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THE EFFECT OF SMOOTH PARTICLE HYDRODYNAMICS MODELING FOR BIRD STRIKE NUMERICAL SIMULATION APPLICATION IN LEADING EDGE

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ABSTRACT

This study investigates the effect of smooth particle hydrodynamics (SPH) modelling in bird strike simulations for leading-edge structures of aircraft wings. The primary aim is to simulate the interaction between a bird and the leading edge of an aircraft wing under various impact conditions using finite element analysis (FEA) software. Data from literature reviews inform the creation of a geometry model of the leading-edge structure and bird. The wing model dimensions include a span of 400 mm, with root and tip lengths of 2500 mm, and a plate thickness of 3 mm, while the bird model, consisting of a capsule shape, is designed with a mass of 1.8 kg. The bird is modeled using gelatin, chosen to replicate the dynamic behavior of bird meat during high-speed impacts.

The study examines 8 simulation variations based on four bird strike speeds ($75\ m/s, 100\ m/s, 125\ m/s, and\ 150\ m/s$) and two impact angles (0° and 45°). The results in force vs. time graphs show differing deformation responses for each scenario. The maximum force recorded was 17.24 kN for a 0° impact at 150 m/s. Additionally, the simulations reveal changes in force and deformation behavior across the different impact conditions. This research contributes to enhancing the understanding of bird strike effects on aircraft structures and supports the development of more resilient materials and designs for leading-edge protection.

Keywords: Bird strike, smooth particle hydrodynamics (SPH), finite element analysis (FEA), leading-edge structure, aircraft wing, simulation

1. INTRODUCTION

Bird strikes, which occur when a flying bird collides with a moving aircraft, represent a significant risk to flight safety. These events typically happen at high speeds (approximately 150 m/s) and can result in serious accidents, leading to loss of life and property. In recent years, bird strike incidents have been reported at an increasing rate [1].

Four key factors are believed to contribute to this rise: the growth in the population of large birds and flocks, aided by successful wildlife protection programs; increased air traffic as airline transportation continues to expand; the fact that modern jet engines, with their high thrust forces, tend to attract birds more easily; and heightened awareness of bird strike risks due to an increase in scientific research [2].

Statistical data reveal that in cargo aircraft and private jets, bird strikes typically cause accidents when the bird strikes the engine (76%) or the windshield (7%). In passenger aircraft, bird strikes most commonly result in accidents when the bird hits the windshield (54%), the engine (13%), or the wings (12%). For helicopters, accidents primarily occur when birds strike the windshield (39%), rotor (11%), or nose (11%) [1, 3].

Bird strikes, especially during takeoff and low-altitude flight, severely threaten aviation safety. Not only do they cause structural damage, but they can also lead to crashes and fatalities in the most severe cases. As such, developing reliable safety measures for bird strikes during the early stages of aircraft development is essential. According to the Code of Federal Regulations (CFR) Subpart 23.571, airframes and supporting structures must withstand a collision with a 4-pound (1.82 kg) bird at maximum speed (relative to the bird along the flight path) during a flap approach [4].

Bird strike incidents (Figure 1), also known as Bird Hit or BASH (Bird Aircraft Strike Hazard), represent a major threat to flight safety. Bird strikes can cause substantial damage, such as dents or holes, to these critical components. Overall, bird strikes are a significant threat to aviation, with the global economic losses to the industry estimated to exceed $1 billion annually [5].

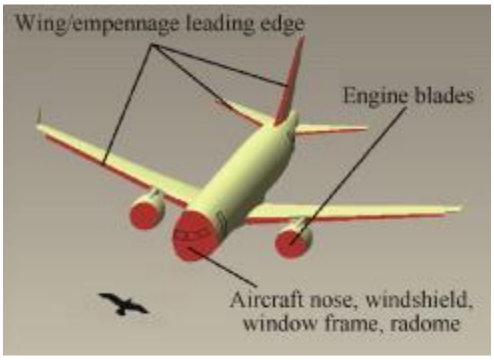


Figure 1: the aircraft structures most at risk from bird strikes

Bird strikes can result in significant loss of life and property, prompting certification authorities such as the FAA and EASA to establish specific requirements to ensure aircraft flight safety during such events [6]. For example, according to FAA/CS 25.775, the windshield or canopy must be designed to prevent penetration by a 1.8 kg bird when the aircraft is traveling at cruising speed. Additionally, FAA/CS 25.571 and FAA/CS 25.631 mandate that when a 1.8 kg bird strikes the wing leading edge and a 3.6 kg bird strikes the tail leading edge at operational speeds, there must be no deformation in these components that could compromise flight safety. Furthermore, FAA/CS 25.571 stipulates that if a 1.8 kg bird enters the engine, the engine must be shut down before any fire occurs [7].

2. THEORETICAL BASIS

The collision between the bird and the structural component shows that the bird experiences large deformation and tends to follow the shape of the target surface. This occurs when the stress caused at the time of impact yield stress from the structural component is greater than the yield stress in the bird material. The behavior of the bird material is known as a 'soft body' material, the strength/stiffness of the bird material is very low compared to the structural component that is the target of the impact.

The behavior of the bird material that resembles a fluid during impact can be calculated analytically using hydrodynamic theory. The limitations of analytical methods due to complex geometry and materials, the bird strike analysis approach was developed using numerical methods, namely the finite element method.

2.1 Elastic Plastic Properties

Elastic-plastic, elastic is a change in shape due to loading that does not exceed the yield strength of a material. Elastic deformation, or Young's modulus, is a mechanical property that measures the stiffness of a material to undergo elastic deformation when stress is applied to the material.

Plastic deformation is a change in shape due to loading that exceeds the yield strength of a material. This causes the deformation to be unable to return to its original shape. Loading on the material can produce true stress and true strain values which are illustrated in the form of a graph as seen in Figure 2.1.

