A Predictive Methodology for Soft Impact Damage in Jet Engines Incorporating Hybrid Composite Structures

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ABSTRACT

This work presents a detailed predictive modeling methodology for comprehensive crashworthiness analysis of advanced jet engine forward sections, containing hybrid and composite structures, when subjected to soft impact. Bird strike onto the fan assembly is chosen as the impact event to be studied. The aim is to develop a numerical methodology capable of accurately capturing the full range of multifaceted damage in hybrid and composite structures as they evolve throughout the forward section of a propulsion system.

Effective strategies are developed within an explicit finite element framework for modeling a bird, an engine forward section, intra-ply and inter-ply composite damage, and hybrid structural failure. The accuracy of each approach and their numerical modeling considerations are thoroughly investigated. These techniques are then combined to form the full crashworthiness methodology.

It is demonstrated that the complete methodology effectively captures progressive hybrid fan blade fracture, leading edge de-bonding, composite casing delamination, and other significant progressive damage effects caused by direct impact and subsequent engine component interactions. The full damage prognosis capabilities demonstrated by this approach encompass aspects which have remained mainly unaddressed in soft impact analysis. A methodology for assessing the complete extent of impact damage for advanced structural engine designs represents a breakthrough that can contribute greatly to the rapid development of these systems in the future.
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Publications Based Upon This Work


Invited Keynote Presentations


Submitted Abstracts


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## Nomenclature

\( a \)  
Time step scale factor

\( a^n \)  
Nodal acceleration vector \([m/s^2]\)

\( c_0 \)  
Initial sound speed \([m/s]\)

\( c_e \)  
Element sound speed \([m/s]\)

\( C \)  
Bulk modulus \([Pa]\)

\( D_i \)  
Displacement vector \([m]\)

\( E \)  
Elastic modulus \([Pa]\), Energy \([J]\)

\( \langle f(x) \rangle \)  
Approximate field variable value

\( f_i \)  
Body force per unit volume \([N/m^3]\)

\( F^n \)  
Internal force vector \([N]\)

\( G \)  
Shear modulus \([Pa]\)

\( h \)  
Smoothing length \([m]\)

\( H^n \)  
Hourglass force vector \([N]\)

\( k \)  
Compressibility coefficient

\( L \)  
Bird length \([m]\)

\( L_e \)  
Characteristic element length \([m]\)

\( m_j \)  
Mass of particle \(j\) \([kg]\)

\( M \)  
Mass matrix \([kg]\)

\( n \)  
Normal vector

\( N \)  
Number of particles within smoothing length

\( N_i \)  
Shape function

\( p \)  
Hydrostatic pressure \([Pa]\)

\( P \)  
Interface pressure \([Pa]\)

\( P_H \)  
Hugoniot pressure \([Pa]\)

\( P_s \)  
Steady dynamic pressure \([Pa]\)

\( p^n \)  
External force vector \([N]\)

\( q \)  
Bulk viscosity \([Pa]\)

\( r \)  
Radius \([m]\)

\( r_i \)  
Inner hub radius \([m]\)
\( r_m \)  Mid-span radius [m]
\( r_o \)  Outer tip radius [m]
\( s_{ij} \)  Deviatoric stress [Pa]
\( t \)  Time [s]
\( t_i \)  Traction vector [s]
\( t_k \)  Time at index \( k \) [s]
\( \Delta t_{\text{max}} \)  Maximum stable time step [s]
\( T \)  Impact duration [s]
\( u \)  Distance between particles [m]
\( U_0 \)  Initial relative impact velocity [m/s]
\( U_s \)  Shockwave speed in a bird [m/s]
\( U_s' \)  Shockwave speed in a target [m/s]
\( v \)  Linear velocity [m/s]
\( v_i \)  Velocity vector [m/s]
\( v_{\text{takeoff}} \)  Aircraft takeoff velocity [m/s]
\( V \)  Relative volume
\( W \)  Kernel function
\( x_i \)  Coordinate vector [m]
\( X_\alpha \)  Convected coordinate vector [m]

