

Article

An Efficient Analysis Method of Aluminum Alloy Helicopter Fuselage Projectile Damage Based on Projectile Breakdown Theory

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Abstract: The shape and structure of helicopter fuselage are complex, and it is difficult for a finite element method (FEM) to investigate helicopter fuselage projectile damage in a multi-projectile environment. An efficient analysis method for helicopter fuselage projectile damage is then proposed by coupling the projectile breakdown theory, which is derived from the existing empirical formula for penetrating ductile metals, and the model of projectile impact. Then, the characteristics of the helicopter fuselage impact coordinate, residual velocity, and fuselage damage area under a multi-projectile attack are investigated. The results show that the predicted residual velocities agree with the experiments. The maximum errors of the residual velocity and the fuselage damage area are 4.7% and 9.56%, respectively. Compared with the FEM, the computational time of the proposed method is reduced by 92.1%, and its efficiency is obviously improved. As the incidence angle increases, the residual velocity decreases, and the damage area increases. When the incidence angle of the projectile body is large, the projectile body cannot penetrate the surface of the fuselage, resulting in flume skid damage and a large area of damage.



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Keywords: helicopter fuselage; projectile impact; projectile breakdown theory; residual velocity; fuselage damaged area

1. Introduction

Aircraft battle damage assessment assesses the extent of an aircraft battle injury, the time and resources required to repair it, the repair work to be accomplished, and the operational capability after repair. Battle damage assessment is the prerequisite and necessary condition for battle damage repair. In modern local warfare, the helicopter fuselage is vulnerable to damage caused by gunfire during low-altitude operations, and rapid assessment of projectile wounds is a prerequisite for helicopter battle wound repair. Therefore, the analysis efficiency of helicopter fuselage damage directly affects the efficiency of battlefield rapid repair.

Neural network and decision tree regression models were trained by Pushkar through finite element simulations and applied to predict the penetration analysis of projectiles on laminates [1]. Amin used FEM to compute the high-speed impact of the projectile and studied the impact damage effect characteristics of mass, diameter, warhead shape, and properties of ceramic materials [2]. Senthil and Iqbal found that monolithic aluminum targets have higher ballistic performance than double-layered in-contact targets against ogive-nosed projectiles [3]. Wei et al. [4] assessed the effectiveness of monolithic and layered steel targets in single, double, triple, and quadruple-layered configurations against cylindrical blunt-nosed steel projectiles. Mohammad et al. [5] and Gupta et al. [6] investigated the ballistic resistance of monolithic and layered plate targets of aluminum 1100-H12 subjected

to a nosed projectile at oblique incidence angles. This study showed that the ballistic limit of all targets increases with an increase in inclination. Additionally, Mondal et al. [7] and Fars et al. [8] investigated the ballistic behavior of the conventional aluminum alloy. It showed that the failure mode changes from plugging to dicing as the velocity of the projectiles increases. Those FEM-based numerical simulations focused mainly on the residual velocity and damage form of simple flat plate models but not on complex models, such as helicopter fuselages. Thus, it is difficult to efficiently analyze and evaluate the projectile injury of helicopter fuselage with complex structures in multi-projectile environments due to its huge computational time.

Based on the initial velocity of the fragment and residual velocity, Cheng [9] established regression equations to obtain the ballistic limiting velocity of the fragment. The effect of dimensionless projectile length and dimensionless target thickness on the ballistic limiting velocity was also investigated. Liu [10] applied the trust domain method to obtain the model coefficients and establish the ballistic terminal velocity calculation model. Gao [11] developed a theoretical model for the penetration resistance surface of tungsten spheres, pillars, and blocks on armor steel plates. This model was based on both theoretical and experimental studies on the penetration performance of combat prefabricated breakers. The equation for the limiting penetration velocity and the limiting penetration velocity of three typical prefabricated breakers were also developed. The study considered the effect of target attitude on the limiting penetration velocity to provide a comprehensive analysis. Zhao [12] analyzed the force characteristics of prefabricated fragments intruding through homogeneous armor steel, derived the equation for the limiting penetration velocity of prefabricated pieces, and obtained the correction coefficients for the limiting penetration velocity calculation equation by combining the live-fire drive test and the ballistic gun simulation review test. The ballistic limiting velocity of projectiles penetrating materials was derived from test data, while residual velocity and damage characteristics were still missing. Furthermore, tests were limited to structural parts, and the material and structural properties were significantly different from those of helicopter fuselages. In actual war, ground artillery quickly fires multiple projectiles, which will form a multi-shell encircle around the helicopter space. The encircling circle is normally distributed in 3D space. Therefore, it is difficult to analyze and evaluate the projectile injury of helicopter fuselage structures in complex multi-projectile environments.

