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Experimental study on the performance of multi-layered bulletproof vest

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Abstract
A bulletproof vest should have high strength and durability to resist a bullet as vital war equipment. However, the cost of creating good quality bulletproof vest is expensive. Therefore, research about an alternative bulletproof vest with affordable cost and competitive quality is needed. This research aims to review and compare two alternative vest types with one commercial type IV vest. Both alternative vests have similar components, except the second one has an additional Ultra High Molecular Weight Polyethylene (UHMWPE) component. The ballistic test shows that alternative vests are still not enough to resist a 5.56 mm bullet, but it has the potency to handle a 9 mm bullet. Furthermore, the influence of UHMWPE to resist 9 mm bullets is shown in this research.

Keywords:
Alternative vest;
Ballistic;
Bulletproof vest;
Commercial vest;
UHMWPE;

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INTRODUCTION

The armor is designed to minimize injuries due to war. In general, the armor will absorb, reduce, and stop attacks caused by weapons of war. In the current era, the armor is more known as bulletproof vests because the armor generally functions to reduce bullet attacks [1].

Armor can be divided into two categories based on the type: soft and hard armor. Soft armor is categorized as a vest that can absorb bullets up to 500 m/s and has a mass under 4.5 kilograms which are ineffective against the military rifle. Usually, it is composed of multiple layers of fabric. On the other hand, hard armor is a vest that can resist the movement of bullets with a velocity of more than 500 m/s [2]. Other than the two types, based on the USA National Institute of Justice (NIJ), the armor is divided into more specific categories, namely Type IIA, Type II, Type III-A, Type III, and Type IV and special type [3].

Along with the times, the technology applied to bulletproof vests is increasingly sophisticated and can produce lighter and more durable vests. Unfortunately, however, it makes the cost increase significantly. Therefore, alternative bulletproof vest innovation is needed to create affordable vest costs, but it also has competitive performance with the commercial ones.

There are many types of research and review about optimizing bulletproof vests [4, 5, 6]. The researchers are using many types of material such as polyethylene [7, 8], ceramic composite [9, 10, 11, 12, 13], ceramic [14, 15], and Titanium [16, 17, 18, 19]. The previous research shows the potency of some materials used in this research, e.g., polyethylene and titanium, which have good resistance to stopping the bullet. Furthermore, the use of the polymer becomes the fundamental idea of the alternative vests' components. Basically, the method applied in this research is following the ones applied by Adam Kurzawa and NIJ 0101.06 standard approach [12]. However, the experiment is adjusted due to the limited available tools.

This paper tested two samples of alternative vests and compared with commercial vest type IV composed of Kevlar and Manganese Steel. The alternative vest 1 is composed of some titanium plates and some soft PVC layer, and the second one, alternative vest 2, is the optimization form of alternative vest 1, where polyethylene replaces some layers. All vest types were tested using 9 mm and 5.56 mm bullets. Based on the experimental results, it is hoped that the potential of these vests can be explored further.

METHOD

Bulletproof Vest Specimen Information

The three types of tested vests are two alternative vests provided by PT. Cawisadi Indonesian Aksatriya and the commercial one which the Indonesian National Army usually uses. The details of each vest are presented in the following part.

Commercial Vest

The first is a commercial vest. It weighs 2.31 kg and is about 13 mm thick, with a density of 2.7 g/cm^3 that consists of 11 Kevlar layers and one manganese steel plate, as shown in Table1 and Figure 1.

Both of them have different leading roles. The Kevlar fabrics at the front are intended to reduce bullet pressure. The manganese steel plate will absorb the bullet's kinetic energy, and the Kevlar layers at the back have a role in stopping the shattered steel fragments when the spalling phenomenon occurs [20].

Alternative Vest 1

The following description is about the alternative vest 1. This vest has a 1.7 kg weight and is 14 mm thick. The published work has 1.91 g/cm^3 of density consisting of two main components, namely Ti_6Al_4V and Soft PVC with a dibutyl phthalate plasticizer. This soft PVC is a damper absorbing a bullet's impact energy [21]. Further information regarding these vests is listed in Table 2, and the overview of alternative vest 1 is shown in Figure 2.