**Greek Letters**

\( \alpha \)  Linear bulk viscosity coefficient
\( \beta \)  Quadratic bulk viscosity coefficient
\( \Gamma \)  Subset of problem domain
\( \varepsilon_{ij} \)  Strain
\( \kappa \)  Smoothing length scale factor
\( \nu \)  Poisson’s ratio
\( \Pi_{ij} \)  Artificial viscous pressure
\( \rho \)  Mass density [kg/m³]
\( \rho_0 \)  Initial mass density [kg/m³]
\( \rho' \) Target mass density \([kg/m^3]\)

\( \rho_j \) Density of particle \( j \) \([kg/m^3]\)

\( \sigma_{ij} \) Stress tensor \([Pa]\)

\( \tau, x' \) Variables of integration

\( \phi_i \) Test function

\( \Psi_i \) Basis function

\( \omega \) Rotational velocity \([rad/s]\)

\( \Omega \) Problem domain

Other Characters

\( \nabla \) Spatial divergence operator (del)
1. INTRODUCTION

1.1. The Soft Impact Threat

Jet engines commonly ingest birds, hailstones, tire debris, and other foreign objects during flight due to their large forward-facing intake area and strong suction forces induced at the front of the engine. For engine components moving at high translational and rotational velocity, even collisions with these relatively soft, weak objects can cause extensive damage that decreases the engine’s performance and poses a safety threat to the passengers and crew of an aircraft.

Bird strike represents the largest threat to commercial aviation, with about 90% of all foreign object damage (FOD) cases being attributed to birds [1]. Impact with a bird most often occurs during take-off or landing, leaving little time for a pilot to respond should an engine fail. As of 2008, it was estimated that 262 fatalities have directly resulted from catastrophic bird strike events on aircraft [2]. Over the past 18 years, the estimated cost to the civilian aviation industry due to bird strike-related damages was approximately $291.1 million [3]. In recent years, severe collisions between commercial aircraft and birds have increased by as much as 40% compared to the average from 2000 to 2008, due to both increased air traffic and more consistent reporting of incidents [4]. These and other statistics are the motivation for extensive testing by engine manufacturers for resistance to bird strike.

Novel turbofan engines used in commercial aviation feature larger inlet diameters in accordance with the desire for higher bypass ratios and greater fuel efficiency. This presents a larger forward-facing area for each engine and, thus, a higher likelihood of ingesting birds. In addition, modern aircraft designs are mostly employing twin-engine architectures, rather than quad-engine schemes, for increased fuel efficiency and lower maintenance costs. Therefore, the loss of a single engine poses greater loss of thrust and, thus, a higher risk to the safe operation of an aircraft.
1.2. Composites in Aircraft Structures

Fiber-reinforced polymer (FRP) composite materials possess superior mechanical properties that include lower mass density, high stiffness, and high corrosion resistance. For these reasons, modern aircraft designs have seen a dramatic shift from metals to composites in numerous components throughout the structure. New-generation aircraft, such as the Boeing 737 and the Airbus A380, incorporate a composite fuselage, wings, and other primary aircraft structures [5], as shown in Fig. 1-1.

![Boeing 787](Image Source: Boeing)

![Airbus A380](Image Source: Airbus)

**Fig. 1-1. Composites incorporated into new-generation aircraft systems.**
Engine manufacturers have also begun employing composite materials for their lower weight-to-stiffness ratio, higher thermal stability, and greater ease of manufacturing parts with complex geometry, such as advanced swept fan blades, in comparison to metals. These advantages allow for tighter design tolerances, increased fuel efficiency, and reduced manufacturing costs. One example of an engine employing composites is the GEnx developed to power the Boeing 787 (Fig. 1-2). These engines, and some variants of its parent engine the GE90, utilize composites in the fan casing and fan blades in the forward section.

