mould, etc [26].

Most of the AM processes basically share some similarities, especially the fundamental additive principle of building parts, but the build materials and the procedure used to combine the layers are distinct in respective processes [27]. Implementation of this technology has enabled the reduction of design restrictions in traditional Design for Manufacturing and Assembly (DMFA) method, which leads to the limited redesign by only removing fasteners and combining existing parts together [28].

2.2 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 [29]. The world's first 3D conformal seamless AM textile garment was designed and manufactured using a SLS system, as shown in Figure 1. In the textile industries today, AM techniques are widely implemented to direct produce complicated contour profile garments which are designed in 3D model using computer with connecting internally to the additive manufacturing machine [4]. Figure 2 shows some examples of AM garments with complicated contours in the perspective of fashion design.

Figure 1 The world's first 3D conformal AM textile garment [29]

Figure 2 Additive manufactured garment with complicated contours [30]

Johnson et al. [18] 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 [18]. The applications of AM textiles mostly via LS and 3D printer, especially in the field of fashion design continue to increase. However, there is no study about the creation of additive manufactured textiles via FDM system reinforced with composite layers for stab-resistant body protective armour. Therefore, this research has been initiated in order to find out a novel and an enhanced solution for the protective body armour via FDM system.

2.2 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 [31]. 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 [32]. 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.

3.0 CONCEPTUAL DESIGN

In this study, two types of CAD models were generated for the simulation. A planar CAD model was created to a dimension of 80 × 80 mm with thickness of 5.6mm, as shown in Figure 3.

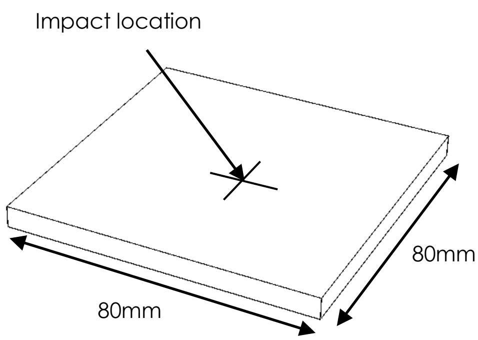
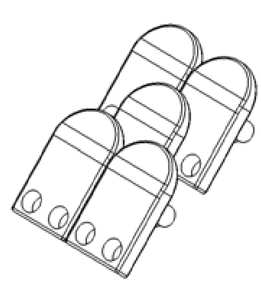
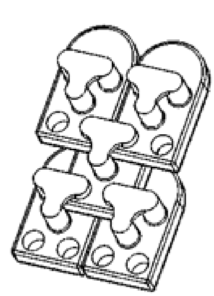
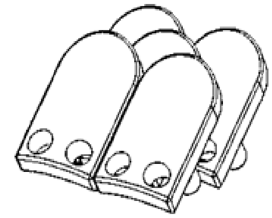
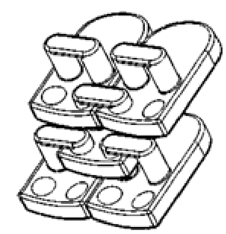
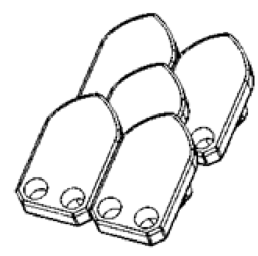
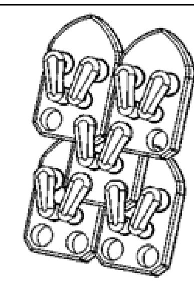
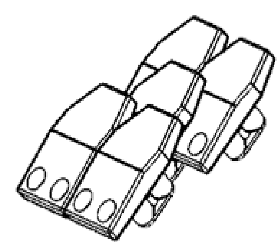
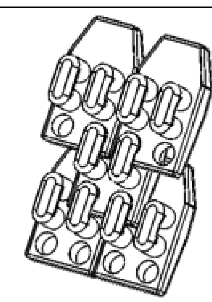
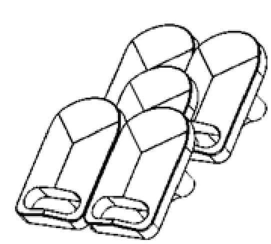
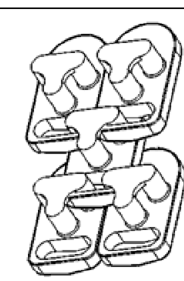


