



Using 3D design technology and a combination of carbon fiber and 16% HGM epoxy resin, female troops are wearing bulletproof vests

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Abstract

Women are becoming more active in the defense industry. Since the morphology of the female body differs from that of the male during military activities, it is required to modify personal protection equipment to accommodate the female body shape. According to a literature review, a survey of a sample of female soldiers from different nations revealed that they felt the impacts of breast soreness when running, as well as a sense of "distorted breasts" and breathing difficulties. The woman's petite frame and the bulky, hefty bulletproof jacket both draw criticism for their respective dimensions. Using 3D design technology, a female mannequin with a 95B breast size was scanned in order to create a bullet-proof vest that is tailored to the contour of a woman's body. Changes in the breast's contour, which affect changes in the surface point parameters, result in adaptive breasts. Utilizing a combination of carbon fiber and 16% HGM epoxy, bullet-proof vests can be modified to provide lightweight dimensions and have the benefit of good ballistic resistance. This results in a material that is 20 mm for thick, 1,348 kg in weight, and capable of absorbing 348.27 Joules of energy from bullets. The results of this research are not optimal, so developments are needed in further research.

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INTRODUCTION

In maintaining national defense, Indonesia also involves female soldiers in order to maintain territorial integrity. The role of female soldiers is certainly no less important than male soldiers, such as helping with logistical support and helping to spy on opponents during war ([Kumar, 2016](#); [Suton, 2023](#)). In addition to weapons that need to be continuously developed, of course, it is necessary to have personal protective equipment ([Boussu & Bruniaux, 2012](#)). One of the pieces of personal protective equipment that is most often used is a bulletproof vest ([White, 2011](#)). Bulletproof vests are widely used by the military personnel to maintain safety and impact reduction from projectile attacks and explosive scattering materials on the front, rear, and sides of the torso ([Eng Yaneva et al., 2007](#)).

Bulletproof vests are worn to stop the body from absorbing energy from projectiles, particularly in the chest, abdomen, and back ([Breeze et al., 2016](#)). Before being transferred to the wearer's body, the kinetic energy of the bullet is first absorbed and distributed by the vest around

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the point of impact. There are two types of bulletproof vests: soft body armour and hard body armour (Tom, 2010). Soft-body armour is a vest made entirely of fabric fibres, with no metal or other rigid components. Hardbody armour, on the other hand, is a vest that is larger, heavier, more intricate, and stiffer than soft body armour (Niculescu et al., 2010). The front, back, and sides of the vest's strong body armour reovered with thick, hard trauma plates. Soft body armor is flexible, light, comfortable and versatile, allowing the wearer to move freely and widely, so it is more recommended for use on small arms ([Pulungan, 2017](#); [Malbon, 2021](#)).

There are many women who are TNI members in Indonesia, and many of them take on combat and non-combat tasks that call for the wearing of body armour. Body armour has the purpose of reducing the risk of ballistics, fragmentation, and piercing ([Mawkhlieng & Majumdar, 2019](#)). Body armour restricts troop mobility and is uncomfortable due to its massive proportions, rough, and stiff construction ([Peoples et al., 2010](#)). To reduce effects on human performance and mobility, armour must fit well and adhere to body shape ([Coltman et al., 2020](#)).

Some researchers have analyzed at how running affects breast pain and how the type, style, and size of bra affect the wearer's perceived comfort ([Coltman, Brisbane, & Steele, 2021](#); [Peoples et al., 2010](#)). Women with larger bust sizes reported having trouble breathing and experiencing a "distorted breast" feeling when wearing a unisex ballistic vest ([Zochowski et al., 2021](#)), according to a survey of female Victorian police officers. Compared to male troops, female soldiers typically have smaller bodies, a significantly distinct body shape, and more developed breast tissue ([Smith & Ting, 2009](#); [Mahbub et al., 2017](#)). Therefore, a military body armour system must be designed and measured to fit the anthropometry of the torso of female soldiers. Large-sized, heavy body armour hurts and irritates the musculoskeletal system in the shoulders, hips, and abdomen ([Coltman et al., 2021](#)).

