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Numerical Simulation of Ballistic Impact Behavior on Soft Body Armor Based Carbon Fiber Reinforced Polymers Composite

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Abstract. Bulletproof vests are made to protect the human body from bullets that cause injuries or other dangerous conditions. Research on composite materials as bulletproof vests continues to develop to get bulletproof vests that are more flexible and lighter. Carbon Fiber Reinforced Polymers (CFRP) composites are widely developed as soft body armor materials because they have high strength, good impact strength and light weight. In this study, an analysis of the soft body armor bullet-proof vest made of carbon fiber reinforced plastic was carried out using the finite element analysis (FEA) method. The simulation was carried out in accordance with the national institute of justice standard 0101.06 U.S department of justice where the initial velocity of the bullet was 373 m/s for the soft body armor type by varying the thickness of the bulletproof vest until the optimal thickness was obtained. The simulation results show that the thicker a dinner vest, the better it will absorb impact energy, this is due to the nature of carbon fiber which is able to distribute stress evenly.

INTRODUCTION

The development of body armor vests has been starting since the invention of firearms. Initially, body armor was made of animal skin, then shields made of wood were made, until armor made of metal was invented. The use of this metal material still has the disadvantage namely it is very stiff and heavy, making it difficult for the user to move even though the level of security is quite high [1]. Based on its safety level, the NIJ standard classifies body armor into two, namely soft body armor and hard body armor. Hard body armor generally uses hard materials such as ceramics and metal, while soft body armor uses fiber as a material for making body armor[2]. The fiber must have low density, high tensile modulus, and low elongation in order to be used in body armor application [3].

Currently, fiber types such as Kevlar, Nomex, Twaron and Dyneema are widely used to improve the ballistic performance of soft body armor [2]. Kevlar, with its promising performance, has been used in ballistic and bullet-proof applications such as helmets, vests, and various other equipment that can provide protection to the user [4]. However, the high price and the difficulty of obtaining it domestically are still a serious problem in the use of the fiber material. With the widespread use of carbon fiber in various fields such as aircraft and automotive due to its strength, high rigidity, light weight, and high penetration resistance makes this fiber easily obtained domestically [5].

Research on the comparison of ballistic impact properties between plastic-reinforced carbon fibers and metal structures shows that plastic-reinforced carbon fibers can withstand higher impacts and absorb energy better than metal structures [5]. Carbon fiber composites and hollow glass microspheres with a thickness of 20mm are eligible to be used as body armor because it can release 138.77 J of energy with a penetration depth of below 44mm [6]. In terms of retarding the rate of bullets, the polymer composite which is added with a layer of carbon fiber can withstand the rate of bullets well, namely 13mm before impact to 5mm after impact [7]. On the other hand, body armor made of a composite material of polyester resin and carbon fiber which has a thickness of 15mm can withstand the bullet rate of the Pindad G2 Elite Pistol with a shooting distance of 15 meters [8].

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In this study, numerical simulations of the ballistic impact behavior of bullet-proof vests made of carbon fiber composites with plastic reinforcement are carried out to determine the optimal thickness that can withstand the rate of bullets with residual kinetic energy values below 170 J.

MATERIALS AND METHODS

Simulation is done by using the finite element method. The modeling consists of two parts, namely the bullet and plate models and then assembled. The bullet is modeled in the form of a rigid body and the plate is modeled in a deformable form. The simulation modeling can be seen in Figure 1. The mechanical properties of composite plates can be seen in table 1 .

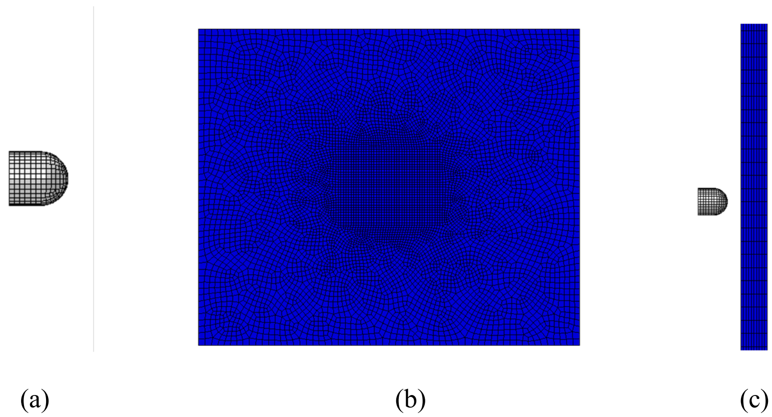

FIGURE 1. Model (a) bullet, (b) composite plate and (c) bullet and composite plate assembly

The thickness of the plastic-reinforced carbon fiber composite is varied from 10 layers to 30 layers in multiples of 5 layers. The speed of the bullet is 373 m/s with a weight of 8.1gr. The value is in accordance with the NIJ standard for level II vests.