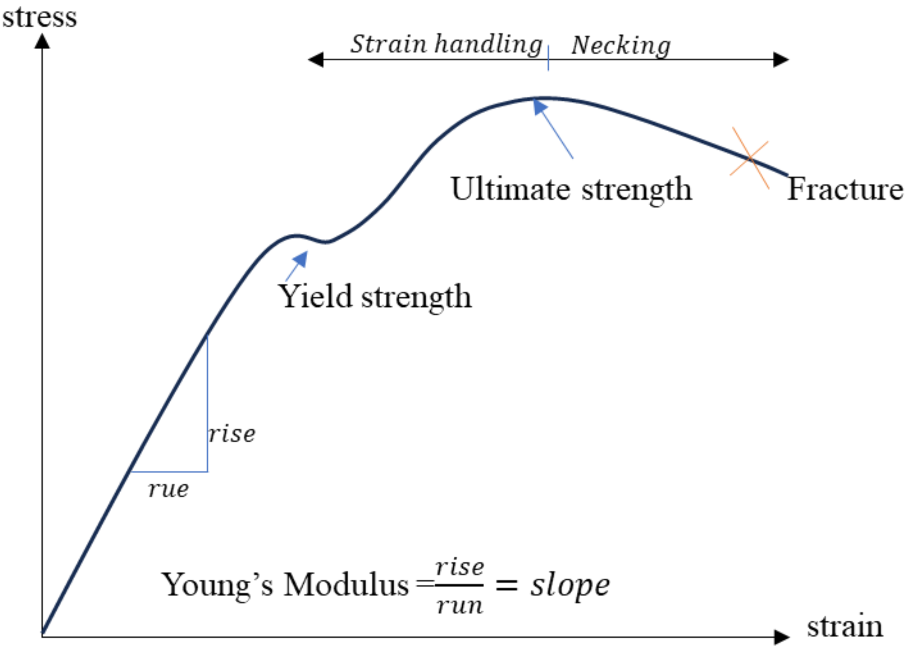


Figure 2.1 Stress-Strain Graph [8]

2.2 Hydrodynamic Theory

In the 1970s, Wilbeck and Barber [9] tried to explain the problem of bird strikes theoretically and experimentally since there were not yet advanced computers and analysis programs. Birds of different sizes were subjected to impact tests at different speeds, and pressure-time graphs were obtained accordingly.

Accordingly, a bird strike problem can be seen in Figure 2.2. If we assume that the cylinder moves at a speed called particle speed (V_P) before hitting the target (a), the cylinder is exposed to a high pressure called Hugoniot pressure at the moment it hits the target (b). The front region of the cylinder, which is exposed to high pressure, tries to spread as a shock wave into the material. The speed of this shock wave is called shock speed (V_s). At the same time, radial waves propagate from the ends of the cylinder inward at a speed higher than the shock speed, V_r. As seen in (c), when the radial waves reach the axis of the cylinder, the front surface of the cylinder is no longer exposed to the shock wave. The time between (b) and (c), the time from the beginning to the end of the shock wave, is called the shock duration. From (d) onwards, the shock wave moves inside the cylinder, and at this stage, the pressure formed in the cylinder is much lower than the Hugoniot pressure [10].

To repeat, when any object hits a target, the particles on the front surface of the object become immobile relative to the target surface and a shock wave is formed. The particles that come after it hit the target surface in turn and flow radially on the surface. In general, the pressure formed on the target after the object hits the target changes with time.

The Hugoniot pressure can be found using the experimental equations given below.

$$P_H = \rho_1 V_s V_p \quad \text{(Eq 1)}$$

$$\frac{V_s}{V_s - V_p} = (1-\alpha)\left(\frac{V_s V_p (4k-1)}{c_0^2}\right)^{-\frac{1}{4k-1}} \text{(Eq 2)}$$

In these equations; P_H is the Hugoniot pressure, ρ_1 is the particle density before impact, V_s is the shock speed, V_p is the initial speed of the particle, c_o is the speed of sound, α and k are the experimental constants.

In region C, there is an approximately constant pressure and this pressure (stagnation pressure) is found with the following equation (Eq 3);

$$P = \frac{1}{2}\rho_1 V_p^2 \text{ (Eq 3)}$$

In a bird strike event, two different equations numbered Eq 4 and 5 can be used for the pressure created radially by the bird on the target.

$$P = \frac{1}{2}\rho_1 V^2 e^{-\delta_1\left(\frac{r}{a}\right)^2} \quad \text{(Eq 4)}$$

$$P = \frac{1}{2}\rho_1 V^2 \left(1 - 3\left(\frac{r}{\delta_2 a}\right)^2 + \left(\frac{r}{\delta_2 a}\right)^3\right) \text{(Eq 5)}$$

In these equations, r is the radial distance from the center to the outside, a is the initial radius of the cylinder, δ_1 (0.5) and δ_2 (2.58) are the experimental constants.

Among the various possibilities in composite structures, the concept of sandwich structures has gained increasing popularity, primarily due to advancements in the development of cellular materials used as the core. A sandwich structure consists of two thin, strong face skins that enclose a thick, lightweight core. The core serves to separate the skins while also transferring the load from one skin to the other. Additionally, an adhesive layer is used to transmit shear and axial forces between the skins and the core, providing the necessary material integrity for efficient load distribution.