Alternative Vest 2

The last vest, the alternative vest 2, is the improvement of the alternative vest 1. It has three main components, namely Ti_6Al_4V, Soft PVC, and UHMWPE fabric. It only has 0.8 kg weight and is 8 mm thick with a density of about 1.34 g/cm3. Further information about this vest is shown in Table 3 and Figure 3.

Table 1. Commercial Vest Information

Material	Thickness	Total
Kevlar	0.6 mm	11 layers
Manganese Steel	6.5 mm	1 plate

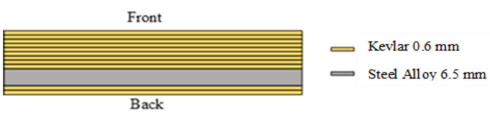

Figure 1. Commercial Vest Overview

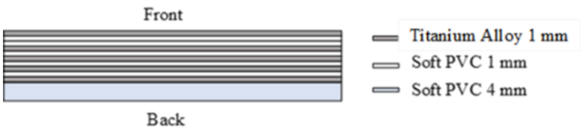

Figure 2. Alternative Vest 1 Overview

Table 2. Alternative Vest 1 Information

Material	Thickness	Total
Ti_6Al_4V	1 mm	5 plates
Soft PVC 1mm	1 mm	5 layers
Soft PVC 4mm	4 mm	1 layer

Table 3. Alternative Vest 2 Information

Material	Thickness	Total
Polyethylene	0.4 mm	5 layers
Ti_6Al_4V	1 mm	2 plates
Soft PVC 1 mm	1 mm	1 layer
Soft PVC 3 mm	4 mm	1 layer

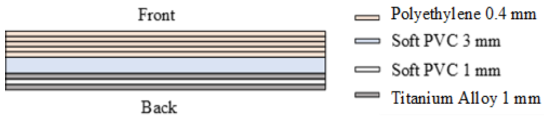

Figure 3. Alternative Vest 2 Overview

It only has 0.8 kg weight and is 8 mm thick with a density of about 1.34 g/cm3. Further information about this vest is shown in Table 3 and Figure 3.

Experiment Setup

A ballistic test is required to review the bulletproof vest's performance. In this evaluation, the vest was fired with 9 mm and 5.56 mm bullets arranged in Figure 4.

This ballistic test was carried out at the Indonesian National Army shooting range, Cijantung, Jakarta Timur. The ballistic test shoot distance followed NIJ 0101.06 standard, as shown in Table 4. The 9 mm bullets were fired with the STI EDGE pistol, whereas 5.56 mm with M16.

In this experiment, only the commercial and alternative vest 1 were tested with both weapons in this evaluation. Likewise, the alternative vest 2 was only tested with 9 mm bullets. The test results will then be compared qualitatively based on the level of damage caused by the bullets on each vest.

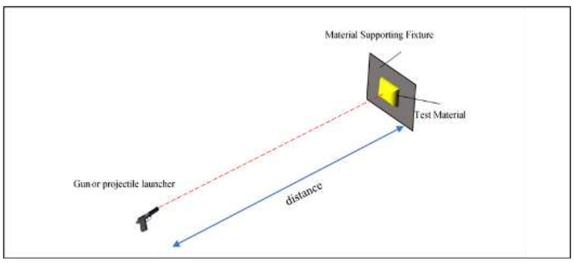

Figure 4. Ballistic Test Setup Overview

Table 4. Weapon Specification

Material	Thickness	Total	Distance
M16	Bullet	MU5-TJ (5.56 mm)	15 m
	Velocity	853.44 m/s	
	Bullet mass	62 grains	
	Rotation	168000 RPM	
STI EDGE	Bullet	MU1-S (9 mm)	5 m
	Velocity	365.76 m/s	
	Bullet mass	124 grains	

RESULTS AND DISCUSSION

Ballistic Test with 5.56 mm Bullet

This section reviews bulletproof vest performance on 5.56 mm. Bullets were fired using an M16 weapon with a range of 15 meters from the target. The results are discussed in more detail in the following explanations.

Commercial Vest

The illustration of the event when the bullet hit the vest can be seen in Figure 5. The figure Illustrates roughly the movement of the bullet during the experiment, showing that the bullet stopped after hitting the steel plate.

