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Experimental and numerical simulation study of the performance of the polyphenylene sulfide thermoplastic composite reinforced with carbon fibers under high-velocity impact of projectiles with different geometries

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Abstract
Nowadays, thermoplastic composites have gained significant popularity in various industries due to their high strength-to-weight ratio. The aim of the current research is to investigate the ballistic performance of a four-layer thermoplastic composite under high-velocity impact. This composite utilizes polyphenylene sulfide as the matrix material and carbon fibers as the reinforcing phase. In this study, the composite was fabricated with a symmetric layering configuration [0/90/90/0] using a hot press method, and its mechanical properties were determined through tensile testing. Subsequently, high-velocity impact tests were conducted on sample specimens, and the exit velocities of the projectiles were measured using a high-speed camera. Additionally, numerical simulations of these high-velocity impacts were performed using the finite element software LS-DYNA, and the results were compared and validated against experimental data. In these simulations, three different projectile geometries, namely, flat-nosed, conical, and spherical, were employed. Ultimately, it was determined that the fabricated composite was capable of absorbing a significant amount of energy from the impacting projectiles. The highest energy absorption was observed at an initial velocity of 120 meters per second, corresponding to the flat-nosed projectile with a 65.67% absorption rate, while the lowest was associated with the conical projectile, with a 36.66% absorption rate.

Keywords: Thermoplastic composite; Polyphenylene sulfide; high-velocity impact; LS-DYNA software; Energy absorption; Carbon fibers

1. Introduction

In the pursuit of safeguarding lives and various equipment, polymer-based composite materials have always been a focus of attention for active scientists and researchers in military domains. In recent years, there has been a noticeable increase in the widespread application of these advanced materials in military industries and weaponry. Numerous studies and research efforts have been conducted to date in the field of characterizing and examining the mechanical properties of these widely used materials. Among the polymers used as the matrix material for polymer composites, polyphenylene sulfide is a thermoplastic with highly efficient performance. It possesses various characteristics, including exceptional mechanical strength, excellent heat resistance, dimensional stability, inherent flame resistance, and good electrical insulation properties. These excellent properties make it a suitable alternative to metals and thermosetting polymers for use in automotive components, household appliances, electronic parts, and military and defense equipment [1, 2]. Furthermore, materials based on polyphenylene sulfide, reinforced with carbon fibers, glass fibers, and various nanoparticles, have recently been recognized as high-performance materials. They find application in industries such as automotive and aerospace, serving as electrodes and separators in various other fields [3]. In the past one or two years, there has been significant attention from scientists and researchers towards this highly robust polymer, and various studies have often focused on improving its mechanical properties through combinations with other materials [4-6]. However, as mentioned, the main focus of these studies has been on mechanical properties and the impact of various factors on these properties. There are very limited studies in the field of impact properties and ballistic performance of these structures, which could provide a basis for extensive research on these materials. Based on the review of previous research and studies, it is evident that the investigation of impact properties in polymer composites has mostly focused on thermosetting polymers and less on composites based on thermoplastic polymers.

The current research investigates the performance of a four-layer composite reinforced with carbon fibers and utilizing polyphenylene sulfide as the thermoplastic matrix under high-velocity impact. This is a novel and unexplored area in the field, and it has not been studied before. Additionally, simulation of this test using three different types of projectiles was conducted in the LS-DYNA finite element software, and the results were validated against experimental data. Such high-precision numerical simulation on the mentioned composite using this software has not been performed before, making this research innovative in this regard. The considered projectiles in this study are conical, flat-nose, and cylindrical, shot at the composite target with four different initial velocities of 80, 100, 120, and 140 meters per second to ensure the comprehensiveness and completeness of the study concerning various projectile types and different initial velocities. Finally, new results in the field of mechanical properties, energy absorption, ballistic performance, velocity-time and acceleration-time profiles, etc., are presented, and discussions are made regarding the trends observed in these results.