TABLE 1. Material properties of user material model used in Abaqus simulations for composite[9]

Notation	Properties	Magnitude
E_{11}	Young's modulus (GPa)	235
E_{22}	Young's modulus (GPa)	17
E_{33}	Young's modulus (GPa)	17
μ_{12}	Poisson's ratio	0.32
μ_{13}	Poisson's ratio	0.32
μ_{23}	Poisson's ratio	0.45
G_{12}	Shear modulus (GPa)	4.5
G_{13}	Shear modulus (GPa)	4.5
G_{23}	Shear modulus (GPa)	2.5
X_{1t}	Tensile failure stress (MPa)	3900
X_{1c}	Compressive failure stress (MPa)	2400
X_{2t}	Tensile failure stress (MPa)	111
X_{2c}	Compressive failure stress (MPa)	290
X_{3t}	Tensile failure stress (MPa)	50
X_{3c}	Compressive failure stress (MPa)	290
S_{12}	Failure shear stress (MPa)	120
S_{13}	Failure shear stress (MPa)	137
S_{23}	Failure shear stress (MPa)	90
ρ	Density (kg/m^3)	2190
β	Damping parameter	10^{-9}

RESULT AND DISCUSSION

When the bullet hits the composite plate, the kinetic energy of the bullet will move to the plate so that the bullet will have a decrease in kinetic energy. The decrease in the kinetic energy of the bullet can be seen in Figure 2.

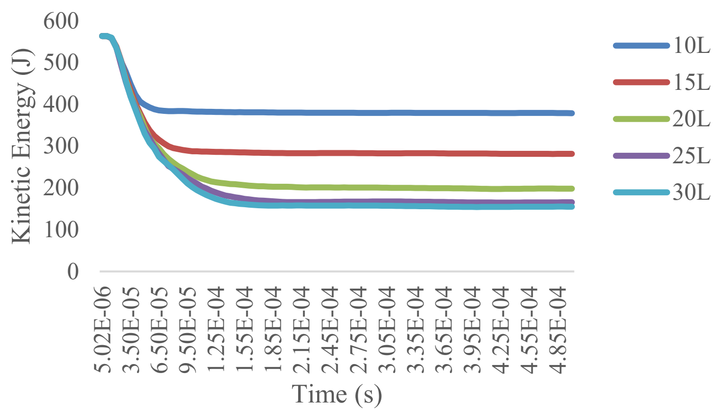

FIGURE 2. Graph of the decrease in the kinetic energy of the bullet

The bullet will experience a sudden decrease in kinetic energy when it collides with the composite plate. On a 10-layer composite plate, a sudden decrease in the kinetic energy of the bullet occurs in the time range between 10 microseconds and 75 microseconds and then continues with a constant decrease in kinetic energy. In the 15-layer composite plate, a sudden decrease in the kinetic energy of the bullet occurs in the time range between 10 microseconds and 100 microseconds and then continues with a constant decrease in kinetic energy. On a 20-layer composite plate, a sudden decrease in the kinetic energy of the bullet occurs in the time range between 10 microseconds and 130 microseconds then continues with a constant decrease in kinetic energy. In a 25-layer composite plate, a sudden decrease in the kinetic energy of the bullet occurs in the time range between 10 microseconds and 165 microseconds and then continues with a constant decrease in kinetic energy. On a 30-layer composite plate, a sudden decrease in the bullet kinetic energy occurs in the time range between 10 microseconds and 180 microseconds and then continues with a constant decrease in kinetic energy. The difference in the time span of decreasing the kinetic energy of the bullet is caused by the difference in the number of layers on each composite plate. The higher the number of layers on the composite plate, the higher the time required for the bullet to penetrate the composite plate. This is due to the increase in the thickness of the composite plate increasing the ballistic resistance [5]. The magnitude of the decrease in the kinetic energy of the bullet when it penetrates the composite plate for 0.5 ms for each number of layers can be seen in Figure 3.