Given the importance of the problem at hand, an efficient analysis method for helicopter fuselage projectile injury is proposed by coupling a projectile penetration theory with a projectile collision calculation model, which is then compared with experiments to validate its accuracy. Projectile impact coordinates, residual velocity, and fuselage damage area under multiple projectile strikes are then investigated.

The efficient method can describe the situation of a helicopter being hit by multiple projectiles in actual war. When the helicopter is fighting at a low altitude, the ground artillery fires multiple projectiles, and the engineer can generate the distribution of multiple projectiles around the helicopter according to the relative position of the gun and the helicopter by this method. Then, the possible strike point position and projectile incident situation of the helicopter in the multi-projectile encircle are obtained by rapid simulation calculation. Finally, the damaged area of the striking point is quickly analyzed according to the empirical formula. It allows engineers to quickly determine the damage to the helicopter.

2. Computational Methods

An efficient analysis method, including projectile penetration theory and the projectile collision model, is first established to quickly compute the residual velocity of the projectile body and the damaged area of the fuselage under multi-projectile environments, and FEM is then used to analyze the process of helicopter projectile injury and damage in detail.

2.1. Projectile Breakdown Theory

The current quantitative calculation of projectile injury vulnerability mainly focuses on the damage caused by conventional weapon threat end products, such as projectiles and fragments. The projectile penetration theory studies the actual ballistic and movement state changes after the projectile strikes the target plate of various materials. It involves the calculation of ballistic limits, projectile residual velocity, and damage area.

2.1.1. Ballistic Limits

The ballistic limit V_{50} refers to the minimum velocity required for the projectile to pass through the target plate, and the calculation of the ballistic limit is used to pre-determine whether the projectile penetrates the struck structure. V is defined as the projectile incidence velocity. If $V > V_{50}$, the projectile will penetrate the structure and cause perforation. If $V < V_{50}$, the projectile will bounce off and cause scratches on the structure. For this purpose, the JTCG/ME [13] equation is used to represent the ballistic limit as:

$$V_{50} = C_{bf} \left(\frac{\rho_f T A_{pf}}{W} \right)^{b_f} \sec \theta^h \left(\frac{\rho_f T A_{pf}}{W_0} \right)^f \quad (1)$$

where ρ_f is the projectile density, T is the normal phase thickness of the struck structure surface, A_{pf} is the average exposed area of the projectile, $A_{pf} = C_f w d$, C_f is the projectile shape factor, w is the projectile width, and d is the projectile length. W is the initial mass of the projectile, θ is the angle between the direction of attack and the normal direction of contact surface, W_0 is the reference mass. C_{bf} , b_f , h and f are the ballistic limit constants.

2.1.2. Residual Velocity

Assuming that the perforation occurs as a blunt projectile strike [14], when $V > V_{50}$, the residual velocity of the projectile after penetrating the structure, V_r , is written as:

$$V_r = \sqrt{V^2 - \frac{V_{50}^2}{\left(1 + \frac{\rho_f T A_{pf}}{W \cos \theta}\right)}} \quad (2)$$

If the projectile ricochets, the remaining velocity, V_{rr} , is written as:

$$V_{rr} = V \sin \theta \sin^2 \theta_{rr} \quad (3)$$

where θ_{rr} is the exit angle of the projectile after striking the ricochet. J , m , b , and K_2 are dimensionless parameters.

2.1.3. Damage Area

The damaged area is dependent on the exposed area of the structure [15], and the expression for the exposed area of the struck structure is written as:

$$A_{p_i}(A_p) = \sum_{j=1}^W w \times h \quad (4)$$

where w is the number of structural surface hits.

The expression for the vulnerable area of the structure at this point is written as:

$$A_{v_i} = \sum_{j=1}^W P_{k/h_{ij}} \times w \times h \quad (5)$$

where $P_{k/h_{ij}}$ represents the kill probability of structure number i in hitting track number j strike, which is determined by the form of the strike and the characteristics of the struck position. For penetration damage, the kill probability expression is written as:

$$P_{k/h_{ij}} = \begin{cases} 0 & E_b \leq 4.5 \\ 1 + 2.65e^{-0.34E_b} - 2.96e^{-0.14E_b} & E_b > 4.5 \end{cases} \quad (6)$$

where E_b is struck by the structure per unit area of normal thickness to withstand the specific kinetic energy ($\text{kg} \cdot \text{m}/(\text{cm}^2 \cdot \text{mm})$).

$$E_b = \frac{m_f v_f^2}{2Sh} = \frac{m_f^{1/3} v_f^2}{2C_f h} = \frac{m_f^{1/3} v_f^2}{2C_f \delta} \cos \theta \quad (7)$$

where m_f is the projectile mass, v_f is the projectile strike velocity, S is the expected value of the contact area between the projectile and the struck structure, and $S = C_f m_f^{2/3}$. δ is the structure thickness, and θ is the angle between the projectile firing line and the normal to the struck structure surface.