2. Experimental Procedures

Polyphenylene sulfide, which is a thermoplastic polymer with exceptional strength and a high melting temperature, has been used as the matrix material for the composite in question. Additionally, in this research, unidirectional T300 carbon fibers have been used as the reinforcing material to fabricate composite specimens.

To produce this thermoplastic composite, a four-layer pre-impregnated structure containing polyphenylene sulfide and carbon fibers is subjected to hot pressing. The production method for these pre-impregnated layers involves melting polyphenylene sulfide in a chamber, then immersing pre-opened carbon fiber strands into the molten material. The combination of carbon fibers and polyphenylene sulfide is uniformly blended together between two rollers through pressing to achieve a homogeneous mixture. After cutting the desired dimensions from the pre-impregnated sheet, four layers of these cut sheets, each with a thickness of 0.25 millimeters, are arranged on top of each other with a stacking sequence of [0/90/90/0]. They are then placed inside the hot press and the final specimens will be achieved. The image of the final created specimens, used for high-velocity impact testing and simple tensile testing, can be observed in Figure 1.

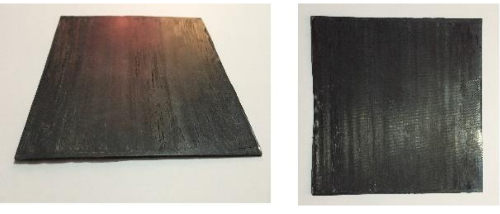

Figure1. The four-layer thermoplastic composite, after hot pressing

To obtain the mechanical properties of the created composite, uniaxial tensile tests were conducted using a universal testing machine based on ASTM D3039 standards on the prepared specimens for this test. Moreover, a gas gun apparatus was used to perform high-velocity impact tests, and its reservoir contains compressed air. For this test, different countries typically use standards that are suitable for their conditions. In this regard, various standards such as MIL-SAMIT, FRA, NIJ, DIN Germany, etc., have been provided. The method of conducting this test with the mentioned apparatus in this research closely follows the FRA standard of the United States, and it adheres to the rules and instructions specified in this standard.

3. Numerical Simulation

In this research, LS-DYNA software has been used for simulating high-velocity impact. To create the target (desired composite) and the projectile in this software, shell (2D) and solid (3D) elements have been used, respectively. Initially, in the software, a composite target sheet with dimensions of 1×120×120 millimeters is modeled using two-dimensional shell elements. The meshing of the target is done uniformly and quadrilaterally, with the ability to apply loads both inside and outside the sheet. Then, using three-dimensional solid elements with eight-node meshing, the desired projectile is modeled. Subsequently, the projectile's tip is positioned 1 millimeter away from the sheet. The image of the projectile and the target is shown in Figure 2.

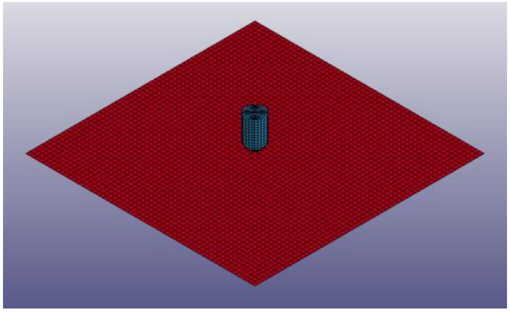

Figure2. composite modeled The image of the . sheet and the projectile along with their meshing

In the simulation conducted in this research, three types of projectiles with different geometries have been modeled, including a spherical-headed projectile, a flat-headed projectile, and a conical-headed projectile. All these models have been designed to precisely match the dimensions and weights used in real-world laboratory conditions.

A total of 57 elements have been considered in the x and y directions for the composite sheet, resulting in a total of 3249 elements for this sheet. To ensure the accuracy of the obtained results using this mesh count, the convergence of the projectile exit velocity in different meshes, as well as the independence of the results from the applied meshing, have been investigated. Table 1 presents the convergence of the exit velocity in different meshes and the independence of the results obtained for an input velocity of 120 meters per second.

Table 1. Investigation of the convergence of the obtained results and their independence from the applied meshing.