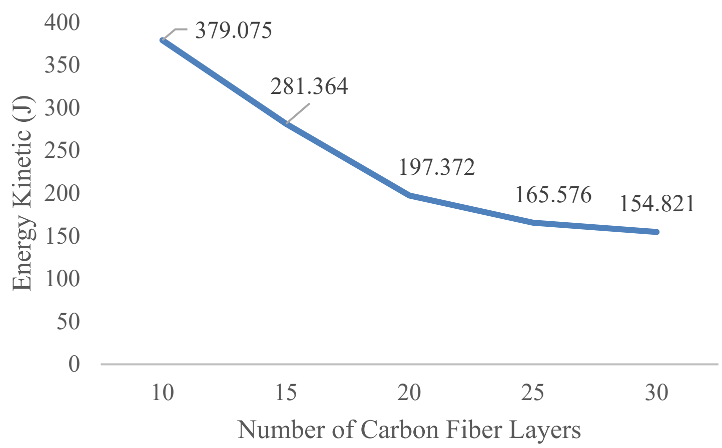

FIGURE 3. Graph of the decrease in the kinetic energy of the bullet

The decrease in the kinetic energy of the bullet when it collides with the composite plate is caused by the absorption of energy by the composite plate. The kinetic energy of the bullet is absorbed by the composite plate in various ways such as fiber failure, delamination, fiber deformation, matrix cracking, and plaque build-up on the fiber [10]. The energy absorbed by the composite plate from the kinetic energy of the bullet will be converted into the internal energy of the vest. The increase in the internal energy of the vest can be seen in figure 4.

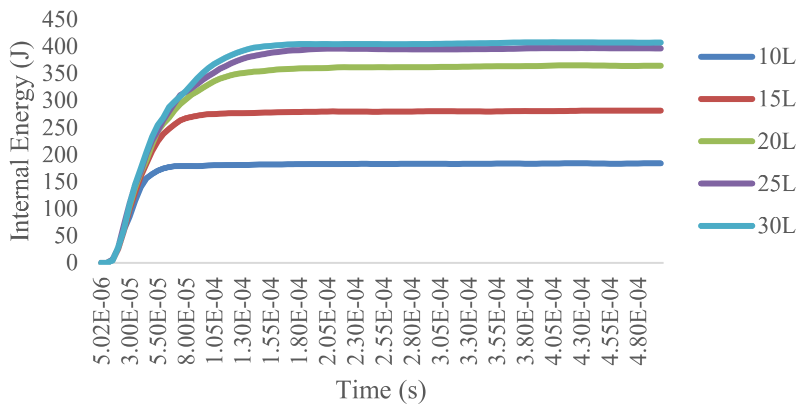

FIGURE 4. Graph of energy increase

Since the internal energy is the energy absorbed by the composite plate when the bullet collides with the composite plate, the increase in the internal energy of the composite plate is directly proportional to the duration of penetration of the bullet into the plate. The longer the duration of penetration of the bullet into the plate, the greater the energy that can be absorbed by the composite plate will be. The amount of energy that can be absorbed by the composite plate at 500 microseconds can be seen in Figure 5.

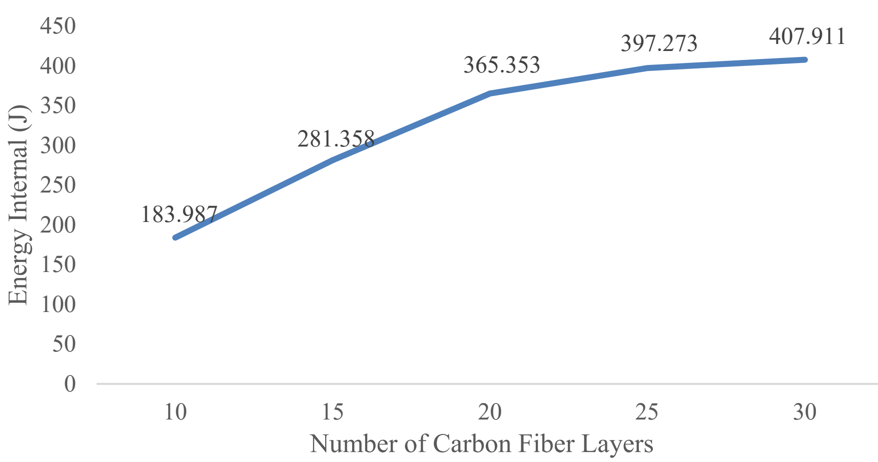

FIGURE 5. Graph of the increase value in internal energy

Besides phenomenon of a decrease in the kinetic energy of the bullet and an increase in the internal energy of the composite plate, a decrease in the velocity of the bullet also occurs when the bullet collides with the composite plate. The decrease in the velocity of the bullet can be seen in Figure 6. The initial velocity of the bullet is 373m/s.