The experiment shows that the bullet was crushed after hitting the vest, as shown in Figure 6, which shows that the vest has a high performance in stopping the 5.56 mm bullet. As shown in Figure 7, the Kevlar has successfully penetrated the Kevlar and left a distinct mark about 10 mm in diameter and 1 mm deep on the plate.

The exciting part came from the result which happened to Kevlar, showing that the bullet created consistent hole size (Table 5) on Kevlar. Furthermore, the high velocity of the shot made the Kevlar layer torn neatly, which shows that the effect of Kevlar on the impact caused by the 5.56 mm bullet was insignificant and also indicated that the bullet was crushed after hitting the steel plate, as shown in Figure 8 [22].

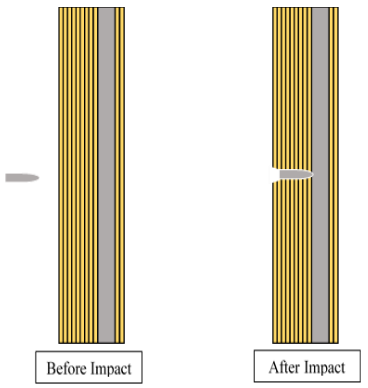

Figure 5. Illustration of Ballistic Test Result with 5.56 mm Bullets on the Commercial Vest.

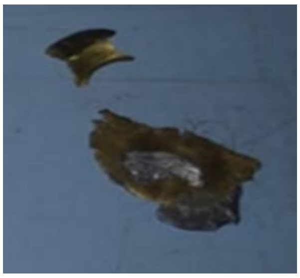

Figure 6. Condition of 5.56 mm Bullet after Impact

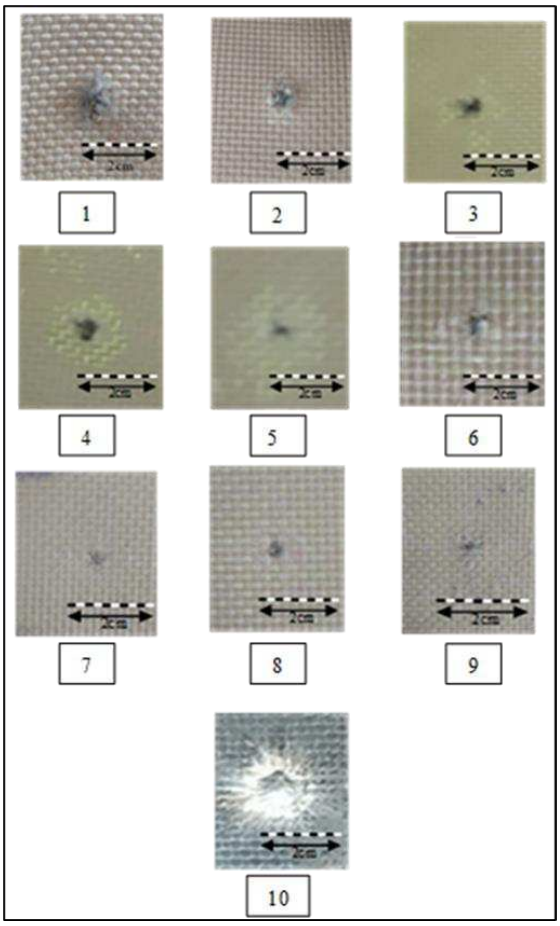

Figure 7. Condition of Commercial Vest after Impacted by 5.56 Bullet (the number shows the sequence of the layer)

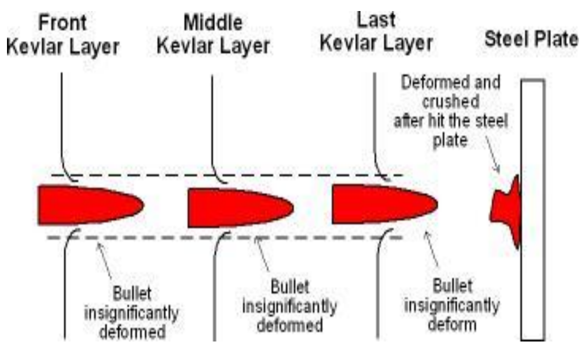

Figure 8. Illustration of 5.56 mm Bullet Deformation

Alternative Vest 1

Next are the ballistic test results with a 5.56 mm bullet against the alternative vest 1. As illustrated in Figure 9, the bullet successfully penetrated the entire vest layers. Furthermore, each vest layer forms a uniform hole size similar to the commercial [22]. The actual results of this trial are presented in Figure 10.