The typical bulletproof vests used nowadays are composed of Kevlar with a thickness of 1 mm, have up to 32 layers, and weigh up to 10kg, which limits the wearer's movement. Therefore, it is essential to create a lightweight composite material with great bullet resistance. Compared to Kevlar, carbon fiber and HGM have advantages in that they can absorb impact energy and lighten the weight of bulletproof vests ([Pulungan, 2017](#)).

In the shape of a tiny glass ball with a hole filled with an inert gas, Hollow Glass Microspheres (HGM) are a type of reinforcing particle. HGM is a good material to use when creating lightweight composite materials since it has a low density, low thermal conductivity, and good resistance to compression loads. Carbon fiber is one of the composite materials whose properties are influenced by the shape and direction of the constituent fibers ([Toma et al., 2016](#)). Carbon fibre has a high specific modulus and specific strength and a high tensile modulus and strength at high temperatures; at room temperature, carbon fiber is not affected by moisture, solvents, acids, or bases. The research method in this scientific work is a literature study through journals, books and scientific articles regarding women's body armor which is designed to suit the shape of a woman's body ([Chen & Zhou, 2016](#)).

METHOD

Female body armour designed according to the shape of the female body through a 3D scanning process of a 3D female mannequin. The first step is to understand the female morphology on a 3D scan of a female mannequin transferred to a special CAD program ([Mahbub et al., 2014](#)) namely the 3D design concept in Figure 1a. Previously, two different coordinates were placed: one horizontal line drawn in the center of the top of the breast and another vertical line in the middle of the breast, as shown in Figure 1(b). Next, determine the outline of the breast to form a plane. The natural origin of the breast (Figure 1(c)).

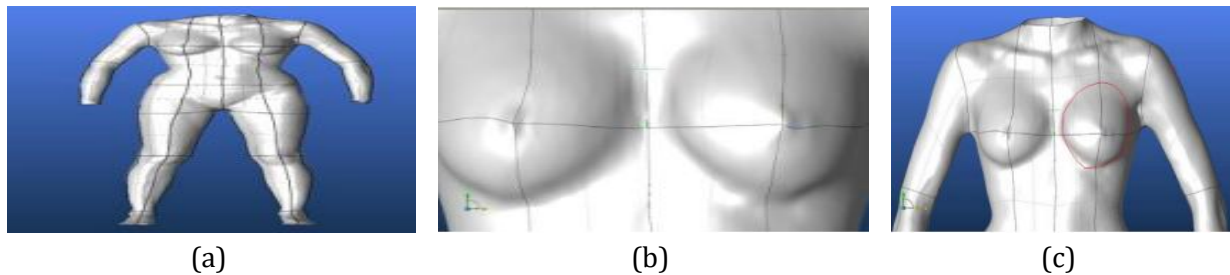


Figure 1. (a) 3D mannequin of a woman, (b) Co-ordinate position, (c) 3D mannequin bust outline
Source: [Abtew et al., 2017](#)

In order to adjust the volume of the breast and obtain an adaptive breast size, different reference points must be set on the surface of the breast. To obtain these coordinates at the origin, the breast has been duplicated on both the X and Y axes by rotating at different angles (25° , 50° , 75° , and 90°), which will give a new different coordinate plane as shown in Figures 2(a) and 2(b).

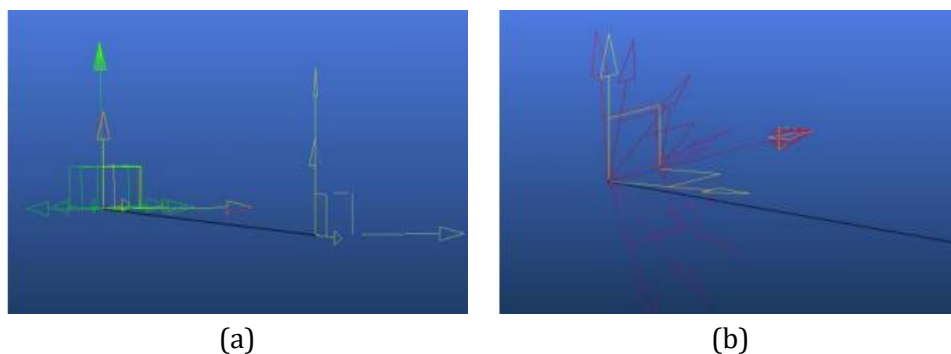


Figure 2. (a) Different planes of coordinates in y-axis, (b) Different planes of coordinates of coordinates in x-axis
Source: [Abtew et al., 2017](#)