The bullet velocity decreases significantly when the bullet collides with the composite plate. On the 10-layer composite plate, the decrease in bullet velocity occurs in the time range of 15 microseconds to 65 microseconds. then there is a constant decrease in bullet velocity. On the 15-layer composite plate, the decrease in bullet velocity occurs in the time range of 15 microseconds to 100 microseconds, then there is a constant decrease in bullet velocity. On a 20-layer composite plate, a decrease in bullet velocity occurs in the time range of 15 microseconds to 125 microseconds, then there is a constant decrease in bullet velocity. On a 25-layer composite plate, the decrease in bullet velocity occurs in the time range of 15 microseconds to 155 microseconds, then there is a constant decrease in bullet velocity. On a 30-layer composite plate, the decrease in bullet velocity occurs in the time range of 15 microseconds to 165 microseconds, then there is a constant decrease in bullet velocity.

The decrease in bullet velocity is directly proportional to the energy absorption ability of the composite plate; the higher the energy absorption value, the higher the decrease in bullet velocity will be. The value of the final bullet velocity at 500 microseconds can be seen in Figure 7.

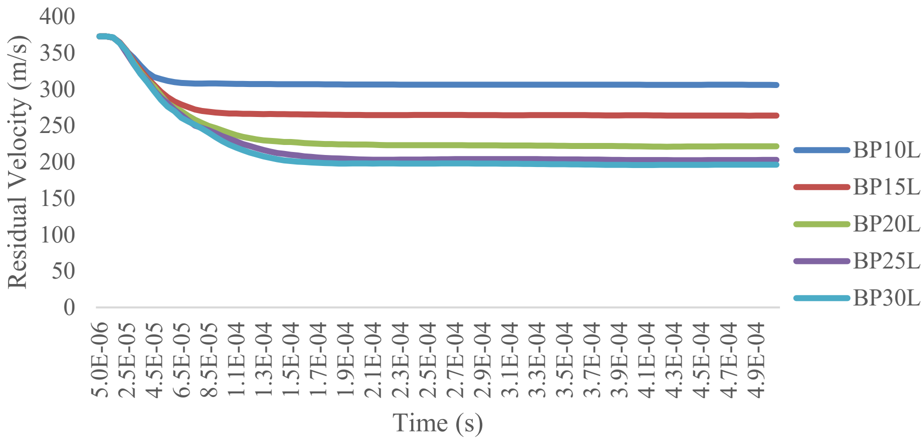

FIGURE 6. Graph of the decrease in bullet velocity

During penetration, the bullet will continue to provide impact energy due to the bullet kinetic until the bullet stops. The number of layers affects the rate of hold of the bullet. The greater the number of layers of composite plates, the greater the resistance to the bullet rate will be.

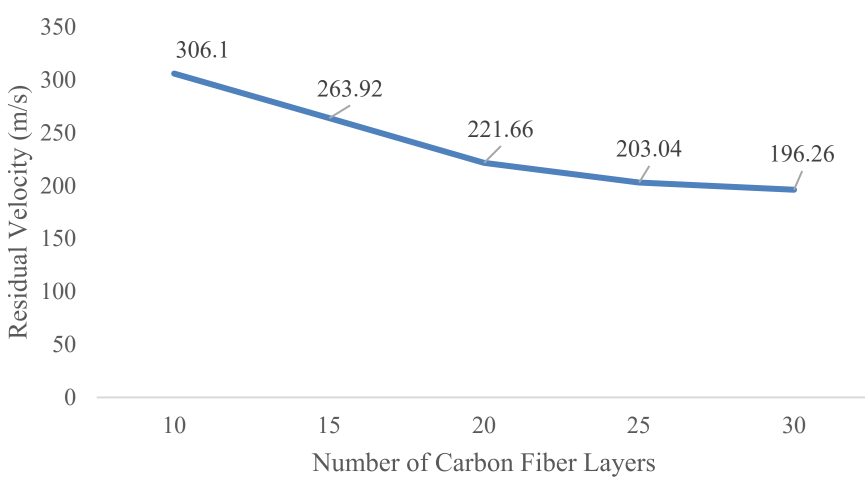

FIGURE 7. Graph of the decrease in bullet velocity

In the figure 9, it can be seen that the composite plate with the number of layers of 10, 15 and 20 is not able to withstand the rate of bullets and fails and almost all failures occur locally. This is caused by the shock wave generated by the impact of the bullet [5]. While the plates with the number of layers of 25 and 30 can withstand the rate of bullets. This is because the kinetic energy of the bullet is mostly absorbed by the composite plate and the remaining energy is unable to penetrate the plate.