2.2. Ballistic Collision Model

2.2.1. Collision Point

The projectile collision involves a 3D helicopter model in STL format, which is made up of numerous triangular facets. The collision between the projectile and the helicopter fuselage is then determined by analyzing the intersection of points and the triangular face pieces in the 3D model.

There is a triangle composed of three points, $P_1(x_1, y_1, z_1)$, $P_2(x_2, y_2, z_2)$, and $P_3(x_3, y_3, z_3)$, in 3D space. A spatial line segment is composed of two other points, $Q(x_q, y_q, z_q)$ and $R(x_r, y_r, z_r)$. The parametric equation represents the line coordinates:

$$\begin{cases} x = x_q + (x_r - x_q)t \\ y = y_q + (y_r - y_q)t, 0 \leq t \leq 1 \\ z = z_q + (z_r - z_q)t \end{cases} \quad (8)$$

Then, the plane where the triangle is located is written as:

$$\begin{vmatrix} x - x_1 & y - y_1 & z - z_1 \\ x_2 - x_1 & y_2 - y_1 & z_2 - z_1 \\ x_3 - x_1 & y_3 - y_1 & z_3 - z_1 \end{vmatrix} = 0 \quad (9)$$

Equations (8) and (9) can be solved for the value of t in the parametric equation of the line segment to determine whether it falls in the interval $[0, 1]$. If it falls in it, there must be an intersection point, and the intersection point can be obtained from Equation (11) to obtain the coordinates of the intersection point between the spatial line segment and the triangle plane.

2.2.2. Judgment of Collision Point and Fuselage Overlap

If the intersection point is within the triangle face piece, it divides the triangle face piece into three sub-triangles. The sum of the areas of these sub-triangles is equal to the area of the triangle face piece. If the intersection point is outside the triangle face piece, the sum of the sub-triangle areas is larger or smaller than the area of the triangle face piece. These calculations provide the coordinate points where the projectile struck.

3. Results and Discussion

3.1. Verification of the Method

Verification with Experiment

The experimental data in the references [16] are selected to verify the accuracy of the proposed method. The experiment used a two-stage air gun system to launch projectiles. The projectile diameter is 12.7 mm, the length of the cylindrical section of the projectile is 75 mm, the front end is a hemispherical head, the mass is 78 g, and the material is steel. Figure 1 shows the shape of the projectile. The test target plate is 800 mm in length, 440 mm wide, 5 mm thick, and made of 2024 aluminum alloy. Figure 2 shows the experiment device. The ejection direction remains normal to the target plate, and the initial velocity is 905.7 m/s, 781.6 m/s, and 451.6 m/s, respectively. The material parameters of the projectile and target plate are shown in Tables 1 and 2, respectively.

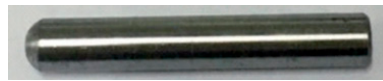


Figure 1. Projectile model.

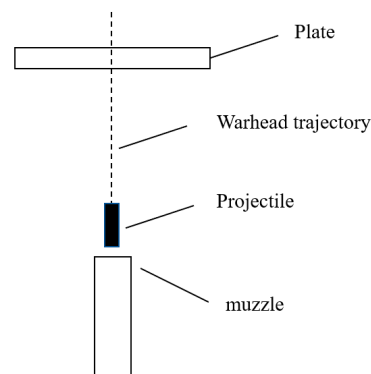


Figure 2. Experiment model.

Table 1. Projectile material parameter.

Material	Density $\rho/(\text{kg}\cdot\text{m}^{-3})$	Elasticity Modulus E/MPa	Poisson Ratio μ
Steel	7800	210,000	0.3

Table 2. Aluminum alloy 2024 material parameters.

Parameter Name	Value
Density $/(\text{kg}\cdot\text{m}^{-3})$	2700
Elasticity modulus E/MPa	71,100
Poisson ratio μ	0.3
A	293
B	737
n	0.58
m	1
C	0.004
D_1	0.25
T_m	775

Note: Strain rate hardening coefficient: C; temperature softening coefficient: m .