The curve of the intersection between the vertical (Figure 3(a)) and horizontal (Figure 3(b)) coordinate planes with the chest surface, obtained by pulling the reference point, forms a mesh on the surface of the breast (Figure 3(c)). Two outline points are obtained, namely, a point on the surface of the chest line to determine the size and a point on the surface of the breast at the intersection of the vertical and horizontal profiles to adjust the volume of the breast ([Ter Haar et al., 2013](#)).

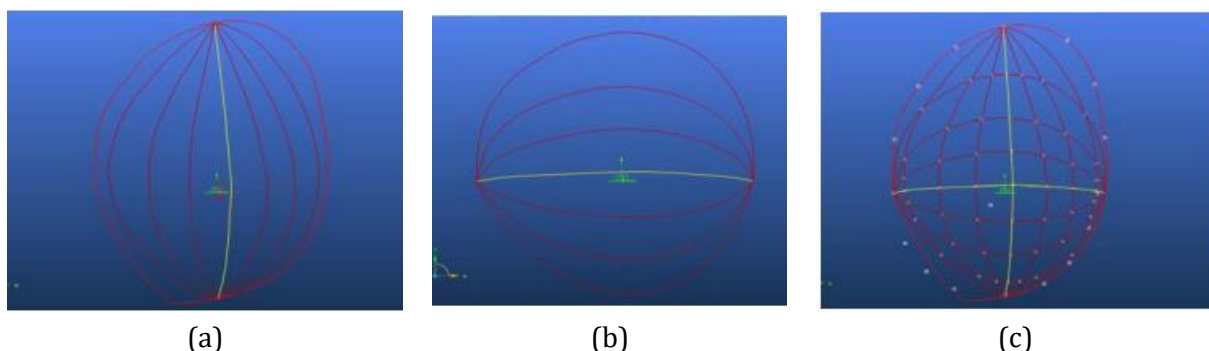


Figure 3. (a) Vertical profile, (b) Horizontal profile, (c) Mesh on the bust surface
Source: [Abtew et al., 2017](#)

Different individual lines are drawn from the center of the breast to the outline and surface reference points to guide the direction of the reference point from the origin of the breast (Figures 4(a) and 4(b)). In addition, curves of various corset sizes were also drawn on the mid-front plane line (Figure 4(c)) and translated to the plane of origin of the breast (Figure 4(d)).

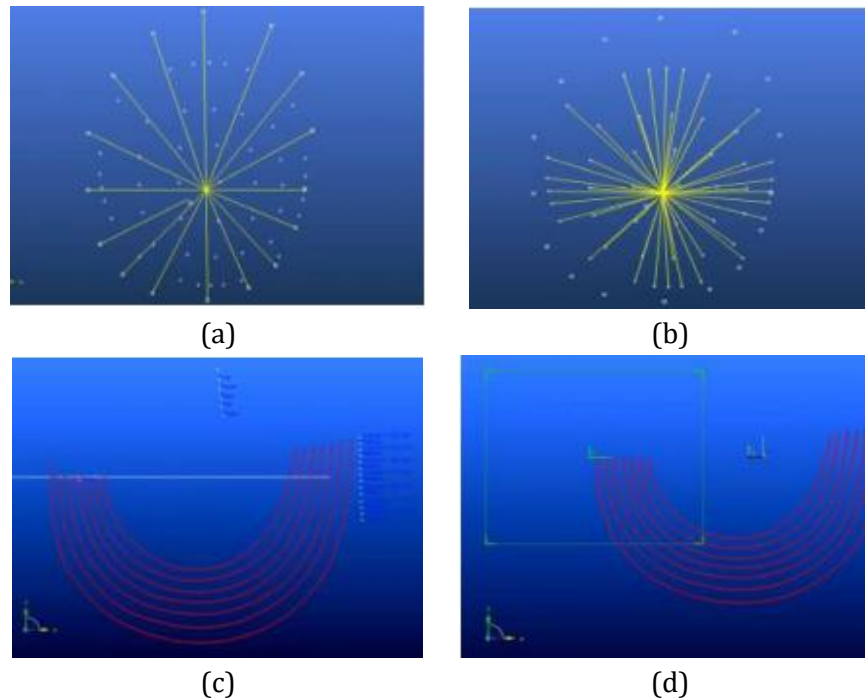


Figure 4. (a) 2D outline points, (b) 3D surface points, (c) Corset sizes curve, (d) Translated corset sizes