![Composite fan casing](image1.png)  ![Composite fan blade](image2.png)

*Image Source: GE Aviation*

**Fig. 1-2. Engine incorporating a composite fan casing and hybrid fan blade structures.**

The primary disadvantages of composite structures, however, include poor impact resistance, low through-thickness strength, complex failure modes, and sudden brittle failure. The lower collision resistance of composites poses a particular risk to the thin, rotating fan blades. The threat of sudden collapse of a blade due to foreign object damage (FOD) has lead engine designers to reinforce each composite blade with metal subcomponents, including titanium leading and trailing edges, to increase the impact resistance of the structure (Fig. 1-2). The resulting metal/composite part is referred to as a hybrid composite structure.
1.3. Aircraft Engine Certifications

Engines incorporating composite and hybrid structures must meet the same flight certification standards as every other engine before being allowed to fly. The Federal Aviation Administration (FAA) has established specific bird ingestion certification standards under Federal Aviation Regulation (FAR) 33.76, requiring each engine design to strictly demonstrate its ability to ingest birds without suffering catastrophic damage.

The specific ingestion tests performed varies with the size of the engine inlet area. Modern commercial turbofan engines typically fall into the upper category of inlet size. Numerous ingestion tests must be performed, ranging from multiple small bird ingestion to single large bird impact. For the upper inlet size category, engines must demonstrate their ability to survive an impact with birds as large as 4 and 8 pounds.

Currently, manufacturers must conduct numerous physical tests to develop safe engine designs that can meet these certification standards. Computational analysis is used extensively to assess the crashworthiness of a design prior to physical testing. However, the complex damage mechanisms of FRP composites have posed great difficulties in accurately modeling composite structural behavior. Further complexities are introduced by hybrid structures incorporating bonded metal and composite sub-structures. As a result, extensive experimental testing is typically required to properly assess the crashworthiness of composite and hybrid structures.

1.4. Need for a Numerical Crashworthiness Methodology

Experimental testing of engines is associated with very high costs and long development times. The incorporation of new composite and hybrid metal-reinforced composite structures into primary engine components requires even more extensive testing to develop robust hybrid structure engine designs. In order to reduce reliance on physical testing that slows new developments, novel computational approaches for assessing the bird strike crashworthiness of
advanced engines are needed.

Modeling damage within hybrid engines due to bird strike presents the challenge of modeling the important complex, transient interactions between engine structures, bird(s), composite damage effects, and other factors in order capture the crucial damage and failure details needed to assess the crashworthiness of a design. This demands high computational cost often associated with complex modeling. A full three-dimensional finite element (FE) analysis of each engine component, even with a course mesh and only considering the engine structural response, would form a problem with many millions of degrees of freedom that would exhaust most computational resources available to aerospace designers and researchers.

It is imperative to identify and capture key factors affecting the bird impact crashworthiness of engines in order to develop an accurate and feasible damage modeling methodology. By identifying damage sources that lead to larger failure, specific measures can be taken to correct the design. This is an especially difficult task for composite structures. The complexity of modern propulsion systems makes it critically important to identify the specific causes of decreased performance and catastrophic failure in an engine that ingests a foreign object.

1.5. Project Definition and Contributions

The goal of this work was to create a numerical methodology for capturing the full extent of damage and failure in a jet engine forward section incorporating hybrid and composite structures subjected to soft impact. Bird strike was the chosen soft impact event for investigation, and methods of accurately characterizing the bird/structure interaction and the subsequent structural response were developed. This work focused on scenarios where a bird directly impacts the rotating fan assembly since this presents the most destructive impact scenario.

In order to form the comprehensive methodology, strategies were developed within an explicit FE platform for modeling a bird, an engine forward section, composite ply damage and
delamination, and hybrid structural failure. The accuracy of each approach and their numerical modeling considerations were thoroughly investigated. Significant contributions were made to the understanding and development of numerical solutions in each of these areas. These techniques were then combined to form the full crashworthiness methodology.

The completed methodology successfully captured progressive hybrid fan blade fracture, leading edge de-bonding, composite casing delamination, and other damage effects caused by direct bird impact to the fan blades and subsequent engine component interactions. The full damage prognosis capabilities of this approach encompass aspects which have remained mainly unaddressed in previous soft impact analysis. This methodology can contribute greatly to the rapid development of future advanced propulsion systems incorporating hybrid and composite structures.