Transverse and longitudinal number of elements	Total elements of the sheet	Residual Velocity (m/s)	Nose Shape
50×50	2500	80.33	
55×55	3025	82.87	
56×56	3136	83.73	Hemispherical
57×57	3249	84.05	
58×58	3364	84.05	
50×50	2500	67.56	
55×55	3025	69.03	
56×56	3136	69.92	Flat
57×57	3249	70.28	
58×58	3364	70.28	
50×50	2500	92.39	
55×55	3025	94.15	
56×56	3136	95.09	Conical
57×57	3249	95.47	
58×58	3364	95.47	

4. Results and Discussion

Before presenting the results, the accuracy and credibility of the obtained numerical results from the simulation are examined. For this purpose, the residual velocity obtained from numerical simulation is compared with the results of experimental tests in Table 2, and the level of difference between simulation data and experimental data is determined.

Table 2. Comparison of the results obtained from numerical simulation and high-velocity impact testing for the spherical-headed projectile.

Projectile’s initial velocity (m/s)	Projectile’s residual velocity (m/s)		
	Experimental test	Numerical simulation	Discrepancy (%)
80	32.4	35.79	10.4
100	58.8	61.67	4.8
120	79.6	84.05	5.5
140	98	104.01	6.1

The velocity-time graph for the projectile is plotted for four different input velocities, considering three types of projectiles, in Figure 3. In this figure, at the initial moment when the projectile's velocity begins to stabilize, it indicates that the projectile has completely penetrated the composite sheet and has fully passed through it. This speed, after complete passage through the target, is referred to as the residual velocity. It can be observed from this figure that as the initial velocity of the projectile increases, the residual velocity also increases, leading to a decrease in the time of complete penetration. It is also noticeable that the lowest residual velocity at all input velocities belongs, respectively, to the flat-headed, spherical-headed, and conical-headed projectiles. This lower residual velocity indicates a higher level of energy absorption.

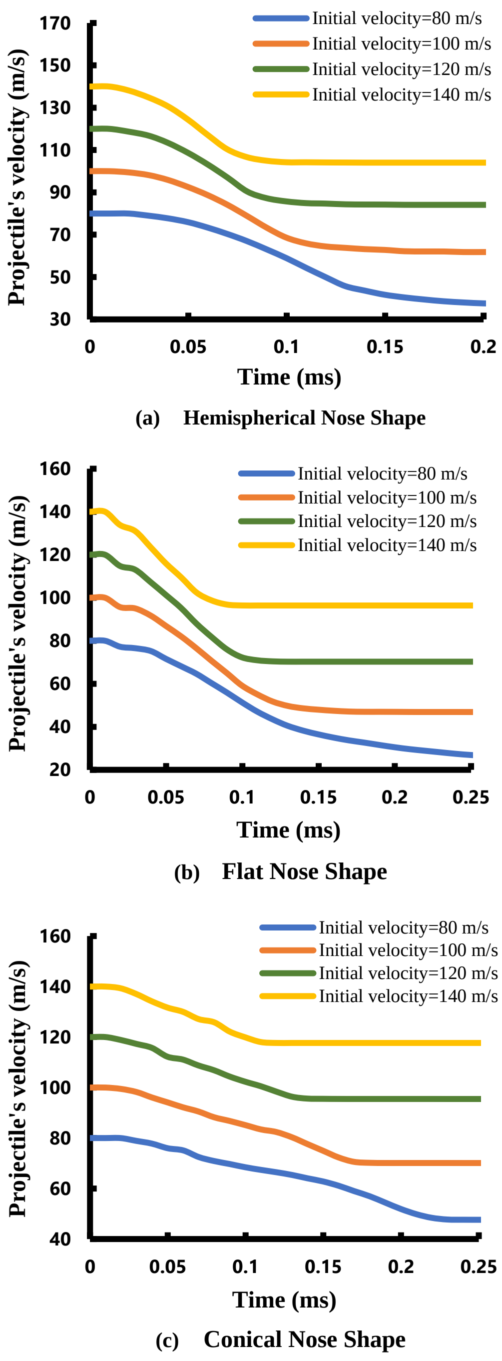

Figure 3. Velocity-time graph for the projectile, considering four different initial velocities for types (a) Hemispherical Nose Shape, (b) Flat Nose Shape, and (c) Conical Nose Shape