Figure 3 Central impact zone located on planar model

By considering the knife resistant performance, five textile CAD models were created individually into articulated which featuring different scale link designs, as illustrated in Table 2.

Table 2 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 the 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.		

Each textile model was 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 4 and Figure 5. In the textile model, a number of scales overlap and imbricate over each other into fish-like scales. Such scales arrangement can provide high flexibility that allows for shape changed and very effective protection performance [33].

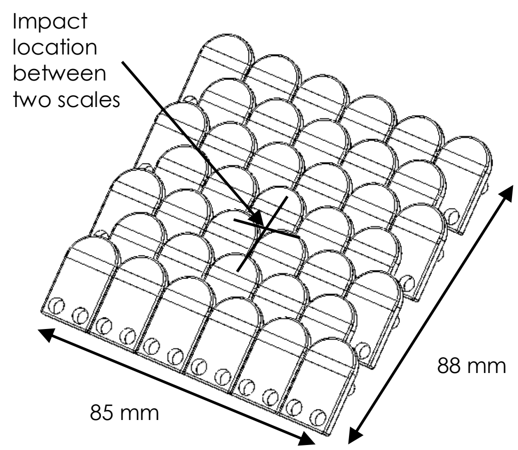


Figure 4 Overlapped scale-linked textile model strike location

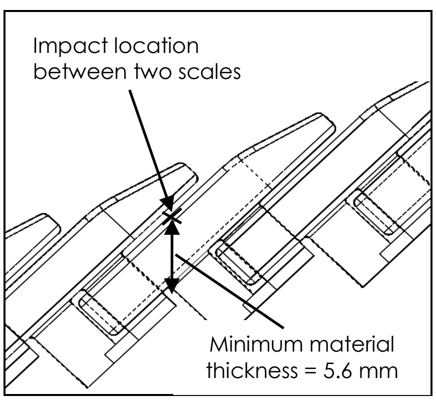


Figure 5 Section view showing minimum material thickness

4.0 MATERIAL USED

By referring to the NIJ Standard-0115.00, B01 type tool steel was used as the material of test blade. Two types of material such as ABS and PC-ABS blend were applied in the respective models. These polymers were used in this study since they are commonly used in FDM system as printing material. Table-3 shows the material properties of both ABS and PC-ABS blend thermoplastics.

Table 3 Material properties of ABS and PC-ABS blend [34-35]

Properties \ Material	Units	ABS	PC-ABS
Tensile Strength	MPa	22	41
Flexural Strength	MPa	41	68
Notched Izod Impact, 23˚	J/m	107	235
Unnotched Izod Impact, 23˚	J/m	214	642
Elongation at Break	%	6	6
Density	kg/m^3	1050	1100

5.0 FINITE ELEMENT ANALYSIS AND METHODOLOGY

Prior to the finite element analysis (FEA), both planar and textile models were generated by using a CAD software and translated to IGES files, which is readable by FEA software. The simulation was under an environmental temperature of 22˚C using ANSYS. The planar model was impact simulated to a centrally located stab zone identified on its top faces, as shown in Figure-2. The NIJ standardized test blade was also created in CAD model and mated with the planar model and every textile model respectively.