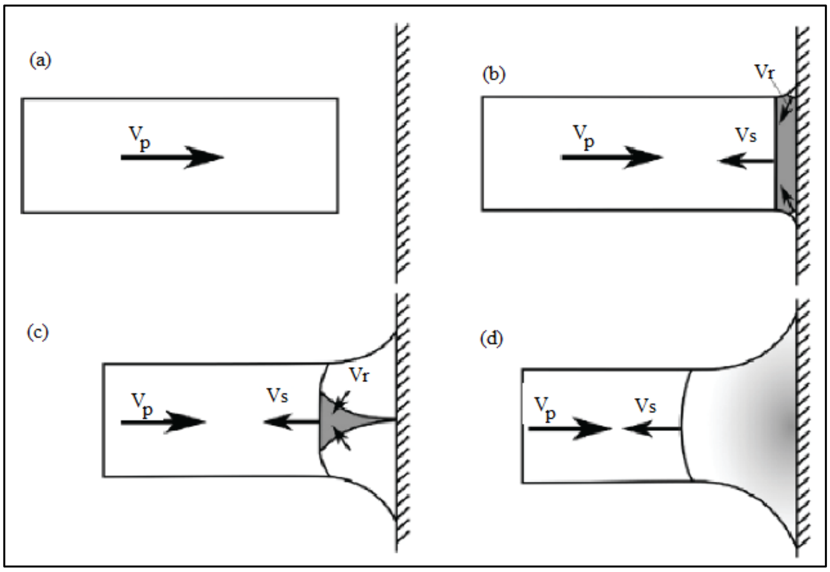
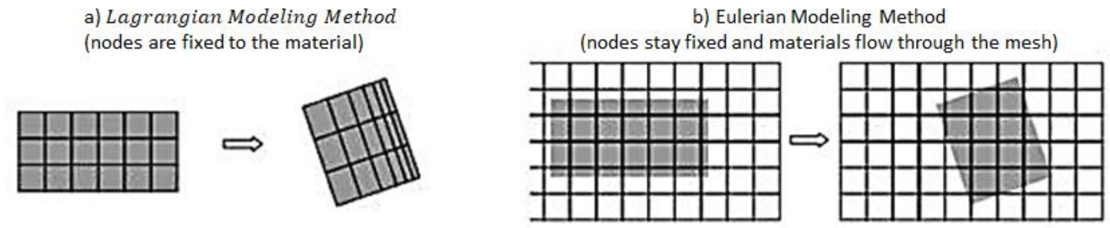


Figure 2.2. Formation and Development of the Shock Wave as a result of a Cylinder with Both Flat Ends Hitting the Target [10]

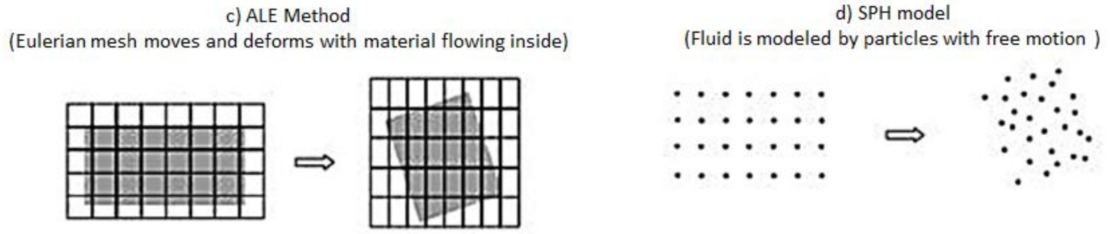
2.3 Finite Element Method

The numerical method commonly used is based on the finite element method. Simulation approaches for bird strikes are carried out using the *Lagrangian Modeling Method*, *Eulerian Modeling Method*, *Arbitary Lagrangian – Eulerian Method* (ALE) and *Smooth Particle Hydrodynamics* (SPH) [11] as shown in Figure 2.3. Smooth Particle Hydrodynamics method approach



a) *Lagrangian Modeling Method*
(nodes are fixed to the material)

b) Eulerian Modeling Method
(nodes stay fixed and materials flow through the mesh)



c) ALE Method
(Eulerian mesh moves and deforms with material flowing inside)

d) SPH model
(Fluid is modeled by particles with free motion)

Figure 2.3 Finite element method approach for Bird Strike case [12]

The characteristics of the Smooth Particle Hydrodynamics method are computational methods used to simulate the mechanics of continuous media, such as solid mechanics and fluid flow. This method is a *Lagrangian* meshfree method (coordinated to move with the fluid), and the resolution of the method can be easily adjusted in relation to variables such as density, so that each node follows the structural response when loading occurs, either in the form of motion or deformation. Each particle has a mass, velocity and material law contained in each particle. In this study, the method used is the Smooth Particle Hydrodynamics (SPH) approach Figure 2.4.

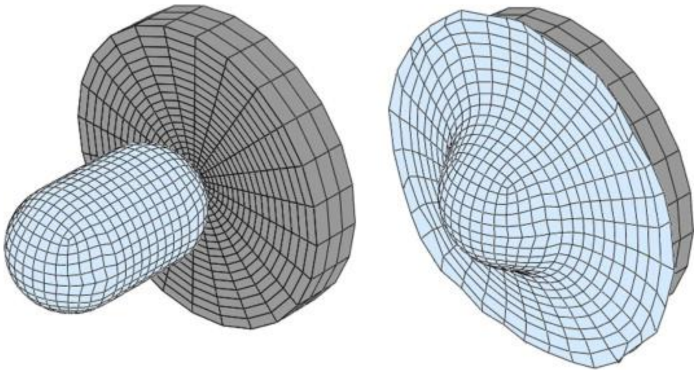


Figure 2.4 Bird strike simulation on rigid plate with SPH impactor [12]

3. RESEARCH METHOD

This research begins with a literature study to understand the problems faced. The literature study will obtain some data, which will then be used to simulate the Leading-Edge structure model on software based on the finite element method. The simulation is carried out by creating the following dimensions:

Table 3.1 STA Geometry of Aircraft Wings

STA-span wing	400 mm
Root Length	2500 mm
Tip Length	2500 mm
Plate Thickness	3mm

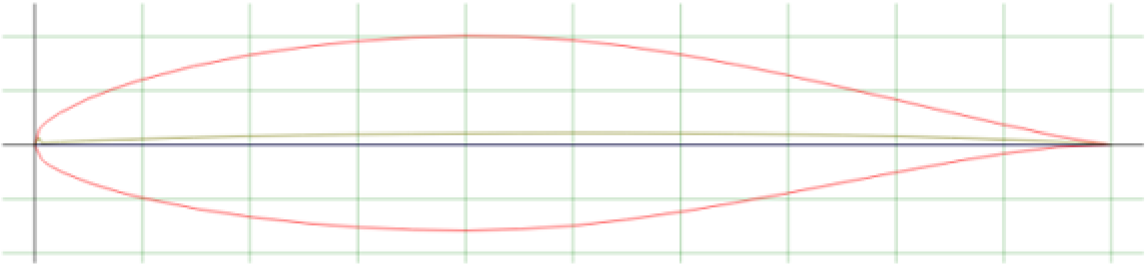


Figure 3.1 NACA 653-218 Airfoil

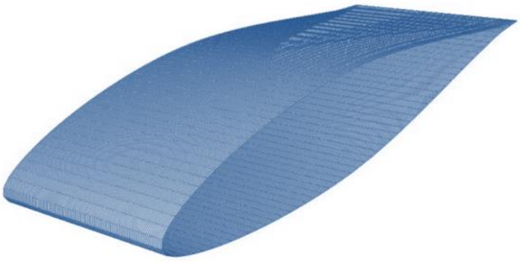


Figure 3.2 Leading edge structure model that has been cut and simplified to focus more on the deformation point where the collision occurs with the bird

Table 3.2 Bird Simulation Geometry

Radius	0.057m
Length	0.114m
Total Length	0.228m
Mass	1.8Kg

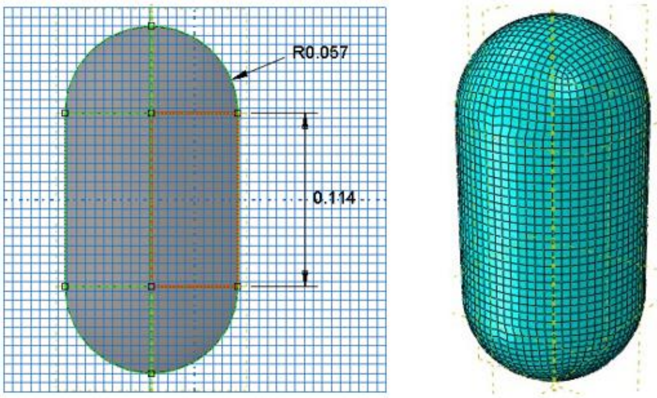


Figure 3.3 Bird model for simulation

The bird model used in this simulation has a capsule shape, designed based on its mass, as illustrated in Figure 3.4. This shape was selected based on the results of the Bird Strike experiment conducted on the leading edge of aircraft, which involved bird strikes on a sandwich structure. The bird model is constructed using three-dimensional (3D) elements to capture its behavior during the collision accurately.

For the material data, the Leading Edge model is made of Aluminum 2024 T4, which is a common material for aircraft structures. This simulation employs gelatin as a substitute since birds possess unique characteristics, including bones, blood, and flesh. Gelatin is used because it effectively mimics the dynamic behavior of bird tissue during high-speed collisions. The use of pure gelatin is considered suitable as it replicates the physical properties of bird meat and water, with gelatin's density being approximately 0.938 g/cm³ due to its high water content (over 90%). This makes it an ideal material for simulating bird impacts under realistic conditions.

Table 3.3 Leading Edge Structure Material Data and Bird Model

Properties	Density (Kg/m3)	Electricity (Pa)	Poission's ratio	EOS	Yield Stress (mPa)
Al 2024 T4	2780	7310000000	0.33		324
Bird	938	10000000		0%	100000

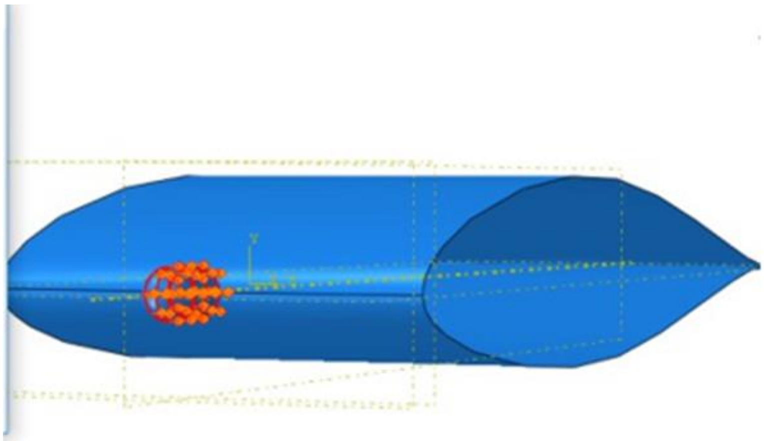


Figure 3.4 Modelling in simulation

4. RESULTS AND DISCUSSION

4.1 The analysis of force and time in the context of bird strikes

Bird Strike analysis involves a comprehensive study with a total of 8 different scenarios. This includes 4 distinct impact speeds: 75 meters per second (m/s), 100 m/s, 125 m/s, and 150 m/s, allowing for an evaluation of various speed-related effects. Additionally, the analysis incorporates two variations in the impact angle—0° and 45°—which helps assess how the angle of collision influences the outcome. These combinations provide a detailed understanding of the forces involved in bird strikes under different conditions, offering valuable insights for safety assessments and impact mitigation strategies. The results of the simulation are presented in the form of force vs. time diagrams, which illustrate how the force changes over time during the collision event. These diagrams provide valuable insights into the dynamic response of the leading-edge structure to bird strikes at different speeds and impact angles. The analysis helps to understand the varying forces exerted during the bird strike event and their effect on the aircraft structure under different conditions.