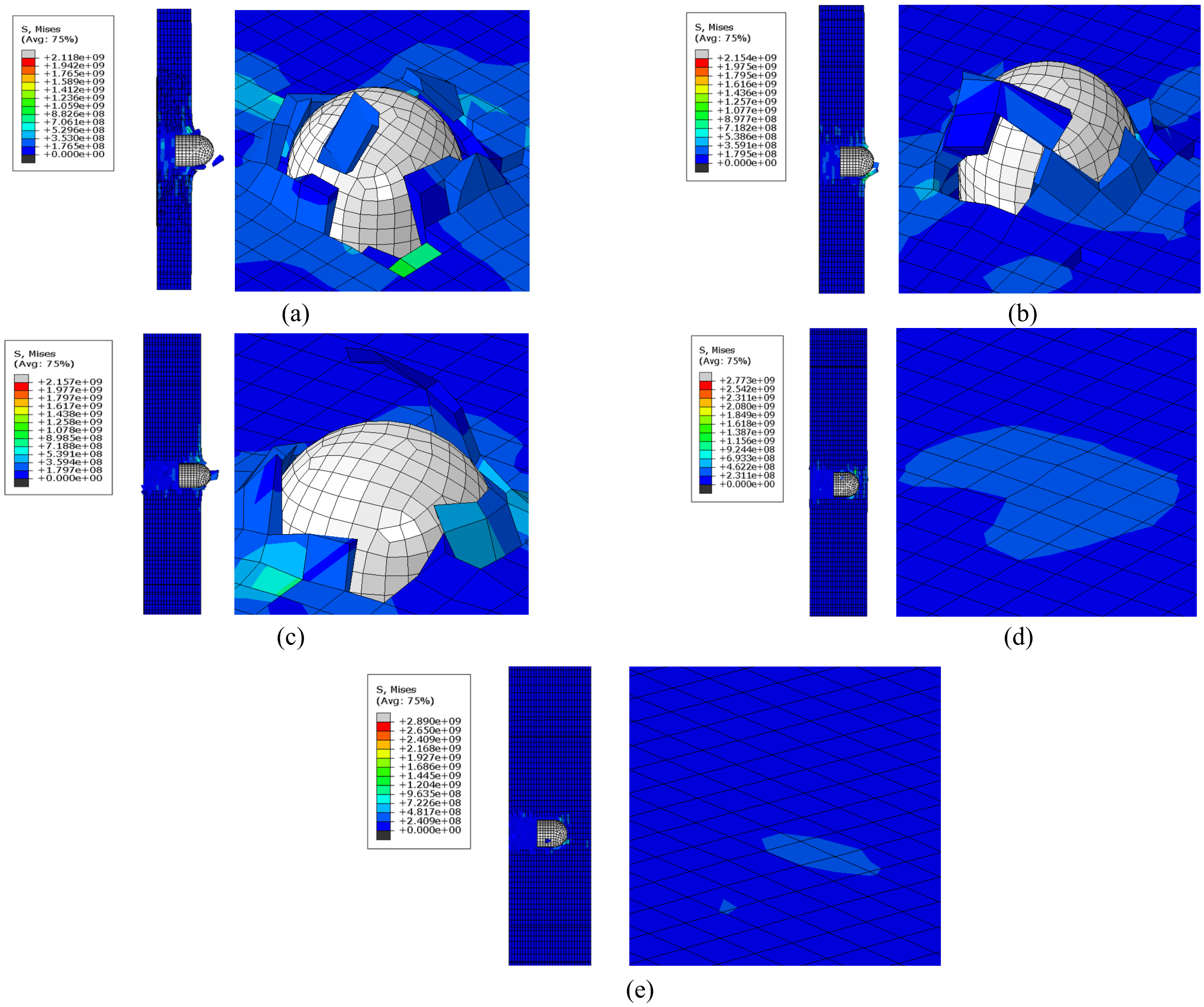

FIGURE 8. CFRP plate with the number of layer (a) 10 layers, (b) 15 layers, (c) 20 layers, (d) 25 layers, (e) 30 layers.

CONCLUSION

In this study, numerical simulations of the ballistic impact behavior of plastic-reinforced carbon fiber vests have been carried out. The number of layers on the composite plate has an effect on decreasing kinetic energy, increasing internal energy, and decreasing bullet velocity. The greater the number of layers of the vest, the greater the value of the decrease in the kinetic energy of the bullet will be. Likewise, the increase in the internal energy of the composite plate increases with the increase in the number of layers of the composite plate. The decrease in bullet velocity is also affected by the number of layers of composite plates. Based on the simulation that has been done, the composite plate with the number of layers of 25 and 30 can withstand the rate of bullets with a residual kinetic energy of 165.5J and 154.8J, respectively. This residual kinetic energy value is still safe for the user's body.

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