Based on the experimental results, it can be concluded that the alternative vest, which consists of Ti_6Al_4V and Soft PVC coating, has an inferior quality compared to the commercial vest. However, the trial shows that the alternative vest 1 is not applicable for a 5.56 mm bullet caliber.

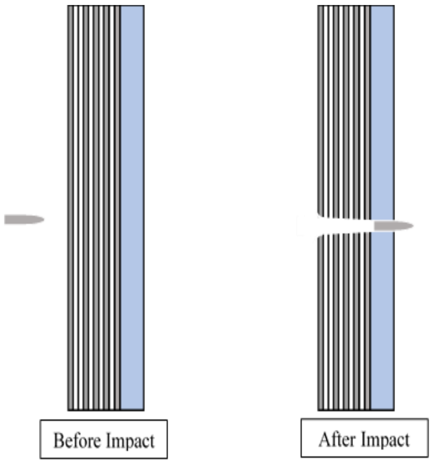

Figure 9. Illustration of Ballistic Test Result with 5.56 mm Bullets on the Alternative Vest 1

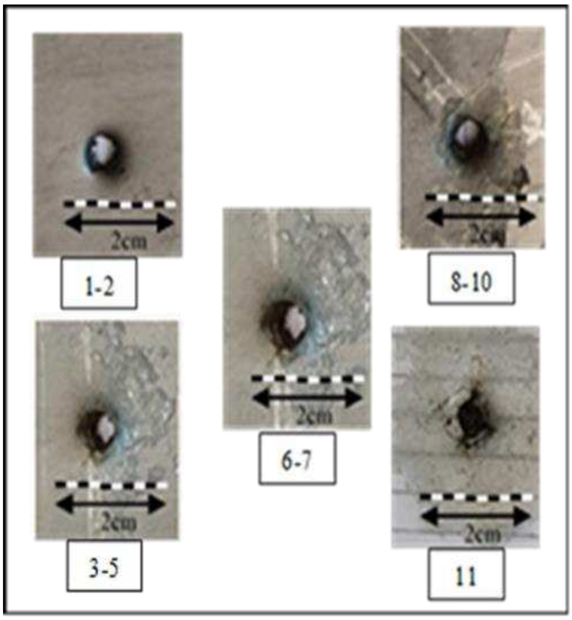

Figure 10. Condition of Alternative Vest 1 after Impacted by 5.56 Bullet (the number shows the sequence of the layer)

Ballistic Test with 9 mm Bullet

Commercial Vest

This section discusses the vest's condition after the impact of a 9 mm bullet fired by the STI EDGE pistol from 5 meters. First, the before and after the ballistic test state is illustrated in Figure 11. Next, the bullet stopped at the manganese steel plate at the exact stop location for a 5.56 mm bullet, and a 9 mm bullet was also destroyed, as shown in Figure 12.

The deformation caused by a 9 mm bullet is presented more clearly in Figure 13. The result shows that only minor marks are left on the tenth layer, namely manganese steel. The minor mark caused by Kevlar has a woven structure that can spread the impact energy, as explained in Zawadzka et al.'s publication [23].

Furthermore, the decrease in bullet velocity is also noticeable from changing the hole size (Table 5) on Kevlar layers. Using a 9 mm bullet, the hole diameter of Kevlar is increasing for each layer, and vice versa with the 5.56 mm bullet. It was shown that Kevlar performs better in stopping a 9 mm bullet than the 5.56 mm ones [24]. It also shows that the 9 mm bullet had been deforming before impacting the steel plate, which is indicated by the increased hole diameter in each layer. The explanation of the event can be understood more clearly in Figure 14.