Source: [Abteu et al., 2017](#)

Judging from the bullet-proof vest material used in the study, the TC-35 series woven carbon fibre, which has a density of 1451 kg/m³, Young's modulus of 59160 MPa, and a poisson ratio of 0.3, which is combined with IM30K type HGM with a density of 1035.4 kg/m³, Young's modulus of 567.02 MPa, and a poisson ratio of 0.12. Polyvinyl alcohol (PVA) is used as an adhesive and protective colloid in the fibre polymerization emulsion process.

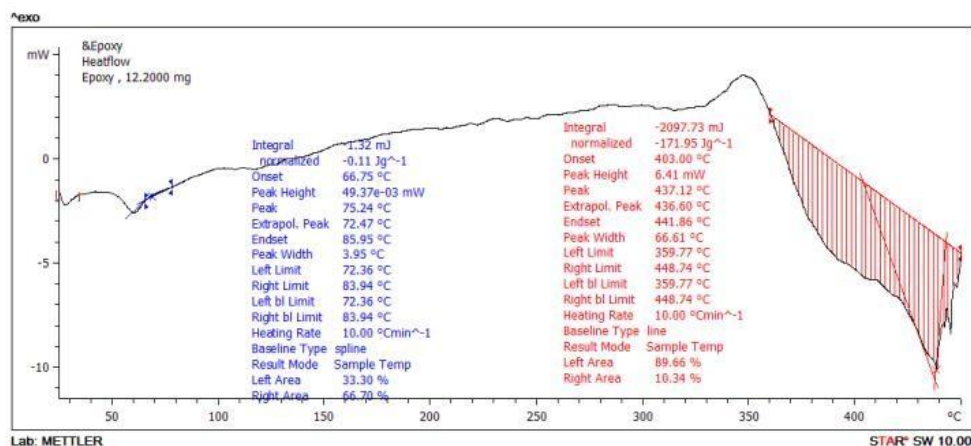


Figure 5. Graphical image of DSC test results on pure epoxy

Source: [Arista, 2013](#)

Several studies have been conducted regarding the impact of impact energy on carbon fibre and HGM-epoxy, which are used as supports and references for this scientific journal. [Arista \(2013\)](#) conducted a study on the effect of adding HGM to the physical properties of composites with an epoxy matrix. Arista conducted a DSC test on pure epoxy and HGM powder at 90 °C for 24 hours. The test results show that the transition temperature (T_g) of pure epoxy resin is 75.24 °C (Figure 5) and the transition temperature (T_g) of HGM powder is 167.92 °C (Figure 6).