Table 3 and Figure 3 show the projectile residual velocity after the high-speed impact. Under the same incidence angle and thickness, the residual velocities of the projectiles

with different initial velocities predicted by the proposed method are in good agreement with the experimental measurements, and the maximum error is 2.3%. It shows that the proposed method for helicopter fuselage projectile wounds can accurately predict the residual velocity of the projectile at different initial velocities.

Table 3. Comparison of residual velocity between experiment and proposed method.

Metal Plate	Initial Velocity/(m·s ^{−1})	Thickness/mm	Injection Angle/(°)	Residual Velocity/(m·s ^{−1})		Error/%
				Experiment	Proposed Method	
Al alloy	905.7	5	0	872.9	865.6	0.8
	781.6	5	0	753.9	744.2	1.2
	451.6	5	0	427.7	417.5	2.3

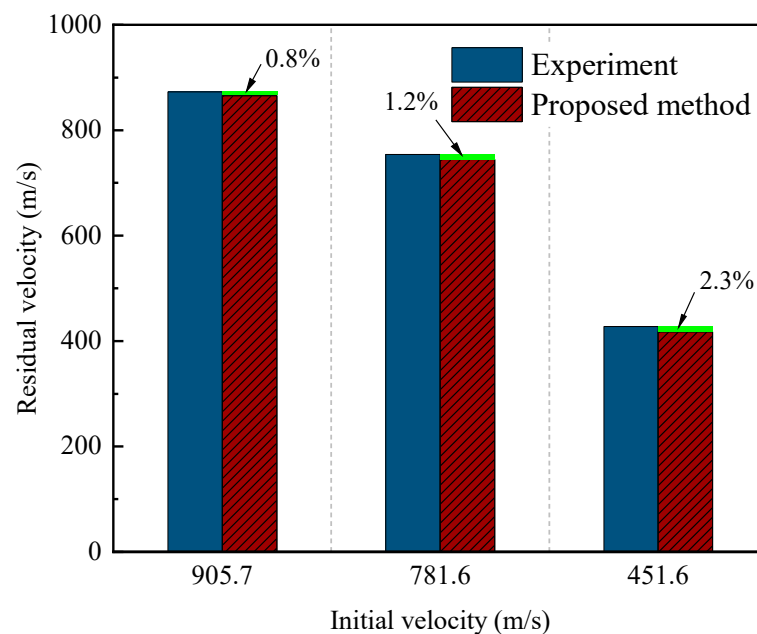


Figure 3. Comparison of predicted residual velocity with experiment.

3.2. Strike Point and Damage Area Characteristics of Helicopter Fuselage

The proposed method for helicopter fuselage bullet damage consists of two parts. The projectile impact point is calculated according to the 3D helicopter model. Then, the residual velocity and damage area after projectile impact are calculated based on the helicopter's structural parameters, including thickness and material at the impact point, so that the impact of the body structure can be reflected.

First, the simulation of a specific type of helicopter projectile damage, the projectile body diameter of 12.7 mm, the projectile length of 75 mm, and the projectile speed of 1000 m/s. The normrnd function randomly generates 50 space projectile points around the helicopter model according to the normal distribution of anti-aircraft projectile points. Figure 4 shows the normal distribution of projectiles in the 3D space around the helicopter. Red circle indicates normal distribution ranges, and blue dots indicate randomly projectile points. Figure 5 shows the visualization of the strike simulation in the numerical program.

Among the 50 randomly generated projectile points, there are six strike points that will strike the helicopter fuselage. Those coordinates are (215.03, 46.74, −23.26), (113.67, 47.93), (248.88, 54.16, 188.23), (308.52, 50.20, −242.55), (48.52, 64.92, −74.00), and (236.57, 54.80, 183.41). The angles between the incident ray and the normal of the collision point surface are 43.51°, 28.99°, 77.01°, 50.53°, 8.16°, and 87.71°, respectively.

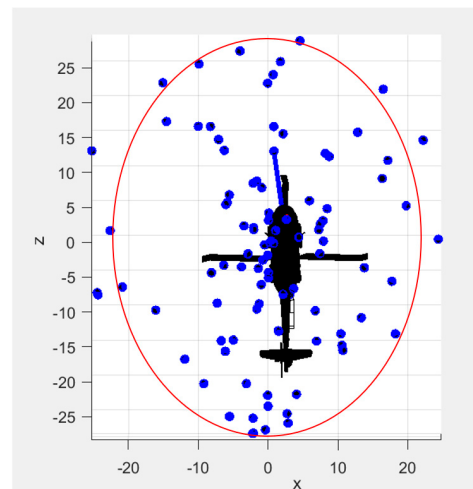


Figure 4. Fifty-projectile points in 3D space.