1.6. Outline of the Thesis

Chapter 2 presents a detailed background and literature review of the methods developed by previous researchers for modeling soft impact and capturing bird strike damage to jet engine forward sections. Numerical methods used to represent a bird during impact are discussed and compared. Then, methods of predicting collision damage to an engine forward section developed by previous researchers are analyzed, including forward sections incorporating composite structures.

Chapter 3 provides an assessment of the important complex mechanics involved in the analysis of soft impact on forward sections with hybrid/composite structures. The difficulties of capturing these physical complexities in a numerical platform are then discussed. An approach for developing the crashworthiness methodology is outlined, and the problems that will be explicitly addressed are presented.

Chapter 4 gives a brief overview of the formulations underlying the analytical tools used in
this work. Specifically, the mathematical basis for the explicit FE code utilized, the governing equations of the particle method used to represent the bird, and laminate theory for modeling composite structural behavior are reviewed.

In chapter 5, a bird model is developed that accurately captures the large deformation and impact pressure characteristics of the soft impact event. Several physical and numerical parameters of the bird model are varied to determine how they influence the impact pressure and the general response of the bird material. A final bird model is developed for use in subsequent forward section impact analyses.

In chapter 6, a method of accurately modeling an engine forward section subject to impact on the fan assembly is formed. A two-stage analysis approach is developed. In the first stage, a quasi-static analysis is performed in which rotating components, such as the fan blades, are pre-stressed and pre-deformed due to centripetal forces that exist prior to impact. Then, a dynamic analysis is carried out for the bird impact analysis. It is shown that inter-component interactions and realistic damage responses are captured effectively.

In chapter 7, methods for predicting composite ply damage and delamination are reviewed. A delamination modeling technique using cohesive elements is developed. Then, a composite modeling approach capturing both ply damage and delamination is used to model an impact plate for comparison with experimental data from the literature.

In chapter 8, a novel hybrid fan blade modeling approach is developed. Both the leading edge and the main composite portion of the blade are explicitly modeled, and a cohesive tied connection is used to bond the two components while also capturing de-bonding due to high normal and shear loads. An array of hybrid fan blades is impacted by a particle bird model, and it is shown that de-bonding of the metal leading edge is effectively captured using the cohesive
approach.

In chapter 9, the developed methods are combined into a comprehensive methodology for predicting the effects of bird strike onto an engine forward section employing hybrid fan blades and a composite fan casing. A forward section model incorporating all of the developed methods is analyzed, demonstrating the applicability of these techniques for analysis in a comprehensive analysis. It is shown that impact damage and failure can be effectively captured, ranging from fan blade damage to blade failure that results in a blade-off event.

Finally, chapter 10 reviews the findings from the previous chapters and presents the contributions of this work. It is shown that the crashworthiness methodology developed shows promise for accurately capturing the full range of damage and failure in advanced engine forwards sections incorporating hybrid and composite structures.
2. BACKGROUND AND LITERATURE REVIEW

In this chapter, a detailed review of the methods developed for modeling soft impact and capturing bird strike damage to jet engine forward sections is presented. First, the predictions of soft impact theory for the pressures within the bird and at the point of impact with a structure are investigated. The behavior of the bird material and the implications for the structure being impacted are explored in detail.

Then, numerical methods used by previous researchers to model the bird are reviewed. The advantages of each FE approach, as well as their shortcomings, are assessed. In addition, the range of different representative geometries, material models, and other parameters used in previous works for modeling the bird are explored in order to identify current modeling trends.

Next, methods of modeling the forward section in a dynamic analysis are examined. Approaches used by previous researchers to capture forward section damage for both bird strike and blade out events are assessed for their strengths and weaknesses. Methods specifically developed for the analysis of composite and hybrid structures are examined as well. A detailed discussion of the loading conditions imposed on forward engine structures due to progressive damage is also included.