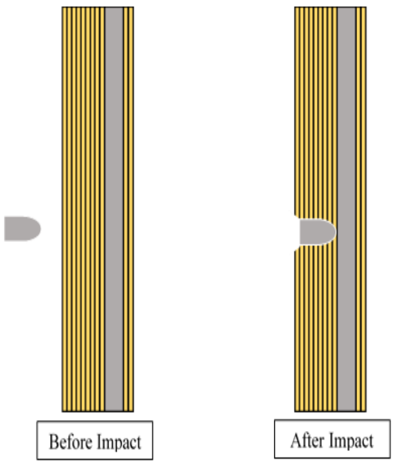

Figure 11. Illustration of Ballistic Test Result with 9 mm Bullets on the Commercial Vest

Figure 12. Condition of 9 mm Bullet after Impact

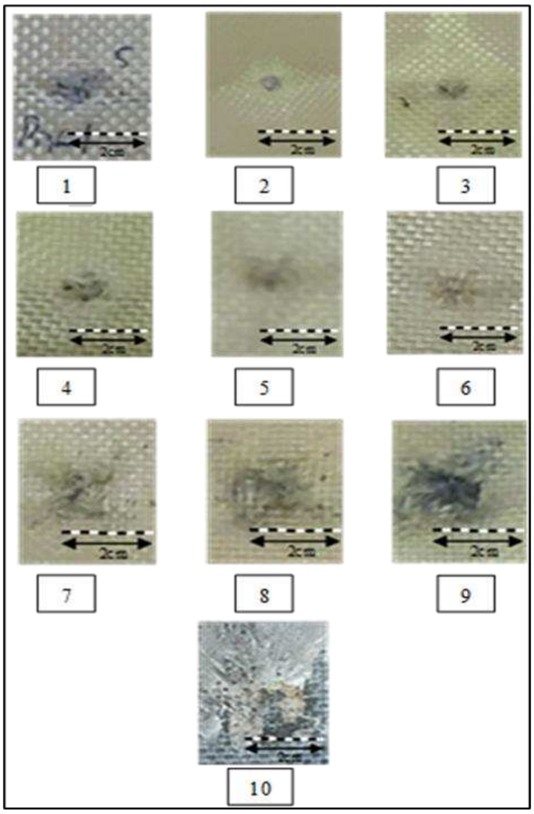

Figure 13. Condition of Commercial Vest after Impacted by 9 mm Bullet (the number shows the sequence of the layers)

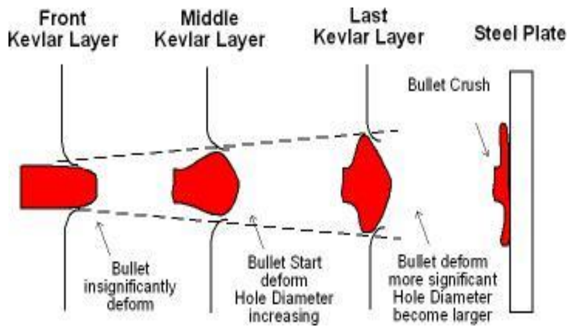

Figure 14. Illustration of 9 mm Bullet Deformation

Alternative Vest 1

The second is Alternative vest 1, in which the experiment overview and result can be seen in Figure 15 and Figure 16. Then, the figure illustrates that the vest stopped the bullet. Finally, the bullet was deformed in the vest, as shown in Figure 17. The trial shows that the vest can stop the bullet until it reaches the fifth layer.

Furthermore, the bullet's impact also left a big dent on the backside of the vest. This result shows that even though the vest can stop the bullet, the user still receives the bullet's impact. However, this vest still has potency as an alternative.