In Figures 4 and 5, the stress-strain curves obtained from tensile testing are presented, respectively. Based on these figures, it is evident that the fabricated thermoplastic composite has exhibited a brittle behavior. However, the obtained tensile strength indicates a significantly high stiffness for this composite. This high stiffness allows the composite to resist penetration well when the projectile impacts these specimen pieces, effectively absorbing and dissipating its energy when the fibers and matrix are under tension.

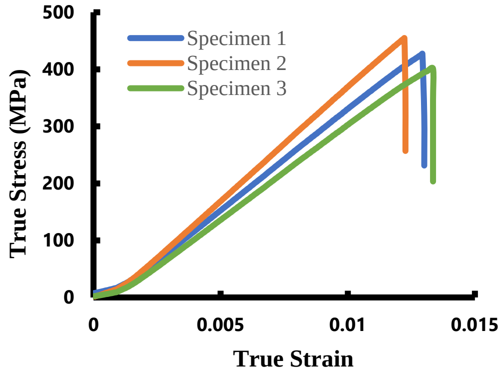

Figure 4. The stress-strain curve obtained from tensile testing at a zero-degree angle.

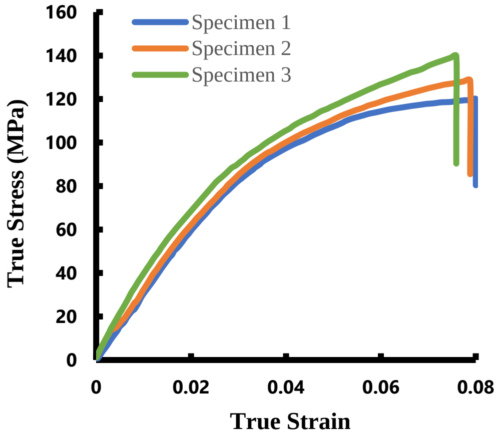

Figure 5. The stress-strain curve obtained from tensile testing at 45-degree angle.

The extracted mechanical properties from these tests and these two graphs are presented in Table 3.

Table 3. The mechanical properties of carbon fiber-reinforced polyphenylene sulfide composite.

Mechanical Properties	Tensile test	
	Zero-degree angle	45-degree angle
Strength (MPa)	400	130
Elastic Modulus (GPa)	31.88	4.4
Poisson's ratio	0.17	0.17
Toughness (MJ/m^3)	2.7	6.8
Strain at break	0.013	0.078
Shear Modulus (GPa)	1.17	1.17

5. Conclusion

In the mechanical properties section obtained from tensile testing, it was demonstrated that the fabricated composite has very high strength and can withstand significant tensile loads compared to its lightweight. Additionally, using the results from high-velocity impact testing and simulation, it was observed that the studied composite performs best when faced with a flat-headed projectile. It managed to absorb the highest amount of energy from this projectile, achieving an energy absorption efficiency of about 90% for an initial velocity of 80 meters per second. After the flat-headed projectile, hemispherical-headed and conical-headed projectiles have respectively expended the most energy to penetrate and pass through this composite. It has also been shown that as the input velocity of the projectile decreases, its exit velocity also decreases, resulting in a higher energy absorption from the projectile. Consequently, the energy absorption efficiency of the studied composite has increased. In general, the highest amount of energy absorption occurred from the flat-headed projectile with an initial velocity of 80 meters per second, while the lowest amount was observed from the conical-headed projectile with a velocity of 140 meters per second. In conclusion, the results of this research demonstrate that the studied thermoplastic composite, with its unique properties including high energy absorption capacity from various projectiles, a high strength-to-stiffness ratio, excellent mechanical properties, and recyclability, can be a highly suitable option for bullet-resistant structures and all applications requiring strong and lightweight structures. It can meet the industrial and military demand for such structures effectively.

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