FEA was generally focused on only protection against low energy threats with a knife resistance (KR) level one impact energy of 24 Joules (J). Both ABS and PC-ABS thermoplastics were used for each model. Explicit dynamics FEA was conducted by applying a constant velocity (v) of 1150 m/s onto 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. While in the planar model, the knife blade was applied with v=1200 m/s in order to show how the planar failures to resist the knife. These speed were applied in order to reduce computation time for the simulation, however, any changes of the speed should not affect the physical phenomenon since the knife energy is constant [36]. The test blade was dropped on the center point of each sample model, as shown in Figure 6. Besides, the blade was modeled as a perfectly rigid body because deformations should not occur on it during impact event. This study mainly presents the total deformation distributed in both planar and textile models with different FDM materials.

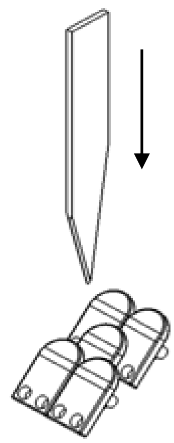
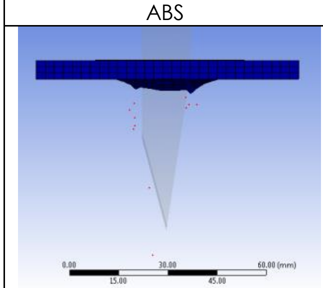
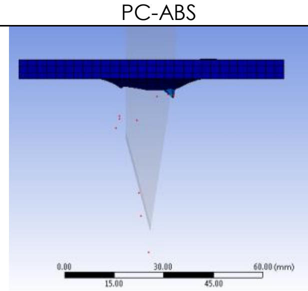
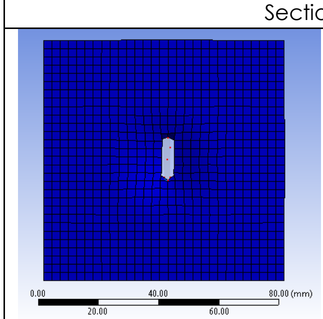
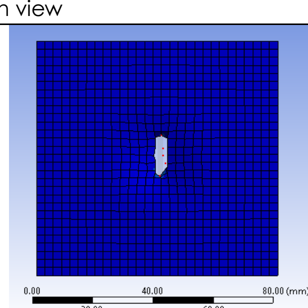


Figure 6 Drop impact test model

6.0 RESULT AND DISCUSSION

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 4 and Table 5 shows respective simulation results obtained at 0.00005 s for planar in sectional and top view and each textile model in sectional view.

Table 4 Explicit dynamics analysis of planar model

Deformation Behaviour at 0.00005 s	
ABS	PC-ABS
	
Section view	
	
Top view	

For the planar model, creation of a damaged hole occurred in the centre of the sample due to the knife dropped with v=1200 m/s. The knife was directly penetrated through the body of planar model and had created a large hole with maximum total deformation of 71.0 mm for ABS, while 54.05 mm for PC-ABS. The maximum shear elastic stress distributed at the surrounding of damaged hole in both ABS and PC-ABS planar models, as shown in Figure 5. The total deformation distributed on PC-ABS planar model was much smaller than in the ABS planar model. PC-ABS is definitely an improvement over ABS due to PC itself contributes superior strength and heat resistance, while the combination of both materials to minimise the drawbacks of PC which are high melt viscosity and notch sensitivity [37].

