A REVIEW ON FLEXIBLE THERMOPLASTIC COMPOSITE LAMINATE FOR ANTI-STAB APPLICATIONS

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ABSTRACT: Research on anti-stab utilizing various types of fiber reinforcement and matrix materials in the production of laminated composite have been increased very rapidly over the past decade to investigate the performances and behavior of anti-stab. This review summarized recent research on production of laminated composite, thickness, design of laminates, various types of materials used, international requirement standards and the failure mechanism on the composite after the anti-stab testing. This review focused on thermoplastic as matrix materials due to good flexibility, stiffness and strength. The review showed that a proper hybridization through laminate system may make the hybrid panel very promising for anti-stab enhancement; however, lot of studies is still needed in the fields of preparation and stability, characterization and applications to overcome the challenges. Thus, the study propose a new flexible composite laminate for anti-stab applications by combining two types of reinforcement materials and embedding them into a proper matrix material.

KEYWORDS: *Flexible, Thermoplastic, Laminate, Anti Stabbing.*

1.0 INTRODUCTION

Composite materials are commonly used in engineering and military applications based on their characteristics in providing benefits in mechanical properties, especially towards the impact of performance characteristics to absorb the impact of energy [1]. As the first impact and damage failure in composite laminate product becomes an ultimate concern of engineers and manufacturers, Aktacs *et al.* [2] state that the real concern is on the behavior of the impact loading which can occur during the manufacture process, normal operation, and maintenance in industry. Based on Mayo *et al.* [3], one of the challenging applications is for the product to have stab and puncture resistance, especially on a product like body armor which must be flexible and comfortable to protect law enforcement officers and security personnel against the stab attack. In European countries, stab assaults are higher compared to the firearm attack. In addition, the most common test for anti-stab behavior and performance is quasi static stab testing using universal testing machine and stab drop tower test as reported by Li *et al.* [4] and Stojanović *et al.* [5].

As a flexible characteristic of composite laminate is its capability of bending easily on certain load without breakout, a higher stiffness characteristic is required to resist elongation when an external load is applied. Therefore, a composite required in this case should have a combination of strength, toughness, and flexibility. Strength is an amount of stress that materials can withstand before it breaks while stiffness is an ability to resist elongation when the load is applied, Kim and Nam [6] argue that the flexibility and toughness of the reinforcing materials required for stab resistant performance and behavior should be viewed from the perspective of manufacture process and materials..

Adel [7] finds that thermoplastic has different properties compared to thermoset related to high ductility and toughness, facilities of processing and recycling potential. According to Kaw [8], thermoplastic can also be formed at high temperature and pressure because of the weak bonding known as Van Der Waals bonding. Meanwhile, thermoplastic elastomers have become a significant part of the elastomers industry since they were first produced about 55 years ago [9]. Physical properties of thermoplastic elastomer are similar to rubber; soft, flexible and resilient. Thus, among these three materials, thermoplastic is more focused because it can enhance mechanical properties compared to thermoset and elastomers. Besides, thermoplastic has more advantages than others.

Tsai and Melo [10] assert that the composite materials must emphasize those materials which contain matrix constituents that bind together and provides stronger and stiffness reinforcement constituents. The composite materials used as suggested by previous researchers are Kevlar/polyester [4], Aramid/LDPE [6], Aramid/Glass Fiber/Epoxy [12] and Kevlar/PE [13]. Hence, aramid fiber is commonly used as reinforcement materials on industry application and human body protection against the ballistic and stabbing threats. According to Tien *et al.* [14], an important parameter for a flexible and toughness composite is the types of resin and fiber used which is related to the stab resistant performance. In addition, the shape of the impactor used is also important to determine a depth penetration against thickness and layer. However, there are only few researchers who focus on the flexibility and air permeability of the composite, especially thermoplastic materials.

Therefore, this review is conducted to investigate the main factor needed when fabricating a flexible composite laminate based on the orientation and numbers of plies to handle force applied towards bending and damage on the surface of the composite laminate through the destructive testing. Hence, this review also needs to find the right selection and decision on the materials, orientation, number of ply, and other important criteria for a new flexible thermoplastic composite laminate. Particularly, the flexible composite laminate which can withstand stab impact using low cost materials.