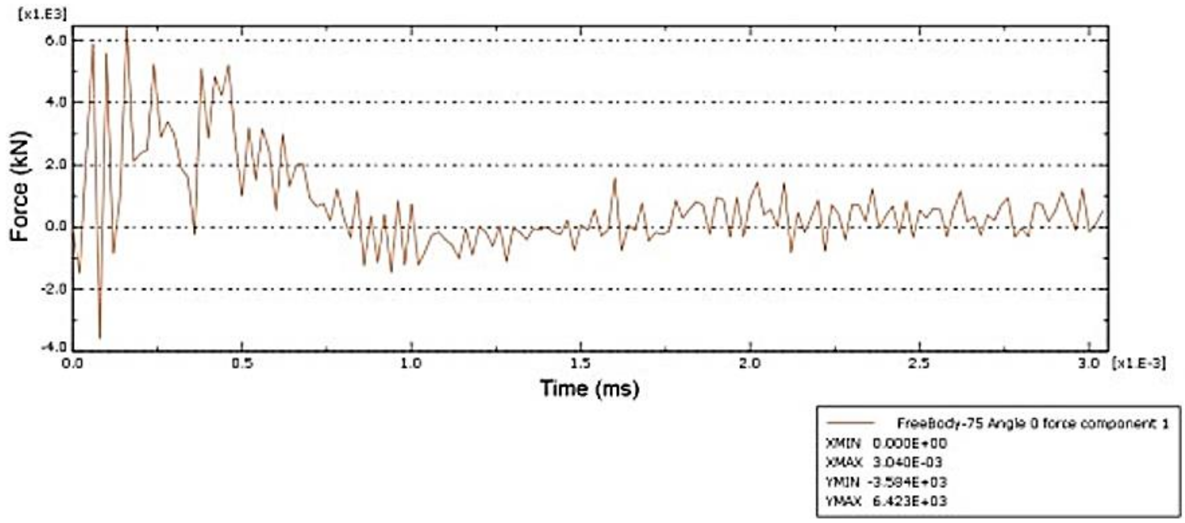


Figure 4.1 Graph of 0^{O} angle collision with a speed of 75m/s

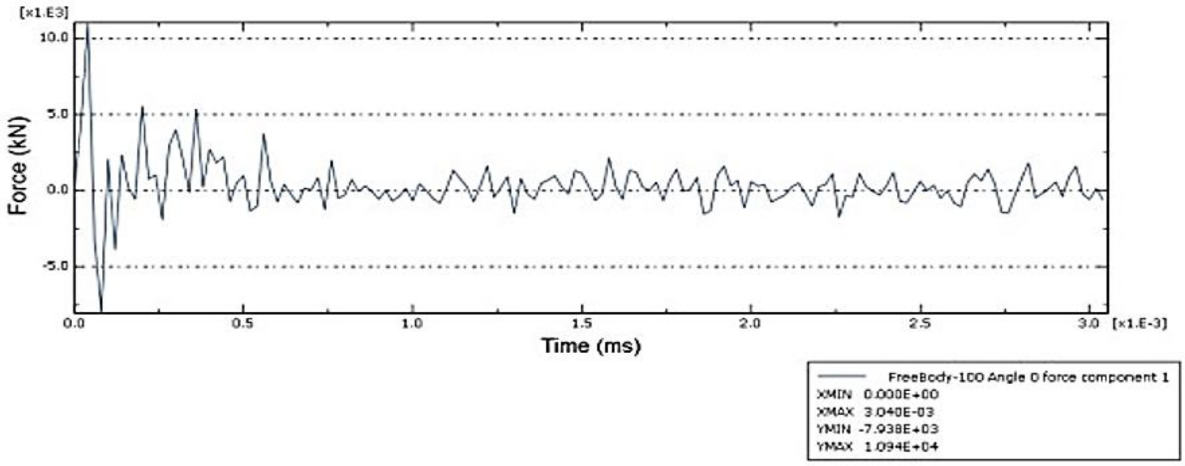


Figure 4.2 Graph of 0^{O} angle collision with a speed of 100m/s

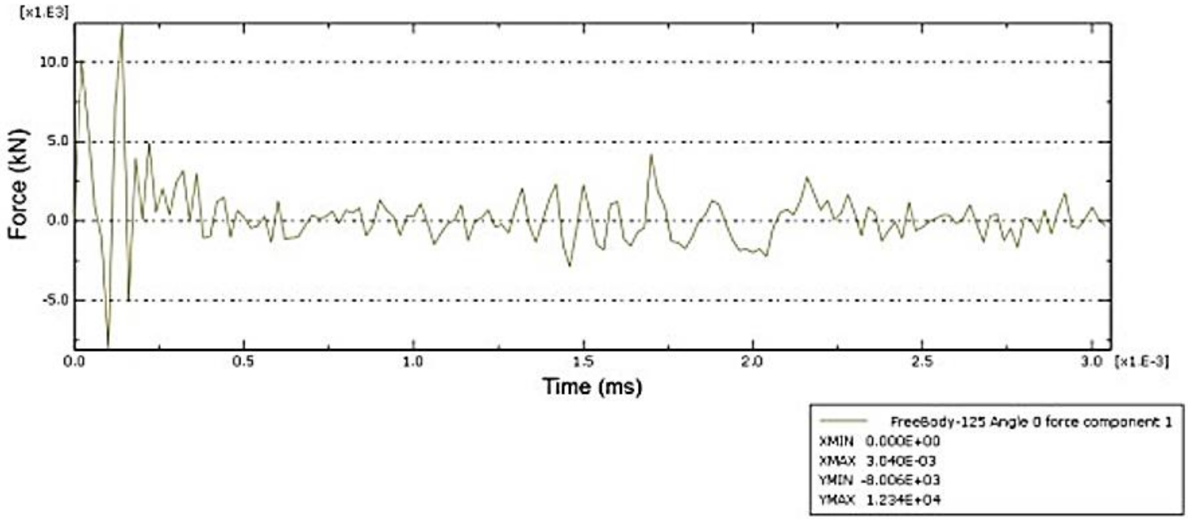


Figure 4.3 Graph of 0^{O} angle collision with a speed of 125m/s

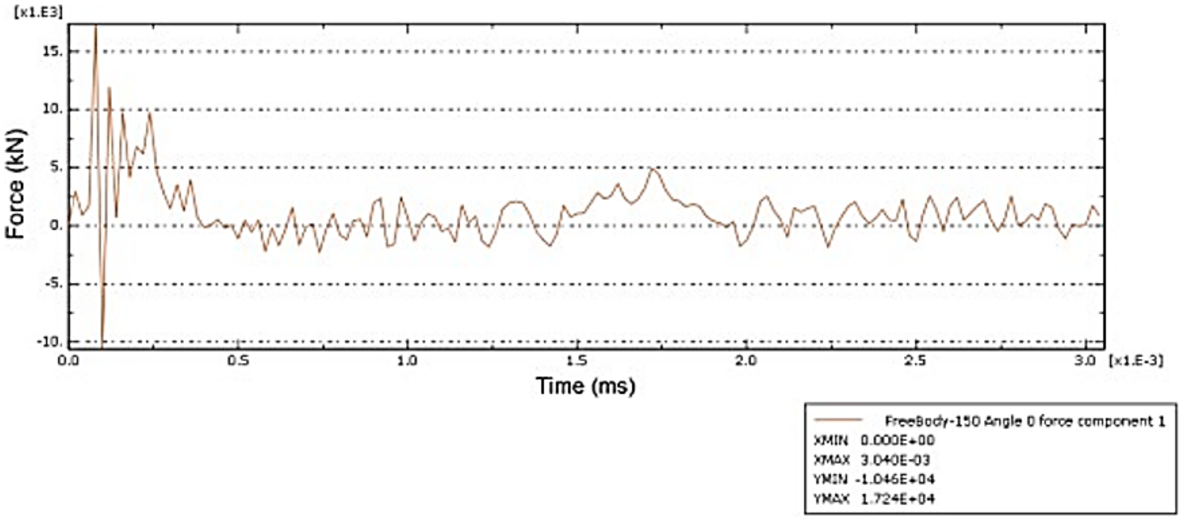


Figure 4.4 Graph of 0^{O} angle collision with a speed of 150m/s

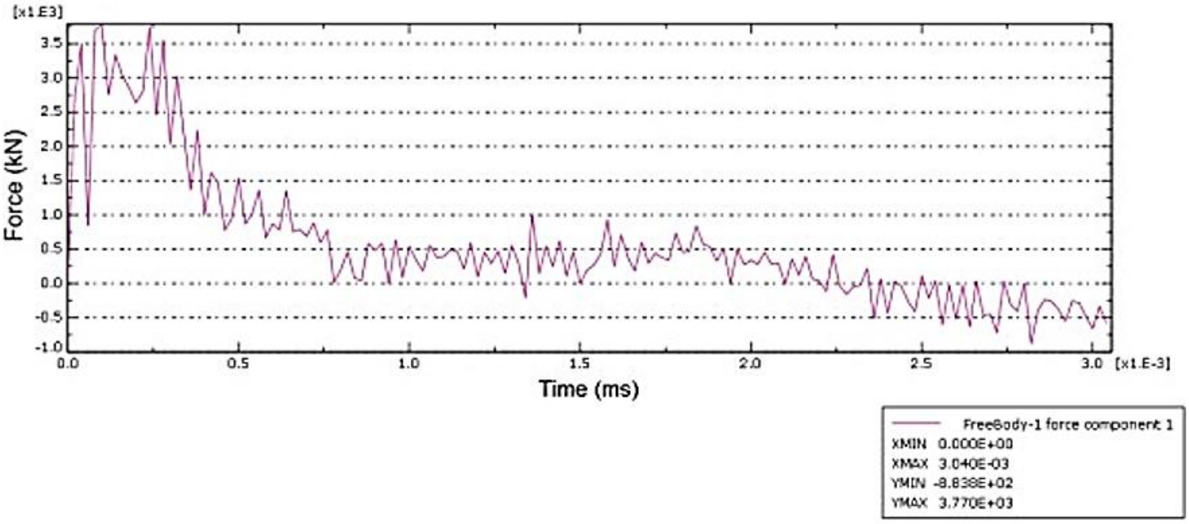


Figure 4.5 Graph of 45^{O} angle collision with a speed of 75m/s

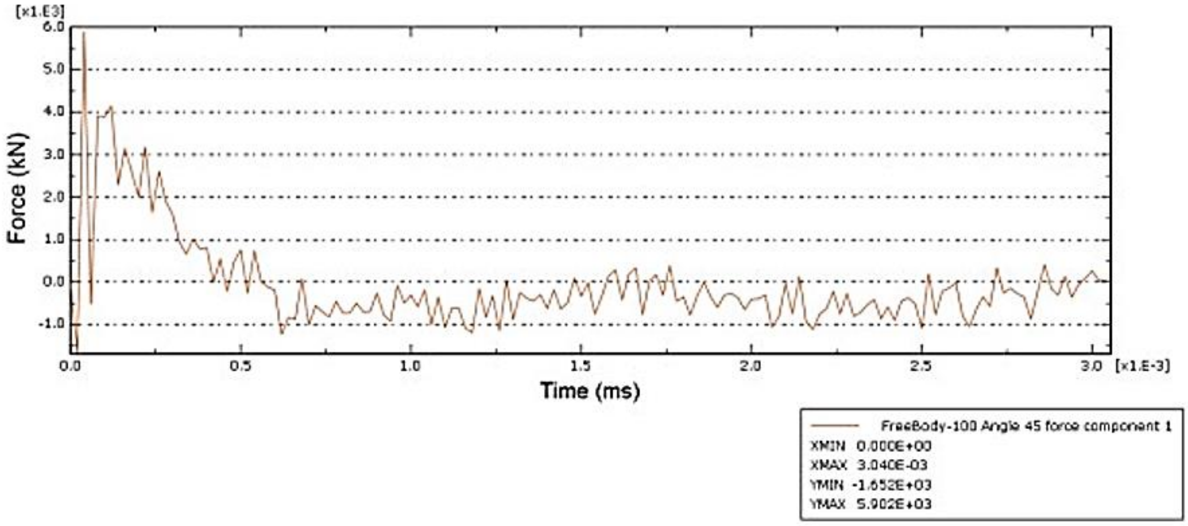


Figure 4.6 Graph of 45^{O} angle collision with a speed of 100m/s

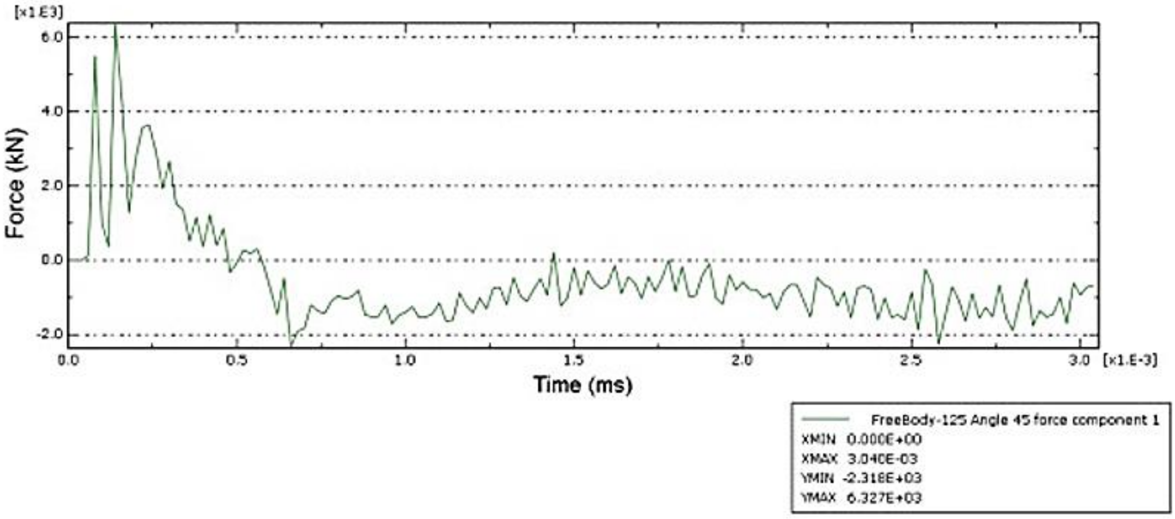