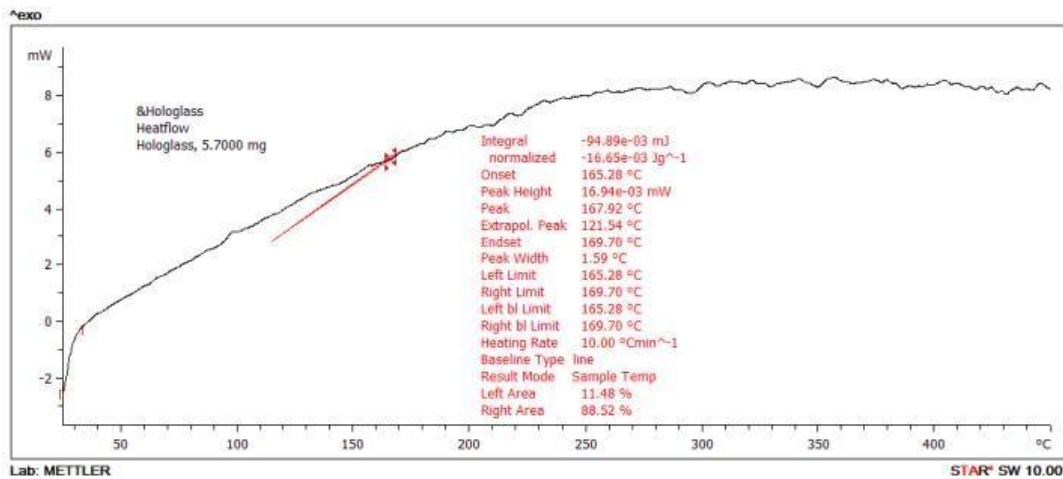


Figure 6. Graphical image of DSC testresults on HSM (powder)

Source: [Arista, 2013](#)

Based on the research of ([Pulungan, 2017](#)) the process of making composites using an epoxy resin matrix with IM30K type HGM reinforcement is:

1. The mould is cleaned and coated with Polyvinyl Alcohol (PVA) evenly. This is so that the composite can be easily removed from the mould when the material is finished.
2. Epoxy resin and hollow glass microspheres were mixed and stirred until evenly distributed with a volume ratio of 84% to 16% for 15 minutes.
3. The mixture is poured and levelled in the mould.
4. The mould is allowed to stand for 24 hours to undergo the curing process at room temperature.
5. Epoxy resin and hollow glass microspheres were mixed and stirred until evenly distributed with a volumeratio of 84% to 16% for 15 minutes.
6. The mixture is poured and levelled in the mould.
7. The mould is allowed to stand for 24 hours to undergo the curing process at room temperature.
8. After the HGM is dry, it is coated with carbon fibre using epoxy resin and hardener in a 3:1 ratio.
9. The results of the HGM and carbon fibre are then vacuumed so that the epoxy and hardener can completely cover the surface of the carbon fibre.
10. The composite is removed from the mould.
11. Composites are observed to avoid defects and then undergo a firing test.

RESULTS AND DISCUSSION

To develop different breast volumes by projecting the breast surface point and the outline point. This results in a suitable new point using the extended function and parameter values to create a corset of varying volumes.

Table 1. Parameter values of the elongation point for adaptive breast size 95B

Description	Curve Name	Point references	1	2	3	4	5	6	7
1 st Horizontal Curve	HC1		10	10	10	10	10	10	10
2 nd Horizontal Curve	HC2		10	10	10	10	10	10	10
3 rd Horizontal Curve	HC3		8	10	10	10	10	15	8
4 th Horizontal Curve	HC4		3.75	6.72	8.30	10.2	12	15	8
5 th Horizontal Curve	HC5		8	10	10	10	10	15	8
6 th Horizontal Curve	HC6		10	10	10	10	10	10	10
7 th Horizontal Curve	HC7		10	10	10	10	10	10	10
Out Line points	LC (aal equal)		5.5	5.5	5.5	5.5	5.5	5.5	5.5

Source: [Pulungan, 2017](#)

From Table 1, size 95B, is 5.5 mm long at all points of the outer breast line and about 10 mm at the breast surface point. Parameter results from table 1 can be seen in Figures 7(a) and 7(b).