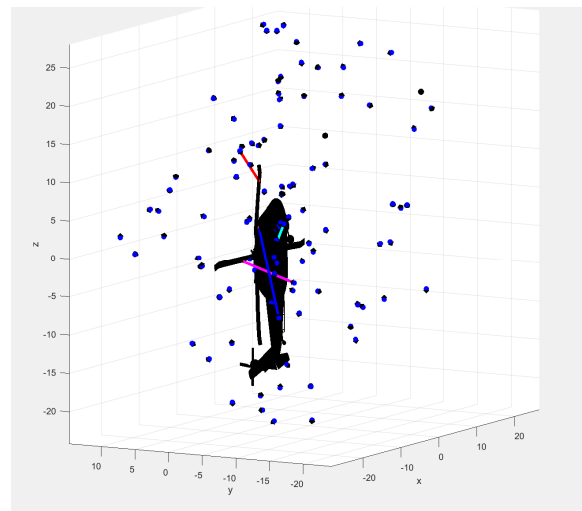


Figure 5. Strike-simulation.

Subsequently, the proposed method is used to analyze the degree of impact of a projectile injury at six collision points. The fuselage material is aluminum alloy 2A50, and the material parameters are shown in Table 4.

Table 4. Aluminum alloy 2A50 material parameters.

Parameter Name	Value
Density/($\text{kg}\cdot\text{m}^{-3}$)	2750
Elasticity modulus E/MPa	70,000
Poisson ratio μ	0.3
A	324.1
B	113.8
n	0.42
m	1.7
C	0.008
D_1	0.77
D_2	1.45
D_3	0.47
D_4	0.007
D_5	0

Note: Strain rate hardening coefficient: C; temperature softening coefficient: m .

The medium damage area is the maximum envelope area of the damaged and destroyed unit after the fuselage surface is hit by the projectile. Table 5 shows the residual velocity and damage area at different incidence angles calculated by the proposed method.

Table 5. Residual velocity and damage area.

Hitting Point Angle/°	Proposed Method Residual Velocity/m·s ^{−1}	Proposed Method Damage Area/m ²
8.16°	858.8	6.21×10^{-4}
28.99°	840.1	9.41×10^{-4}
43.51°	808.6	1.08×10^{-3}
50.53°	764.6	1.26×10^{-3}
77.01°	607.5	2.95×10^{-3}
87.71°	460.2	4.13×10^{-3}

3.3. Damage Characteristics of Helicopter Fuselage

3.3.1. Helicopter Fuselage Modeling

By coupling the ABAQUS software and the proposed method, the damage process and damage form of the helicopter fuselage at six strike points are further analyzed. A 3D model of a helicopter is established based on SOLIDWORKS software. The fuselage size is 15 m in length and 2.4 m wide; the fuselage thickness is 4 mm; and the material is a 2A50 aluminum alloy. The high-speed impact is relative motion between the macro-object collisions, which can lead to serious macro-object deformation and destruction. To analyze the inclination angle and material factors, the projectile diameter is 12.7 mm, the length of the cylindrical section of the projectile is 75 mm, the front end is a hemispherical head, the mass is 75 g, and the material is steel. A projectile velocity of 1000 m/s is used. Figure 6 shows the 3D model of the helicopter.



Figure 6. Three-dimensional model of helicopter.

Based on HYPERMESH software (Altair, Troy, MI, USA), the helicopter fuselage mesh is established. The mesh element is hex8 mesh with a cell mesh of about 4 mm, and the mesh number is 2.2×10^5 . Figure 7 shows the helicopter fuselage grid.

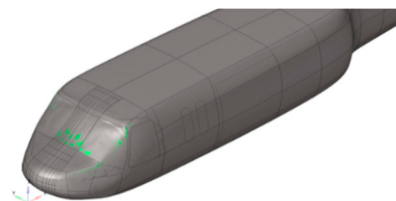


Figure 7. Helicopter fuselage grid.

Based on the coordinates of the six impact points, the angle of incidence, and the projectile injury characteristics calculated by the proposed method in this paper, the projectile and the helicopter fuselage are assembled in the assembly module according to the corresponding incidence points and angles of incidence. ABAQUS/Explicit is selected to calculate the impact with the boundary conditions of rear fuselage solid support and an initial velocity of 1000 m/s.

3.3.2. Comparison of Proposed Method and FEM

The damage area is the maximum envelope area of the damaged and destroyed unit. In finite element analysis, the damage unit can be determined according to the damage value of the material, and the damage area can be obtained by calculating the envelope area of the damage area.