2.0 STABBING AND ANTI-STAB

Campbell [15] discovers that in England, about 30 % increase has been noted in stabbing assaults.. Compared with Asia, stabbing attacks are more prevalent threats because of the ban on gun possession. In a different study, *Li et al.* [11] examine the increasing of uses in body armor with stab protection in recent years. Previous cases involve gun or bullets but recently cases such as using swords, knives or other sharp objects become more prevalent. According to Tien *et al.* [14] personnel body protection can be divided into two groups according to the protection object. Firstly, against the kinetic impact and secondly against the intrusion of a sharp edge. Besides, the stab threats can be classified into two categories which are puncture and cut. Puncture refers to the penetration of an object with pointed tips through a target, for example, ice picks or awls. Cut refers to the destruction of the target with a continuous sharp edge such as knife edge.

3.0 MATERIALS FOR ANTI-STAB

Many types of materials can be used in making composite laminates for stabbing testing. Tien *et al.* [14] indicate that the form of Aramid and Basalt fiber are in filament and metal fiber is in staples. The specifications of the filament and staples are shown in Table 1. Furthermore, Stojanović *et al.* [5] also use p-aramid fiber type of Twaron (Teijin Aramid) and the laminates on the side of the p-aramid use thermoplastic polyurethane film.

Table 1: Specification of the filament and staplwes based on Tien *et al.* [14]

Materials		Fiber Specification
p-aramid filament		22.2 tex (13fil)
Basalt filament		50 tex (200fil)
Metal staple yarn (stainless steel 319- L)		65 tex, -Mean fiber length: 150mm Mean fiber diameter: 12μm
Cotton	Roving	2 x 400 tex-Mean fiber length: 31.5mm Micronaire value: 4.38
	Staple yarn	17.72 tex (2-plied)

In another study, Li *et al.* [11] examine Kevlar fiber which has a high count and high density of fabrics which are commonly used as soft body armor after multiple layer lamination. Besides that the interlayer of nonwoven with glass fabric or Kevlar fabric are called glass compound fabric and Kevlar compound fabric. Table 2 shows mechanical and physical properties of glass and Kevlar fabric.

Table 2: Mechanical and physical properties of glass fiber and Kevlar fabrics [11]

Fabric	Structure	Density (in.)	Tensile Force (N)		Elongation (%)		Modulus (GPa)	
			Warp direction	Weft direction	Warp direction	Weft direction	Warp direction	Weft direction
Glass	Plain	34x26	606.10	514.45	5.26	3.18	1.46	2.05
Kevlar	plain	28x28	2627.52		7.00		4.76	

Yong [16] use soft rubber compound in order to overcome the high rigidity problem by enhancing the flexibility of the laminates. At the same time, high fiber loading can also impact on strength of the laminates. Thus, the mixing of the fibre with either thermosetting or thermoplastic matrix are a well known combination to produce fibre based composite. Table 3 shows a comparison among materials commonly used for anti-stabbing testing.

Table 3: Materials commonly used in anti-stab research

Reinforcement / Fiber	References
Aramid Fiber/p-aramid	[5] & [6]
Aramid, Basalt and metal fiber	[4]
Recycle Kevlar Fiber	[11]
Rubber Wood	[16]
Aramid, Glass fiber	[12]
PET	[17]

4.0 THICKNESS FOR ANTI-STAB

According to Tien *et al.* [14] an armor thickness of a specimen is essential for providing comfort in wear ability. Thus, the thickness of the specimen can determine its penetration depth behavior. Besides, several studies show when the penetration depth increases, the thickness decreases. The cause may be due to an influence of fabric density in each specimen. In addition, Li *et al.* [4] discover that when number of layers increases the thickness also increases automatically. This scenario leads to a penetration through compound fabrics and offers more chance to contact with compound fabrics. Table 4 shows the thickness based on the materials used and the layers of the composites in anti-stab research.

Table 4: The thickness and number of layer used in anti-stab research

Materials	Thickness (mm)	Layer	References
Aramid/Kevlar		8	[13]
P-aramid	0.571	4	[6]
Aramid Fiber p-aramid		4	[5]
Aramid, Basalt and metal fiber	17.6, 17.3, 14.2	-	[14]
Recycle Kevlar Fiber	0.32	5	[11]
Rubber Wood	11.0	-	[16]
UHMWPE	5µm	single	[4]
PET	2.2	single	[17]

5.0 ANTI-STAB TESTING

Stojanović *et al.* [5] shows that most stabbing effect testing use quasi-static knives penetration tests based on modified versions of NIJ standard 0115.00, with engineered knife S1 for the multiaxial composite. Figure 1(a) shows the testing of knives penetration toward the composite. Kim and Nam [6] also find that quasi-static stab resistance testing of the p-aramid and resin reinforced fabrics is performed using a Universal Testing Machine (Instron, Series IX automated material testing system). The knife and spike impactors are mounted in the upper grip, and a single sheet of the target fabric is tightly placed below the impactor using a compression jig. The compression jig for quasi static stab resistance testing is shown in Figure 1(b & c).