Finally, concluding remarks are provided about the current state of the art for modeling bird impact on jet engine forward sections. Overall, it is found that methods of capturing the full range damage in an advanced forward section design lacking.

While bird impact simulations have been conducted for numerous aircraft structures, (including empennages, wing leading edges, and canopies/windshields), this review focuses primarily on those approaches developed specifically for capturing the complexities of soft impact on jet engines, especially for direct impact onto the fan blades.
2.1. Soft Impact Theory

It has been observed that many materials behave in a fluid-like manner when subjected to impact at velocities high enough to induce stresses that far exceed the ultimate strength of the material [6]. In a ballistic impact event between two metal components, such as a bullet hitting a steel plate, stresses are great enough in both the projectile and the target that they each flow like a fluid, with the problem emulating a drop of liquid impacting a liquid body. The projectile is disintegrated, and the target is left with a crater as material is ejected, or “splashed”, away from the area of impact.

A soft impact event is one in which the relative impact velocity induces stress in the projectile that far exceed its strength, but the magnitudes of the stresses experienced by the target are only of the same order or below its ultimate strength. The projectile is completely destroyed by the impact, but the target structure may only experience failure at specific points or none at all. The projectile flows like a fluid over the solid target structure. Most often, the projectile is substantially less stiff than the target structure. Examples of soft impact events for aircraft are bird impact, hail strike, and impact with runway debris such as rubber tire fragments.

A concerted research effort to understand the physical mechanisms of bird strike was carried out by Wilbeck [6-8] and others, including Barber et al. [9], beginning in 1974. The ultimate goal was to develop a substitute bird model for use in engine blade impact experiments that accurately reproduced the impact loading on the structure.

Pressure-time history data at the center of the bird impact obtained from experiments is shown in Fig. 2-1. A sharp rise in the internal pressure of the soft body can be detected as the projectile first comes into contact with the target. This is followed by a sudden pressure drop until a steady dynamic pressure state is attained. The residual pressure then tapers off until finally reaching zero.
After much investigation, a porous gelatin material in a hemi-spherically capped cylindrical configuration with a length-to-diameter ratio of 2 was found to closely match the response of large birds during impact and provide a highly repeatable experimental approach [7].

Recognizing the fluid-like behavior of soft bodies, hydrodynamic theory describing the shock behavior of water columns and droplets during impact were used by Wilbeck to form a theory of soft impact [6]. These concepts, based on Rankine-Hugoniot conservation relations for normal shockwaves [10], were used to understand the generation and propagation of shockwaves in soft
projectiles and predict interface pressures between a soft body and an impacted structure.

### 2.1.1. Shockwave Propagation

At velocities above 50 m/s, a bird may be considered a soft object that acts as a fluid upon impact [11]. Wilbeck idealized the bird as a cylindrical column of fluid with the same average density as the bird material.

A shockwave propagates through the bird in the direction of relative velocity through its body (Fig. 2-2). The rapid pressure change across the shock induces high stresses far exceeding the bird’s strength, causing the bird material to behave as a fluid as its internal bonds are broken. This leads to a multi-stage problem as the bird’s properties across the shock effectively change from solid to fluid. These facets of the impact event can be characterized by the following stages:

1. solid-structure impact
2. solid-fluid transition
3. fluid-structure interaction
4. nonlinear growth of impact region, and
5. structural response and damage.

Stages 1 through 4 occur somewhat consecutively. The last stage, response and damage of the structure being impacted, is present throughout the impact event and may lead to rapid changes in the structural response and pressure around the impact zone. Damage and failure may continue after the bird material has fully impacted as well.
Originally, the bird mass is solid, and the initial impact with an aircraft structure can be labeled as a “hard” impact in which contact forces are highly localized about a relatively small impact region. The velocity of material over the contact area instantly decreases, and a shocked region of material develops in both the projectile and the target at their interface as material is compressed. This is illustrated in Fig. 2-2(1). Assuming both objects behave elastically, an expression for the shock pressure, or Hugoniot pressure, $P_H$, in the bird can be derived from