Table 6 and Figure 8 show a comparison of the residual velocity and damage area. The projectile residual velocity and damage area calculated by the proposed method and FEM are in good agreement. The percentage differences between the residual velocity of the proposed method and the residual velocity of the FEM for the six impact points are 3.1%, 2.0%, 2.20, 2.26%, 4.7%, and 3.4%, respectively. The percentage differences between the damaged area of the proposed method and the damaged area of the FEM are 8%, 5.02%, 5.88%, 9.56%, 4.88%, and 7.97%, respectively. In the case of six different striking points, the residual velocity of the proposed method is less than 4.7%, which compares with the residual velocity of the projectile in the FEM. The damage area of the proposed method is less than 9.56%, which compares with the damage area of the FEM. The results indicate that the proposed method of projectile injury can obtain approximate results with the FEM.

Table 6. Comparison of the proposed method and FEM.

Hitting Point Angle/°	Proposed Method Residual Velocity/m·s ⁻¹	FEM's Residual Velocity/m·s ⁻¹	Proposed Method Damage Area/m ²	FEM's Damage Area/m ²
8.16°	858.8	886.4	6.21×10^{-4}	5.75×10^{-4}
28.99°	840.1	823.6	9.41×10^{-4}	8.96×10^{-4}
43.51°	808.6	790.8	1.08×10^{-3}	1.02×10^{-3}
50.53°	764.6	747.7	1.26×10^{-3}	1.15×10^{-3}
77.01°	607.5	580.3	2.95×10^{-3}	2.82×10^{-3}
87.71°	460.2	445.1	4.13×10^{-3}	3.84×10^{-3}

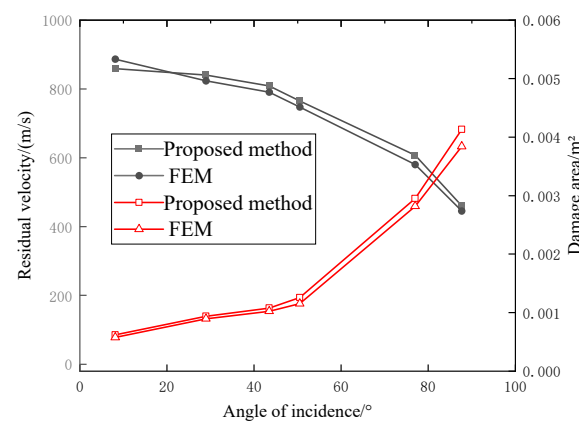


Figure 8. Contrast curve of residual velocity and damage area.

In addition, the proposed method can realize the damage analysis of multi-projectile strikes simultaneously, and the calculation time is the same with an increase in the number of strikes as shown in Figure 9. In contrast, the computational time of FEM shows a linear increase with an increased number of strikes. In the case of six different strikes, the time consumed by the proposed method is reduced by 92.1% compared with the FEM. Therefore, the proposed established method is more efficient than the FEM.

Figure 10 shows the stress nephogram for six impact points. The maximum stresses at the incidence angles of 8.16°, 28.99°, 43.51°, 50.53°, 77.01°, and 87.71° for the six strike points are 462.2, 527.5, 487.4, 547.6, 503.1 Mpa, and 506.4 MPa, respectively. In addition, the damage area increases with an increase in the incidence angle. When the incidence angle reaches 77.01°, the angle between the projectile body and the fuselage surface decreases

slightly, leading to ricochet. The projectile body slips and rubs on the fuselage surface, producing a larger damage area. Therefore, when the angle of incidence at the point of impact is large, the slip–friction damage produced by the projectile will cause the structural strength of the fuselage surface to be reduced more, and the degree of danger is high.

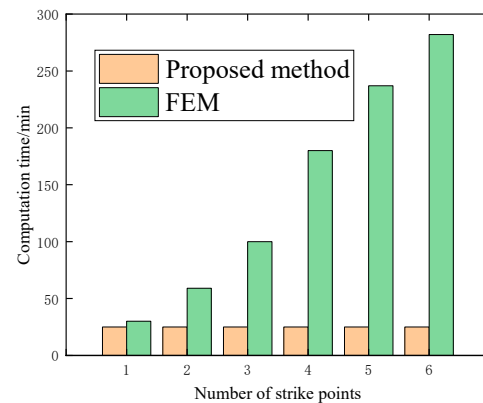


Figure 9. Comparison of computation time.