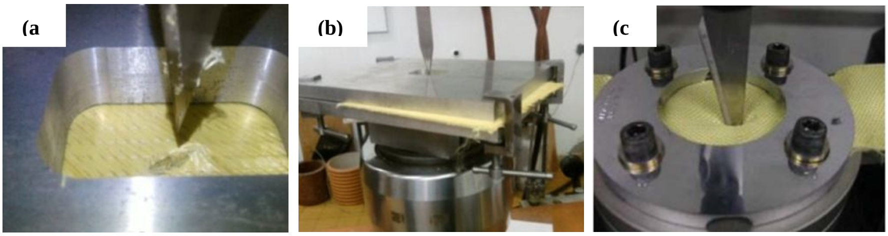


Figure 1: Quasi static knives penetration (a) after, and compression jig (b) [5], (c) [6]

A study by Tien *et al.* [14] show another method in conducting stabbing testing; using a drop mass with standard blades equipped with an impactor as depicted in Figure 2. The blades consist of two types; knives and spikes. Basically, the knife was dropped onto the unclamped fabric which was placed on the top of damped backing materials by certain height. The mass, speed, and damping characteristics of the backing material for the experiment have been designed to mimic the biomechanical process of stabbing assaults. Table 5 illustrates the types of standard and machine researchers used for the anti-stab testing application.

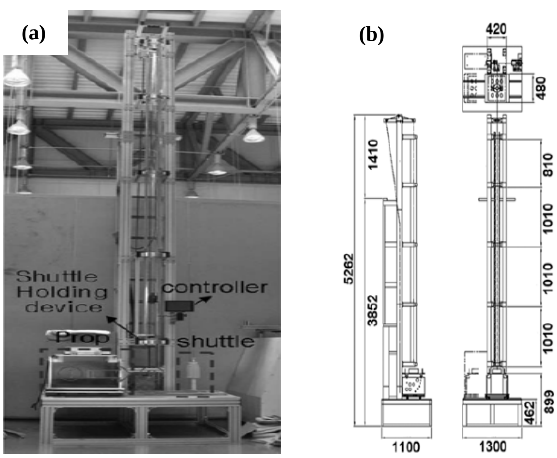
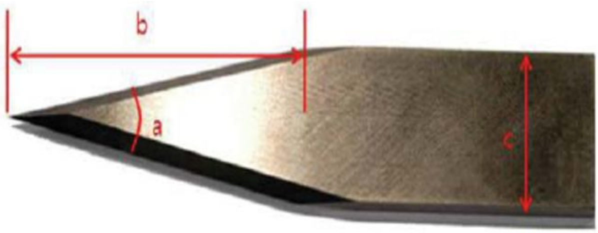


Figure 2: Anti-stab testing (a) drop tower, (b) the schematic of drop tower [14]

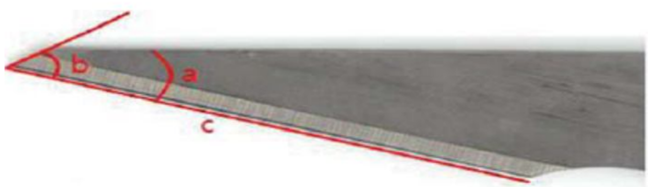
Table 5: Standard and equipment used for anti-stab research

Standard Type	Machine/ Equipment	References
NIJ 0115	Stab Resistance Test Machine	[16]
NIJ 0115	Stab Impact Testing Instron 9250HV (Boston USA)	[4]
ASTM F1342.05	Static Puncture Test Instron 5566 Universal Tester (Instron, USA)	[11]
NIJ 0115	Stab Testing Frame, Conventional Drop Tower	[14]
NIJ 0115	Instron Universal Testing Machine	[5]
NIJ 0115	Quasi-static stab resistance testing using UTM (Instron, USA)	[6]

Kim and Nam [6] analyze two types of knives which are double edge blade known as S1 and spike. These knives are used as impactors for the drop tower testing following the NIJ standard. Figure 3 shows the two types of the impactors. According to NIJ standard, to set the point, it must strike the energy. The total drop mass including impactor is fixed to 1.8 kg and the drop height is adjusted to 1.36 meter. The depth of penetration that strikes to target is detected by the displacement sensor. Before the stab test, the impactor is placed to the drop mass in a rail-guided drop tower, and then it will drop off from a fixed height to impact the target. Tien *et al.* [14] also find that two types of impactors that NIJ recommends are knife, and spike. Figure 3 are example of the impactor with various dimensions.