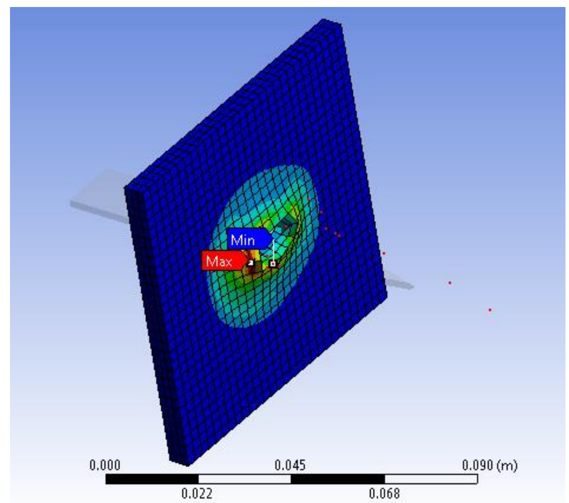
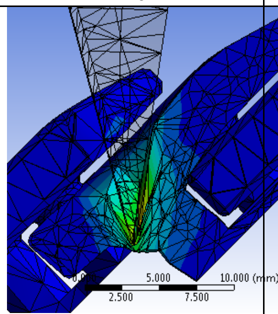
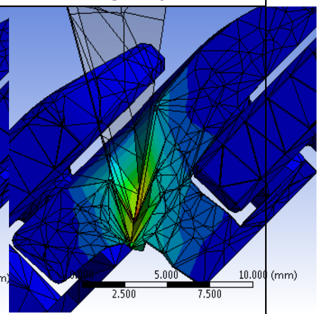
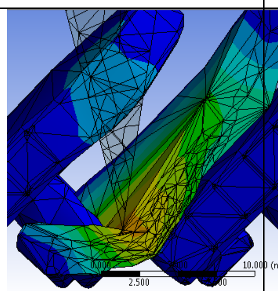
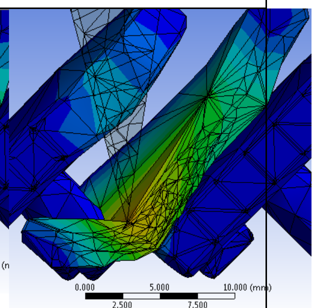
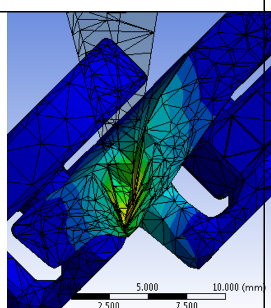
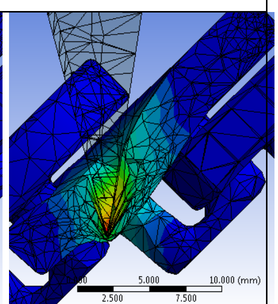
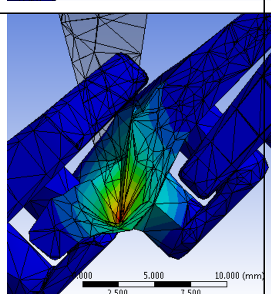
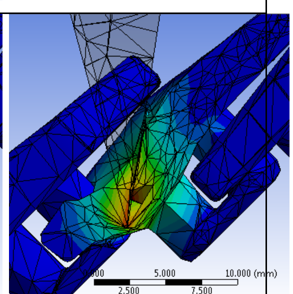
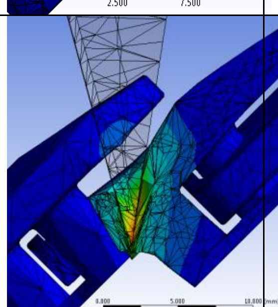
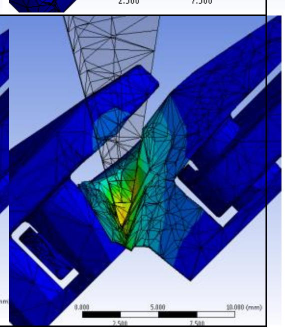


Figure 7 Distribution of maximum shear elastic stress

However, such deformations and creations of the damaged hole should not occur in the articulated textile models even same velocity is applied. This is due to the overlapped scales in 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.

Table 5 Section plane view of five textile models

Model	Deformation Behaviour at 0.00005 s	
	ABS	PC-ABS
Model 1		
Model 2		
Model 3		
Model 4		
Model 5		

Based on the results obtained from textile models as shown in Table 4, the maximum total deformation distributed in both Model 1 made of ABS and PC-ABS were the highest among all the textile models at 0.00005 s with maximum value of 6.952 mm and 5.811 mm. However, Model 2 which designed with a curve surface has a relatively large deformation of geometry against the knife threat and even distort the scale link where one scale is connected to the other. Deformation was not only occurred at the individual stabbed scale, but also highly influenced the neighbour scales overlapped on it, as shown in Figure 7. Maximum total deformation distributed on this model was 5.668 for ABS and 5.672 mm for PC-ABS.