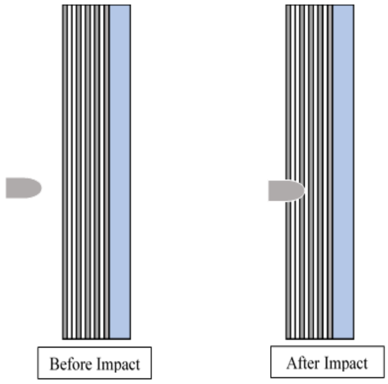

Figure 15. 9 mm Bullet Impacts on Alternative Vest 1

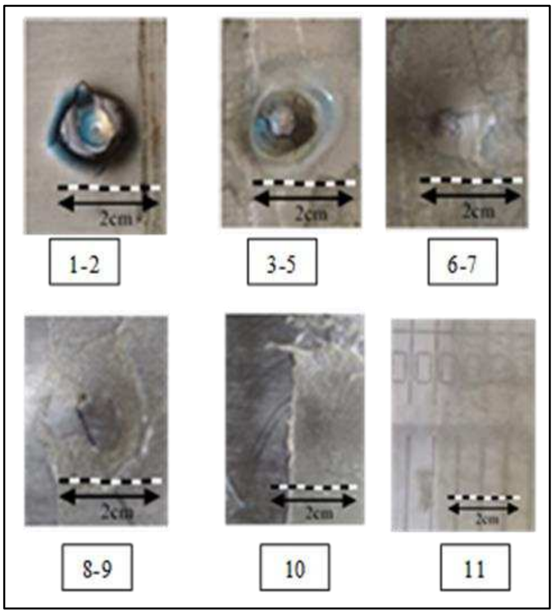

Figure 16. Condition of Alternative Vest 1 after Impacted by 9 mm Bullet (the number shows the sequence of the layers)

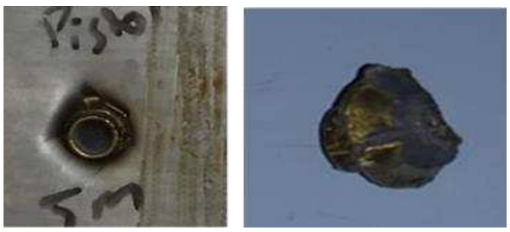

Figure 17. Condition of 9 mm Bullet after Impact

Alternative Vest 2

Last is the alternative vest 2, which the experiment overview can be seen in Figure 18; it is roughly illustrated that the bullet only destroyed the first layer of polyethylene. Furthermore, as shown in Figure 19 and Figure 20, the bullet became flat after hitting the vest, which shows that the vest has a good performance. The result was surprising since the vest is the thinnest among the specimens.

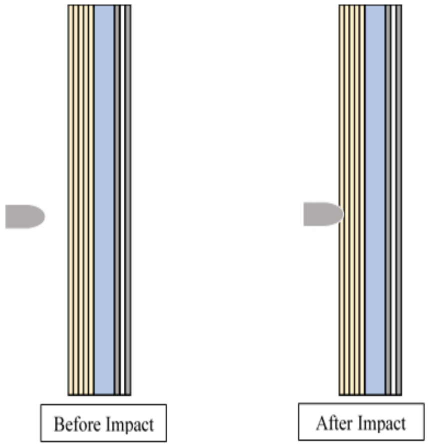

Figure 18. Condition of 9 mm Bullet Impacts on Alternative Vest 2

Figure 19. Condition of 9 mm Bullet after Impact

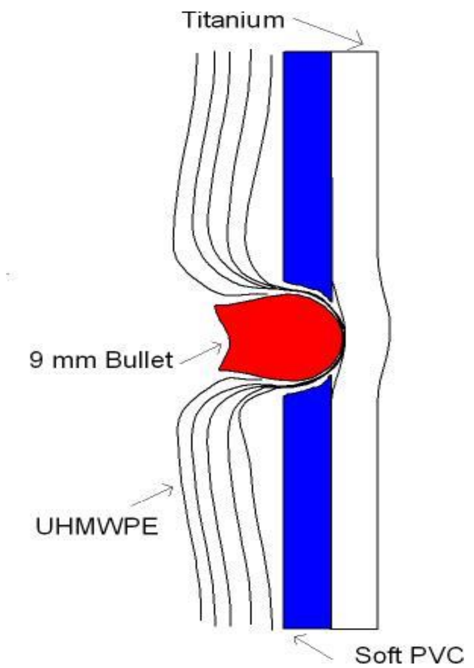

Figure 20. Deformation Illustration of Alternative Vest 2

In Figure 21, the actual result shows that the UHMWPE layer can stop the bullet's movement. Furthermore, the figure shows that only the first layer of UHMWPE was torn (Figure 21, no. 1), and other layers of UHMWPE were unpenetrated [25]. However, similar to the previous alternative vest, the impact left a big dent on the backside of the vest, which can injure the user. Therefore, besides the condition, the alternative vest 2 has high potency to compete with the commercial ones.

Furthermore, from Figure 21, the hole was formed on the sixth layer (soft PVC), even though the previous four layers were safe (Figure 21, no. 6). It was caused by the indirect impact of the 9 mm bullet and UHMWPE fabric structure behavior, as illustrated in Figure 20.