(a) Knife impactor (a: 23˚, b:49.2mm, c: 20 mm) abbreviated S1



(b) Knife impactor (a: 15˚, b: 45˚, c: 85mm) abbreviated P1

Figure 3: Type of impactor nose (a) S1, (b) P1, and (c) spike [14]

Stojanović *et al.* [5] recommend using eight layers of the PU/aramid/PVB fabrics composite plus the 5 wt.% Silicon Oxide (SiO_2) which can provide an excellent resistance to penetration by a ballistic projectile and stab resistance from the front impact. Thus, adding only 5 wt.% SiO_2 can improve the thermo mechanical properties and provide more comfort and flexibility.

Hou *et al.* [17] find that the woven structure has a numerical calculation on the damage that happen to the surface after testing. Parameters that are used in this calculation are warp yarn, weft yarn, the matrix and the relevant composite fiber used for an experiment. However, Yan *et al.* [18] find that a 3D structure can support the drop weight impact and due to the different failure mechanism, the static and dynamic puncture test is observed. It also shows that a hybrid composite can perform exceptionally in static and dynamic impact resistance and areal density can influence impact behavior. A schematic diagram of the static and dynamic puncture is shown in Figure 4. Tien *et al.* [14] also provide a formula to measure value in the stab testing for penetration depth, but the performance of the specimen against the stabbing cannot be interpreted. When penetration depth increases, the tendency of areal density and thickness decreases. Thus, the penetration depth can protect the human body against stabbing treat assigned by the NIJ standard. The anti-stabbing index formula (ASI) is known as thickness times density armor specimen for penetration depth respectively.

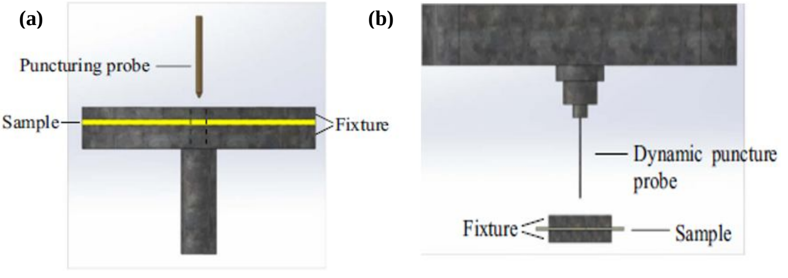


Figure 4: the puncture (a) close-up impact, (b) dynamic [15]

Kim and Nam [6] also find that materials composed with textile structure for stab resistance can provide high flexibility and process ability compared to protective materials such as metal or ceramic plate. The higher performance of fiber is due to aromatic polyamide, ultrahigh molecular weight polyethylene, and polybenzoxazole. All these can prevent the penetration or cut by a sharp impactor on the stab resistance testing. Table 6 shows the results for the resin reinforced p-aramid fabrics.

Table 6: Penetration depth for knives and spikes at fixed number of layer [6]

Sample	Layer	Thickness (mm)	Penetration depth (mm)	
			Knives	Spikes
Untreated	20	11.4	Over 36.0	Over 36.0
Single side	20	12.6	13.0	Over 36.0
Both side	20	15.7	16.7	24.0

In contrast Yong [16] finds that in general, rubber wood fiber shows a good reinforcement behavior for making laminate composite. It also has strong elastomeric features and this behavior can be found in other fibers such as jute and glass fiber. According to him, edge blade and spike only pass the testing on energy level of 1 and 2 and when reaching energy level 3 it shows 100 % failure as shown in Table 7. However, Li et al. [4] find that a knife has a sharp face, so it can only cut fiber along the stab direction during the stab impact, for UHMWPE UD composite stab behavior is directionally independent compared to other fiber reinforced composites which is anisotropy. The structure of the UHMWPE UD composite must be designed first before doing stab resistance test to get better results.