Figure 4.7 Graph of 45^{O} angle collision with a speed of 125m/s

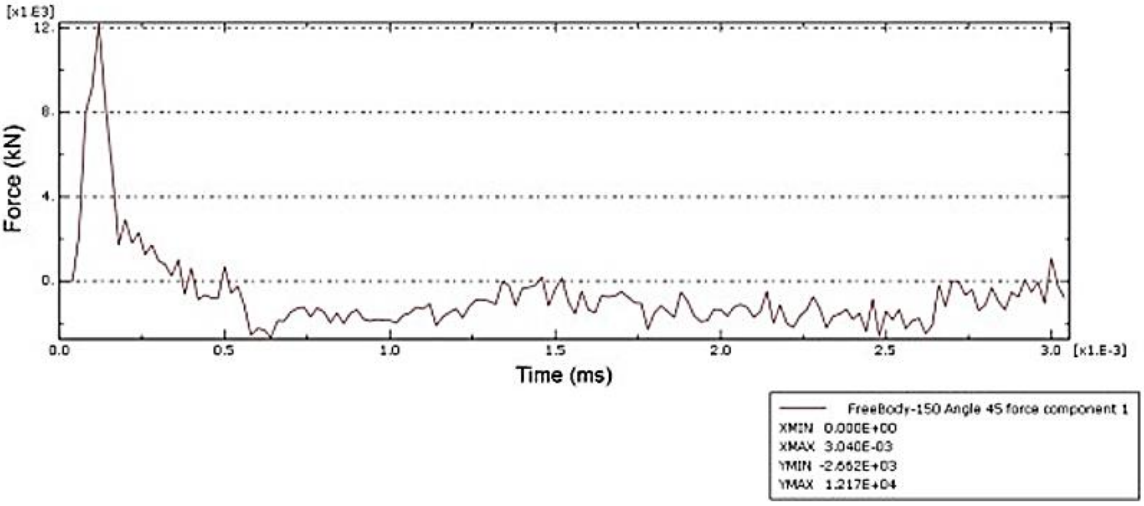


Figure 4.8 Graph of 45^{o} angle collision with a speed of 150m/s

From Figure 4.1 to Figure 4.8 the force vs time graph shows that the deformation that occurs is not the same in each model.

The simulation results for each model reveal a noticeable variation in the resultant force, indicating that the force exerted during the bird strike is influenced by factors such as the speed and impact angle. Additionally, the simulations demonstrate significant changes in the shape and deformation of the leading-edge structure, as the collision progresses. These changes are particularly evident in the visualization of deformation at different speeds and angles. For example, at a collision angle of 0° and a speed of 150 m/s, the maximum force reached 17.24 kN, which is visually represented in Figures 4.9 and 4.10. These figures clearly illustrate the extent of the deformation in both displacement and stress magnitude, emphasizing how the structure responds under high-speed bird strike conditions. The deformation behavior varies not only with the speed of impact but also with the angle at which the bird strikes the leading edge, highlighting the complex dynamics involved in bird strike events and their effects on aircraft structures.