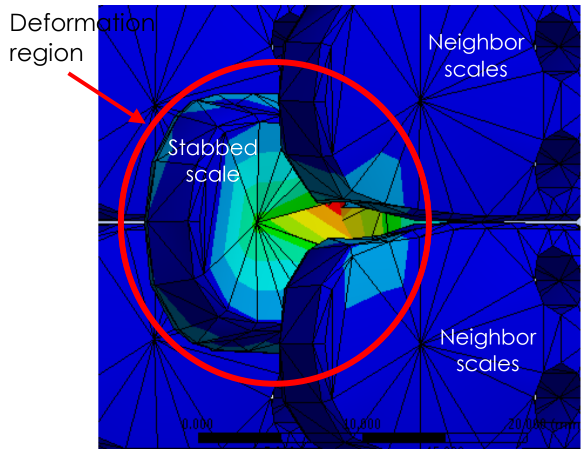


Figure-8 Deformation region in Model 2

For Model 3, the knife blade had slightly distorted over the body thickness, with maximum total deformation distributed of 5.254 mm in ABS and 5.307 mm in PC-ABS. While maximum total deformation distributed in both Model 4 made with ABS and PC-ABS is 4.044 mm and 5.912 mm. Although the value of maximum total deformation in Model 4 made of ABS was the lowest among all designs, but its structure might need some modifications since the maximum total deformation in PC-ABS was higher than in ABS. A high performance material should deserve for a better design, the overall performance of the model is therefore higher. Besides, distortion on the scale link was also larger. In Model 5 which made of ABS, maximum total deformation distributed on the textile body was relatively low, which was only 4.981 mm. However, the deformation in PC-ABS was certainly higher than the ABS. The maximum total deformation distributed on it was 4.665 mm. The test blade was only slightly punctured across the cross section body of textile. 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 neighbour scales were slightly affected in the stab event, but no much effect.

5.0 CONCLUSION

This research was conducted in order to aid the development of stab-resistant additive manufactured textiles geometry features through the 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. FDM commonly uses materials such as ABS and PC-ABS were applied respectively in each model. Based on the results obtained from the finite element analysis, the both ABS and PC-ABS planar model was significantly penetrated by the test blade with v=1200 m/s. However, PC-ABS offers better performance against stabbing since deformation on the PC-ABS planar model was lower than the one made of ABS. Injury will happen if the planar model applied in a real situation. This therefore highlighted the benefits of applying the scale-linked textiles in protecting a wearer. Despite penetration of the knife would also occur on the scale-linked textile models, it was still likely to protect the wearer from injury due to their cross section design of the body as compared with the planar model. However, different design geometry of scale-linked textile models show different protective performance.

Based on the simulation results of the scale-linked textile models, the maximum total deformation basically districted around the tip of knife where it stabbed on. The deformation on Model 1 was the highest for both ABS and PC-ABS as compared to other designs. Model 2 was highly deformed by the test blade, however, the maximum total deformation was lower than Model 1. Its textile surface which was designed with a curve pattern and the smaller space between scales for stabbing, had created a situation to allow the stabbed body largely deformed. However, maximum total deformation distributed on the cross section of Model 5 made of PC-ABS was the lowest, which was only 4.665 mm, even though its neighbour scale were also slightly affected. Due to the pyramid-liked feature of individual scale and the restriction from neighbour 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. However, other designs might need some improvement, so that deformation and penetration of the knife can be reduced.

Other than the design geometry of textiles, methods of enhancing the protective performance of the 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 protection solutions in order to give a promising outlook for the future.

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