Table 7: Stab resistance test at different energy level, angle and threat weapon [16]

Energy Level	Angle of incidence	Threat weapon	Penetration depth (mm)
1	0	P1	3.4
	0	S1	4.1
	45	P1	3.7
	45	S1	4.5
	0	Spike	6.0
	45	Spike	7.2
2	0	P1	4.9
	0	S1	5.4
	45	P1	5.1
	45	S1	5.8
	0	Spike	7.3
	45	Spike	8.1
3	0	P1	7.2
	0	S1	7.5
	45	P1	7.9
	45	S1	8.1
	0	Spike	9.0
	45	Spike	9.8

6.0 FAILURE MECHANISM

Decker *et al.* [19] find that when impact energy increases, the penetration depth on the backing materials also increases. Hence, the drop tower stab performance of the Kevlar and STF Kevlar targets against the spike impactor, resulting in STF-Kevlar provides more exceptional stab resistance compared to Kevlar. Furthermore, at this highest energy level against the STF–Kevlar target, the spike impactor is plastically bent. Figure 5 shows fabric damage on the STF-Kevlar and Kevlar based on the mass 2.34 gram and the height was 0.75 meter.

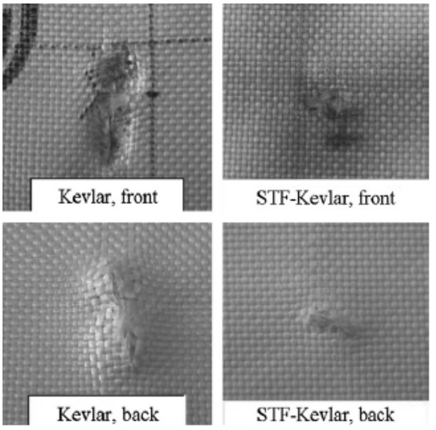


Figure 5: Fabric damage on the STF-Kevlar and Kevlar [19]

Li *et al.* [4] also find the morphology of failure in UHMWPE UD after anti-stabbing testing using Scanning Electron Microscopy (SEM). The main failure is the tensile failure instead of cutting. Hence, the failure is caused by the puncturing tip in the first step. Figure 6 shows the failure morphology. Tam *et al.* [20] state that chain of ultra-high molecular weight polyethylene have a high strength. It is suitable to be a ballistic resistance composite fabricated from a high strength synthetic fiber exhibited a varying degree of resistance to penetration by a high speed impact from projectiles such as bullet, shells, and shrapnel.

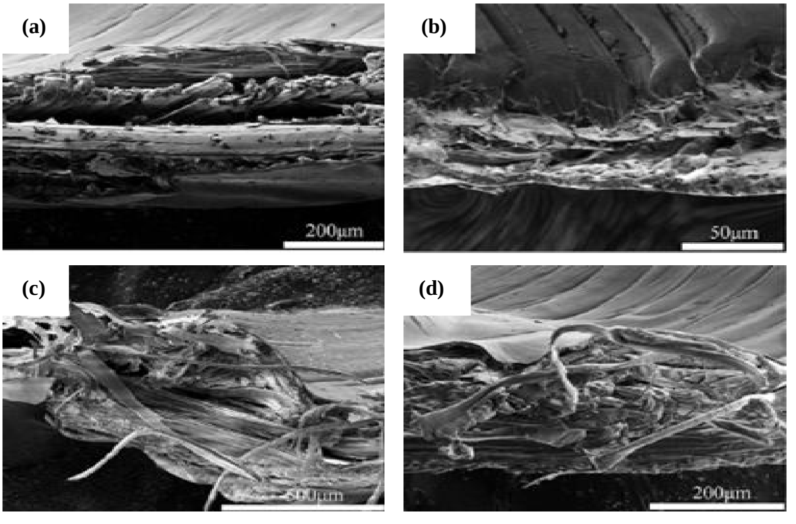


Figure 6: SEM pictures (a) near the tip, (b) in the middle of the stab position, (c) near the blunt sides, (d) near the tip [4]

In a different study, Li *et al.* [11] find that using glass compound fiber and Kevlar compound fiber makes the damage area elongate. This can affect the larger area after dynamic puncture and the fracture fiber becomes higher against the dynamic puncture energy. This statement is verified by the fact that the damage region found is regular and quadrilateral static damage area on the specimen. As highlighted by Raja and Hari [21] the definition of the density is average number of matrix crack in each hybrid layer per unit length in the longitudinal direction. In this experiment, the maximum stress of cracking hybrid sample is 403.42 MPa. The matrix cracks of hybrid specimens are nucleated in the central 45° plies of the angle-ply specimen and the delamination of hybrid specimens are observed to appear from the specimen surface. The damage initiation is delayed by the interleaving in the angle-ply hybrid specimens. Kevlar is more ductile than glass fibers as it creates more damage compared to glass fiber due to more energy required to breakout the Kevlar.