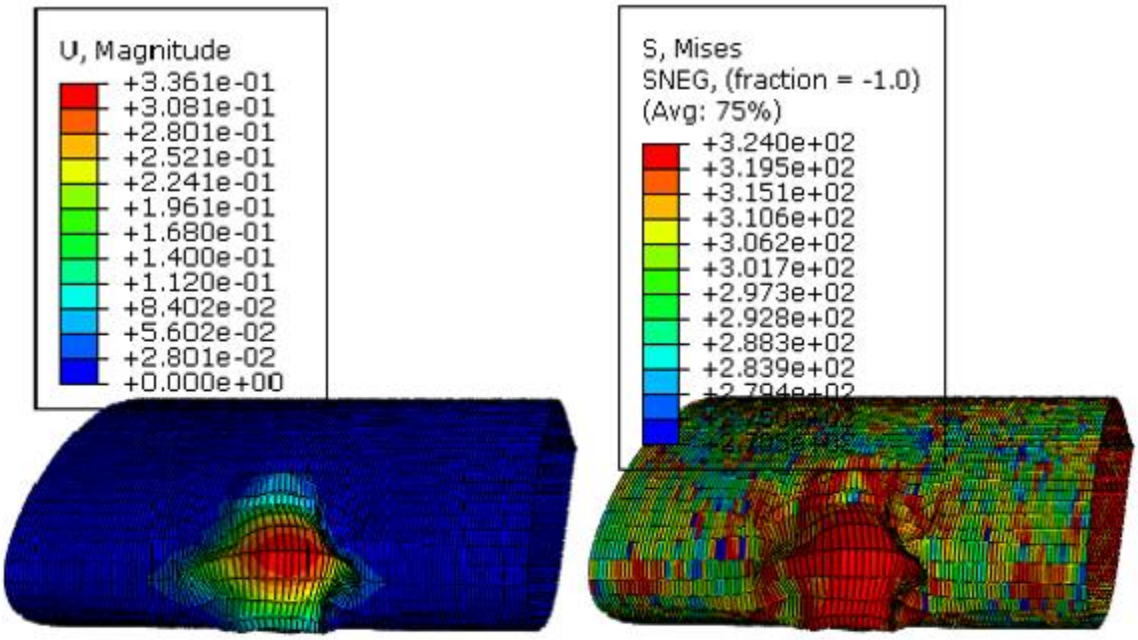


Figure 4.9 Visualization of bird collision at 0O angle with a speed of 150m/s. Displacement/magnitude and Stress/Mises

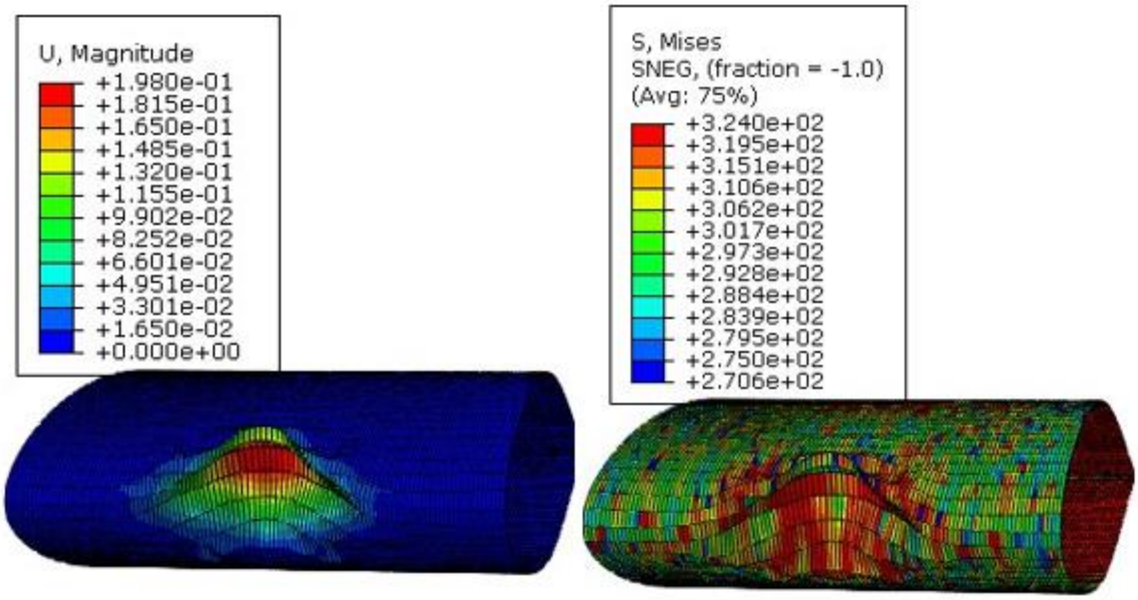


Figure 4.10 Visualization of bird collision at 45° angle with a speed of 150m/s. Displacement/magnitude and Stress/Mises

From the simulation results carried out on each model, the resultant force can be seen in Table 4.1.

Table 4.1 Comparison of force and displacement

		Force		Displacement	
S.No	Speed (m/s)	0° (kN)	45° (kN)	0° (mm)	45° (mm)
1	75	6.29	3.68	145.16	87.90
2	100	10.71	5.78	201.32	120.69
3	125	12.08	6.19	264.29	153.99
4	150	16.90	11.92	329.37	194.08

5. CONCLUSION

This study investigates the effects of bird strikes on aircraft, exploring how the interaction between humans and birds in shared airspace has intensified with the growth of air transportation in recent years. The research employs Mie-Grüneisen and Murnaghan equations of state to model the bird material, yielding results that align closely with experimental data. Finite element simulations were conducted to analyze the collision dynamics across eight leading-edge models. The results indicate that the model with a 0° impact angle and a speed of 150 m/s experiences the highest force, reaching 17.24 kN. This highlights the significant impact forces that can occur during bird strikes, underscoring the importance of designing aircraft structures capable of withstanding such events.

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