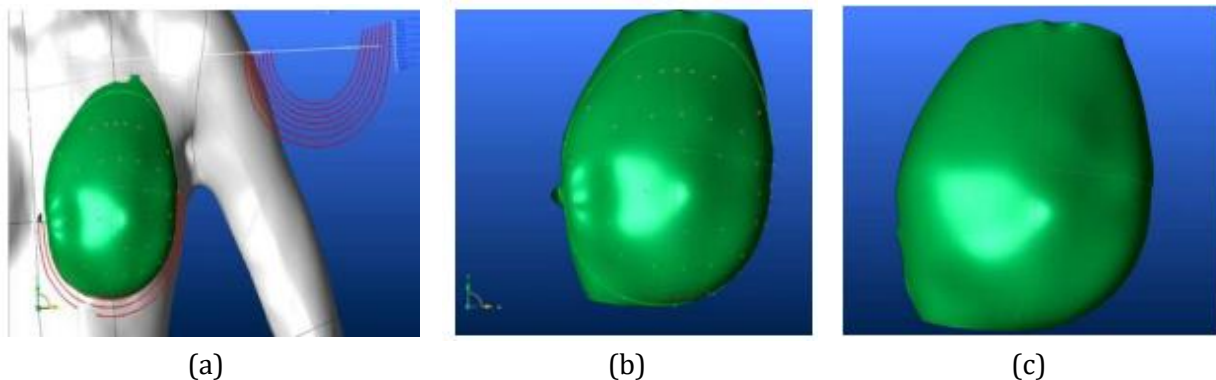


Figure 7. (a) Adaptive bust of size 95B, (b) Conceived 95B size bust front, (c) Adjusted adaptive bust

Source: [Abtew et al., 2017](#)

[Pulungan \(2017\)](#) tested the modeling of bullet-proof vests using composite materials on kinetic energy, internal energy, heat energy, and penetration by varying the thickness of the material between 1 and 20 mm with multiples of 5 mm in each test. The first research was carried out on a 1 mm-thick vest with the addition of carbon fibre in the front, middle, and rear positions of the HGM.

Table 2. Simulation results of 1 mm thick bullet energy absorption

No	Ep (J)	Ek (J)	Eint (J)	E total	Shear Stress (Pa)	Strain (J)	Eq. Stress (Pa)	Energy Absorp. (%)
Front	528.37	328.10	159.16	487.26	857.24×10^6	0.8597	314.03×10^7	02.21 %
Mid.	528.37	296.90	214.39	511.29	359.63×10^6	0.8039	142.82×10^7	06.76 %
Back	528.37	270.99	251.99	522.98	137.97×10^6	0.7651	283.73×10^6	09.62 %

Source: [Pulungan, 2017](#)

From Table 2, it is concluded that a vest with a thickness of 1 mm and carbon fibre behind the HGM is better at absorbing bullet energy, internal energy of 251.99 and kinetic energy of 270.99. This is because the distribution of the effect of the impact force on HM is wider than that of carbon fibre.

Table 3. Simulation results of bulletproof vest specifications

No	Thickness (mm)	Material (mm)	Volume (m^3)	Berat (Kg)
1	1	0.2 mm HGM dan 1 layer serat karbon	0.000074	0.049
2	5	1.8 mm HGM dan 4 layer serat karbon	0.00018	0.472
3	10	5.2 mm HGM dan 6 layer serat karbon	0.00036	0.731
4	15	8.6 mm HGM dan 8 layer serat karbon	0.00051	1.048
5	20	12 mm HGM dan 10 layer serat karbon	0.00098	1.384

Source: [Pulungan, 2017](#)

Table 3 shows the simulation results for the thickness of the vest with variations in the composition of HGM and the number of layers of carbon fibre.

Table 4. Simulation results of the energy distribution of vests and bullets

No	Thickness (mm)	Penetration depth (mm)	Bullet Kinetic Energy (J)	Vest Residual Kinetic Energy (J)	Internal Energy Vest (J)
1	1	44.71	528.37	270.99	251.99
2	5	21.95	528.37	258.10	255.71
3	10	12.39	528.37	228.49	269.63
4	15	9.81	528.37	198.29	291.98
5	20	5.54	528.37	138.77	348.27

Source: [Pulungan, 2017](#)

Table 4 shows that the thicker the bullet-proof vest, the slower the bullet will be due to energy absorption.

The thicker the bullet-proof vest, the smaller the contour of the damage that occurs. This is because the composition of the vest is a combination of carbon fibre and HGM (see Table 5). Carbon fibre has strong mechanical properties, a low coefficient of expansion, a high specific modulus, and a high specific strength ([Chen & Yang, 2010](#)). And HGM has tough properties, good rigidity, and a small density because it has holes that can reduce the strength of the impact so that it can reduce the speed of the bullet.