7.0 REVIEW SUMMARY

Based on extant literature, many findings show the flexibility of thermoplastic laminate composite for anti-stab application. Many researches have used various materials on various experiments related to stab resistance, stab properties, stab behavior, stab performance, and puncture behavior. Based on these studies, a lot of information is overlapped or similar. Besides, discussion is generated on how to make composite laminate more flexible and higher in strength. Most importantly, the thickness, the layer, types of materials used for fiber and resin, and the effect on the composite after testing are highlighted.

Furthermore many researchers use Aramid fiber, glass, rubber wood, flexible woven for the reinforcement on their experiments and research. This Aramid fiber is combined with thermoplastic resin to give some flexibility and high in strength. Most common used material for thermoplastic resin is epoxy but other types of materials are also found in thermoplastic such as TPU, PET, PP or UHMWPE. Other than that, the making of the laminate requires two directions; bidirectional or unidirectional. This review shows that the polyethylene (PE), high density polyethylene (HDPE) and low density polyethylene (LDPE) are not used at all in previous studies for anti-stab research.

Moreover, the most suitable method and machine to test the composite laminate on anti-stabbing is Universal Testing Machine (UTM) using NIJ standard 0.115. Many researchers use this machine for the testing of the specimen. Some researchers use static puncture based on ASTM standard. Important parameters for the testing include the height of the impactor used, the types of impactor and the results show the penetration depth between the thickness and the impact on the composite laminate. Some researchers who investigate the structure of the specimen after the testing use Scanning Electron Microscopy. It can show the structure damage on the specimen based on the drop mass and velocity of the impactor.

In short,, a few researchers use a thermoplastic as a matrix materials. Thus, thermoplastic composite laminate has a high potential which include using thermoplastic as a matrices combined with glass and aramid fiber as reinforcement materials. From the combination of materials, the composite laminate can be formed and stab drop tower and quasi static stab testing can be conducted. In addition, flexural testing can be done to investigate the level of the laminate composite which can be bent to prove its flexibility and elasticity. The Figure 7 shows the overview of studies on anti-stab testing.

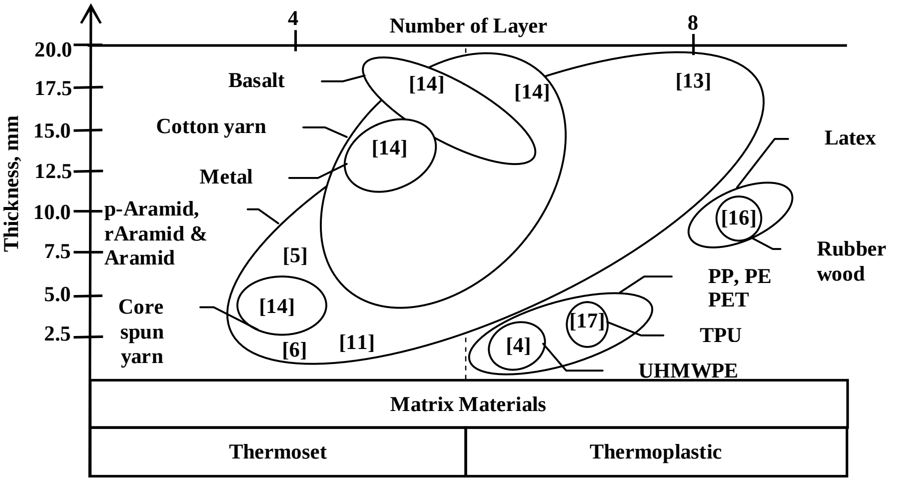


Figure 7: Overview of study on anti-stab

8.0 CONCLUSION

In conclusion, a few important points can be highlighted as follows.

(a) Proper thickness of laminated composite for anti-stab might achieve their highest strength but increasing the thickness will reduce the flexibility performance reduced.

(b) The flexibility of laminated composite can be improved by adding the element of rubber properties in matrix materials beside using the reinforcement materials with good ductility properties. Good candidates to be explored extensively are LDPE and HDPE as matrix materials, whereas the reinforcement materials are Aramid Fiber and glass fiber.

(c) Currently, there is no standard value to account for “flexibility value/index”. Thus this is a good departure point to setup proper and new scientific data base for flexibility in anti-stab research.

(d) The dependency on ballistic materials like Kevlar as anti-stab material can be reduced by integrating other materials to create a so-called hybrid system.

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