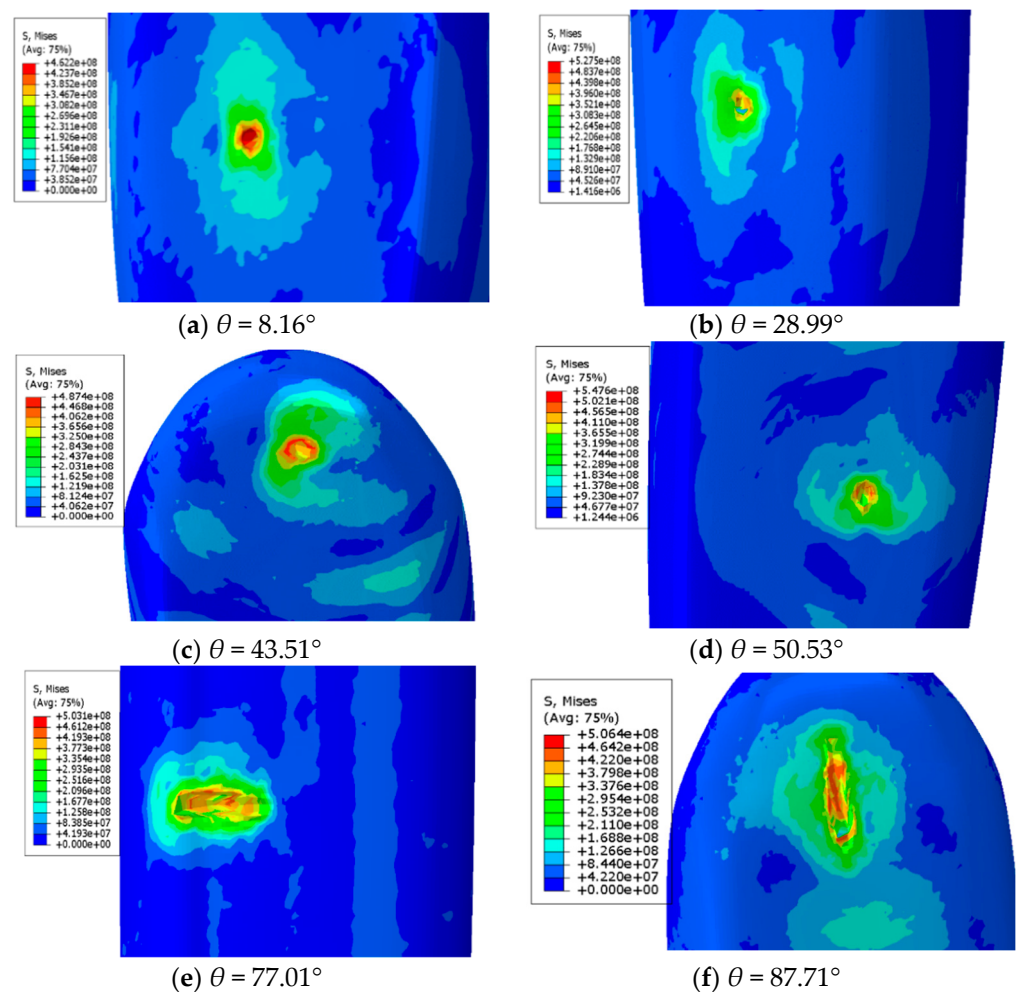


Figure 10. Stress nephogram for six impact points.

Figure 11 shows the maximum stress and residual velocity at different angles. Figure 12 shows the residual velocity with time. The residual velocity of the projectile after striking the helicopter fuselage decreases with the increase in incidence angle at the strike point.

With an increase in the incidence angle, the time for the residual velocity leveling off also increases, and the rate of decrease in residual velocity increases when the incidence angle is from 50.53° to 77.01° , while the rate of decrease in the residual velocity is the same when the incidence angle is 77.01° and 87.71° . Figure 12 indicates that when the incidence angle is larger, the projectile cannot wholly penetrate the fuselage but slips and rubs on the surface of the fuselage, and the contact area between the projectile and the surface of the fuselage increases, which increases the resistance and leads to a faster decrease in the residual velocity. In addition, the residual velocities for the incidence angles of 8.16° , 28.99° , 43.51° , 50.53° , 77.01° , and 87.71° are 886.4, 823.6, 790.8, 747.7, 580.3, and 445.1 m/s, respectively. When the incidence angle is slight, the velocity tends to be stable after the projectile can penetrate the helicopter fuselage. When the incidence angle is too large, the projectile surface and the fuselage surface are in the form of extrusion slip rubbing and cannot wholly penetrate the fuselage, so the phenomenon of ricochet is produced. At this time, the projectile also tends to speed up after slip rubbing.