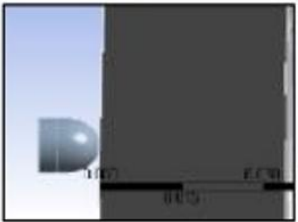
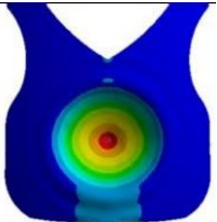
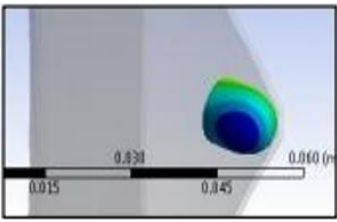
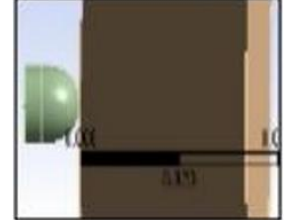
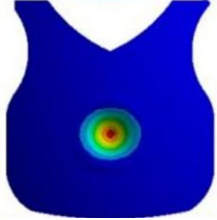
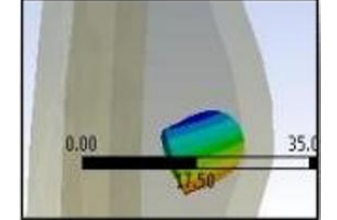
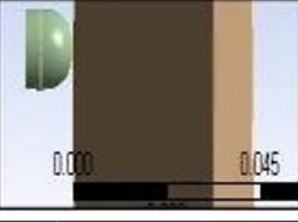

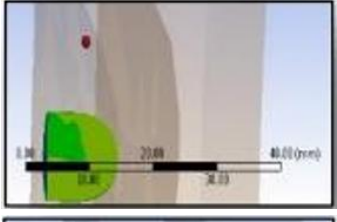

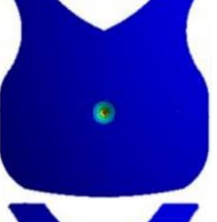
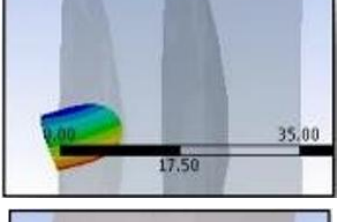


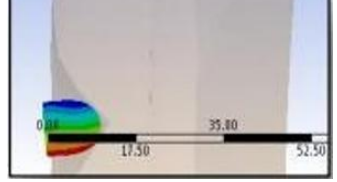
Table 6. Simulation results of the total absorption of the kinetic energy of the bullet by the vest

Thickness (mm)	Internal Energy (Joule)	Kinetic Energy (Joule)	Heat Energy (Joule)	Residual Energy (Joule)
1	251.99	270.99	4.98	0.41
5	255.71	258.10	13.60	0.96
10	269.63	228.49	28.84	1.41
15	291.98	198.29	36.32	1.78
20	348.27	138.77	39.19	2.14

Source: [Pulungan, 2017](#)

Table 6 shows the amount of internal energy, heat energy, and residual kinetic energy that can be absorbed by the vest based on variations in the thickness of the vest. It can be concluded that as the thickness of the vest increases, the internal energy and heat energy increase, but the residual kinetic energy transmitted is smaller.

Table 5. Simulation results of bullet penetration depth in bulletproof vests

Thickness (mm)	Starting position	Deformation	Final Position	Penetration (mm)
1				44.71
5				21.95
10				12.39
15				9.81
20				5.54

CONCLUSION

Different breast volume determinations aid in the development of women's special bulletproof vests by changing certain parameters to produce a smoother surface. Changing these parameters can be used as a foundation to create an adaptive breast volume. The combination of carbon fiber and 16% HGM epoxy on a bullet-proof vest produces a lightweight and strong material because it can reduce the speed of the bullet by transferring the kinetic energy of the bullet to the vest and converting it into internal energy, residual kinetic energy, and heat energy. The bullet-proof vest with a thickness of 20 mm has a weight of 1.384 kg and can absorb bullet energy of 348.27 Joules.

In the future, this research needs to be further developed to obtain optimal results and requires innovative technology in adjusting the body shape of female soldiers.

AUTHOR CONTRIBUTIONS

A.S.L.: Conceptualization, methodology, data curation, formal analysis, & writing – original draft. S.A.: Methodology, validation, & writing – review & editing. R.F.: Formal analysis & resources. V.R.P.: Validation, visualization, & writing – review & editing.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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