The phenomenon probably was caused by the UHMWPE having higher tensile strength than the soft PVC; as a result, UHMWPE was deforming and hit the soft PVC, and the Titanium layers before the UHMWPE layers entirely failed.

Even though UHMWPE layers were safe, they absorbed the high portion of bullet kinetic energy due to distinct inelastic behavior [1].

Data Summary

To make it easier to identify damage to the vest, Table 5 summarize the ballistic trials discussed earlier. Finally, the summary includes the hole diameter and the condition of each layer.

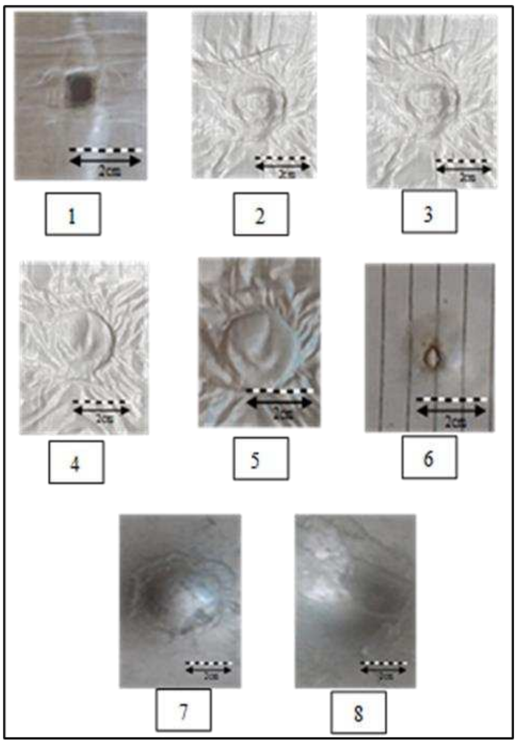

Figure 21. Condition of Alternative Vest 2 after Impacted by 9 mm Bullet (the number shows the sequence of the layer)

Table 5. Research Summary

Vest	Layer	Hole Diameter (mm)		Condition	
		5.56 mm	9 mm	5.56 mm	9 mm
Commercial	1	4	6	Fail	Fail
	2	3	4	Fail	Fail
	3	3	6	Fail	Fail
	4	3	8	Fail	Fail
	5	3	8	Fail	Fail
	6	3	9	Fail	Fail
	7	2	9	Fail	Fail
	8	2	9	Fail	Fail
	9	2	11	Fail	Fail
	10	N/A	N/A	PD	PD
	11	N/A	N/A	ND	ND
	12	N/A	N/A	ND	ND
Alternative 1	1	7	13	Fail	Fail
	2	7	13	Fail	Fail
	3	5	15	Fail	Fail
	4	7	N/A (C)	Fail	Crack
	5	7	N/A (T)	Fail	Fail*
	6	7	N/A (C)	Fail	Crack
	7	7	N/A (T)	Fail	Fail*
	8	8	N/A	Fail	PD
	9	8	N/A	Fail	ED
	10	8	N/A	Fail	PD
	11	N/A	N/A	Fail	ED
Alternative 2	1	--	6	--	Fail
	2	--	N/A	--	PD
	3	--	N/A	--	PD
	4	--	N/A	--	PD
	5	--	N/A	--	PD
	6	--	4	--	Fail*
	7	--	N/A	--	PD
	8	--	N/A	--	ED

N/A : No hole
Fail : Direct penetrated
PD : Plastic deformation
N/A (C) : Crack only
Fail* : Indirect penetrated
ED : Elastic deformation
N/A (T) : Tear only
ND : No Deformation
-- : Not tested

CONCLUSION

Based on the experiment results, it can be concluded that the commercial vest's quality is better than the two alternative vests. The commercial one has high resistance on both type of bullets which is caused by the strength of the steel plate. On the other hand, the other vests are only able to resist 9 mm bullets. Both of the alternative vests have good potency to replace the commercial vest role, especially the alternative vest 2 with a surprising result. The UHMWPE layers are able to improve the vest resistant significantly. However, both of alternative vests still don't have a good level of security, since the vest left a big dent after the impact which caused too much damage for the user.

Some suggestion for further research is needed to improve the performance of the alternative vest. First, there is should be further analysis for the UHMWPE fabric which show good performance. Next, alternative vests components should be modified in order to reduce the dent which can caused significant injury to the user.

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