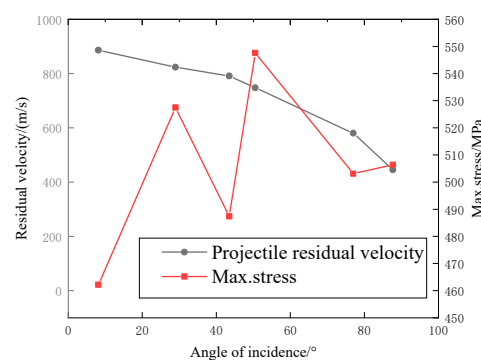


Figure 11. Maximum stress and residual velocity at different angles.

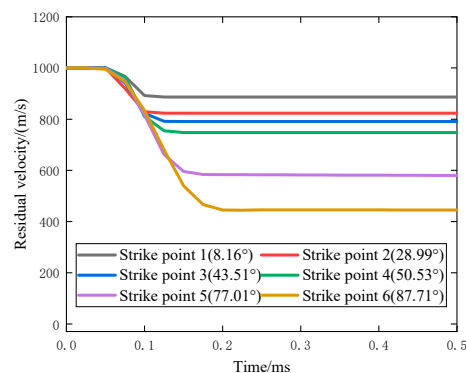


Figure 12. Residual velocity with time.

When the angle of incidence is slight, the projectile completely penetrates the surface of the fuselage to form a hole with a small aperture and a minor damage area. This condition is within the repairable range of the helicopter fuselage structure. When the angle of incidence increases to the extent that it is impossible to penetrate the fuselage surface, the projectile slips and scrapes on the surface, and the damage becomes groove-like. The damaged area is prominent, and the repairability decreases.

4. Conclusions

- (1) The efficient analysis method of helicopter fuselage projectile injury with multi-projectile bodies is established based on the projectile penetration theory and projectile impact calculation model. The calculated residual velocity matches the experimental results, and the maximum error is 2.3%.
- (2) The maximum error of the residual velocity of the projectile body calculated by the efficient analysis method is 4.7%, the maximum error of the fuselage damage area is

9.56%, and the calculation time is reduced by 92.1%, which significantly improves the calculation efficiency.

- (3) With an increase in the incidence angle, the residual velocity of the projectile body decreases. When the angle of incidence is slight, the projectile can completely penetrate the fuselage, causing petal-shaped holes, and the change in damage area is small. When the angle of incidence is too large, it will lead to the phenomenon of ricochet; the projectile on the surface of the fuselage produces slip friction, thus forming a sink-like damage area, and the change in damage area is large.

Author Contributions: X.X.: Methodology, Validation, Formal Analysis, Investigation, and Writing—Original Draft Preparation. J.T.: Conceptualization, Methodology, Formal Analysis, Writing—Review & Editing, Supervision, Project Administration, and Funding Acquisition. Y.Y.: Software, Formal Analysis, and Data Curation. T.Y.: Investigation and Resources. L.Y.: Investigation, Visualization, and Supervision. Y.Z.: Data Curation, and Visualization. All authors have read and agreed to the published version of the manuscript.

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Nomenclature

A_p	area of structural exposure [m^2]
A_{pf}	average area of exposed face [m^2]
A_{p_i}	exposed area of structure number i [m^2]
A_{V_i}	vulnerable area of structure number i [m^2]
b_f	ballistic limit coefficient [—]
C_{bf}	ballistic limit coefficient [—]
C_f	projectile shape factor [—]
d	projectile length [m]
E_b	specific kinetic energy [—]
e	natural number [—]
f	ballistic limit coefficient [—]
g	acceleration of gravity [m/s^2]
h	breakdown thickness [m]
i	structure number [—]
j	track number [—]
m_f	projectile mass [kg]
$P_{k/h_{ij}}$	kill probability of structure number i on a hit track number j strike [—]
S	expected area of contact between the projectile and the hit structure [m^2]
T	normal thickness of the surface of the hit structure [m]
V	projectile incidence velocity [m/s]
V_{50}	ballistic limit velocity [m/s]
V_r	projectile residual velocity [m/s]
v_f	projectile velocity [—]
W	projectile initial quality [kg]
W_0	reference quality [kg]
w	projectile width [m]
ρ_f	projectile density [kg/m^3]
θ	angle between the projectile firing line and the normal of the hit surface [°]
ω	number of hits on the structure surface [—]
θ_r	angle of exit after hitting [°]
δ	structure width [m]

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