$$P_H = \rho_0 U_s U_0 \left( \frac{\rho' U_s'}{\rho'_s + \rho_0 U_s} \right),$$

(2.1)

where $\rho_0$ and $\rho'$ are the densities of the bird and the target, respectively, $U_s$ and $U_s'$ are the shockwave speed in the bird and blade, respectively, and $U_0$ is the relative impact velocity [8]. In the case of bird strike, the density and shockwave speed of the aircraft structure are far greater than that of the bird, expressed as

$$\rho' U_s' \gg \rho_0 U_s.$$

(2.2)
Subsequently, Eq. (2.1) can be simplified to

\[ P_H = \rho_0 U_s U_0 \]  \hspace{1cm} (2.3)

Concentration of the shock pressure along the bird/target interface, bound by the speed of sound in the object, produces a shockwave. The shockwave then propagates at a faster speed than the relative bird/blade velocity. Consequently, a large pressure gradient is formed across the boundary of the surrounding air and the control volume containing the bird.

The shockwave speed is not a static material constant, but rather depends of the impact velocity. Thus,

\[ U_s = f(U_0) \]  \hspace{1cm} (2.4)

Wilbeck estimated the shockwave speed using the linear Hugoniot equation, written as

\[ U_s = c_0 + kU_0 \]  \hspace{1cm} (2.5)

where \( c_0 \) is the speed of sound in the undisturbed material (prior to impact-induced material property changes, such as density, that affect wave speed) and \( k \) is a material compressibility coefficient. The latter value is defined as

\[ k = \frac{\rho}{\rho - \rho_0} \]  \hspace{1cm} (2.6)

where \( \rho \) is the average density of the compressed (or shocked) material, and \( \rho_0 \) is the initial density [12]. Because the compressed density is difficult to measure, \( k \) values are often determined from experiments and tabulated. For moderate impact velocities involved in aircraft impact, \( k \) is approximately equal to 2 for water and biological materials, including birds [12, 13].

Pressure release waves force the fluidic matter away from the bird center, while the shock pressure decays to a lower steady pressure [8]. This steady pressure, \( P_s \), is defined by
\[ P_s = \frac{1}{2} \rho_0 U_0^2. \] (2.7)

The theoretical duration of the impact event is the time it takes for the end of the bird to reach the target. Since the post shock gelatin like material can be considered incompressible, its speed does not decrease significantly throughout the remainder of the impact. Therefore, the initial velocity may be used to estimate the impact window as

\[ T = \frac{L}{U_0}, \] (2.8)

where \( L \) is the length of the bird and \( U_0 \) is the initial bird velocity.

2.2. Bird Modeling

With the advancement of FE codes and computational resources in the late 1970’s and 1980’s, simplified numerical analyses of bird impact on jet engine structures became feasible. Ever since these early studies, the vast majority of methods developed over the years have employed 3-D dynamic nonlinear explicit finite element analysis (FEA). Therefore, unless otherwise noted, the approaches discussed in this chapter for modeling the bird and engine structures rely on this computational framework.

2.2.1. Pressure Load Model

Limitations in computational resources available to early investigators necessitated gross simplifications for the bird model. Storace et al. [14] considered impact on a static metal fan blade by representing the bird with a time-varying pressure load acting on an “impact footprint” over to the blade’s surface. The loads approximated the hydrodynamic pressure-history data observed in experiments of birds impacting thick metal plates [6,8]. Similar methods were used by Engblom [15] and Nimmer et al. [16].
These approaches were successful for limited studies of individual blades, but there is no evidence that this approach was extended to the analysis of multiple blades. Also, it is questionable how well this approach could perform for rotating impact cases considering the complex spread and secondary impact of bird material.

As computational resources and code efficiency improved, investigators began to actually model the bird in the FE simulation using a variety of numerical methods.

2.2.2. Finite Element Model

The four primary FE approaches found in the literature are (1) Lagrangian, (2) Eulerian, (3) Arbitrary Lagrangian-Eulerian (ALE), and (4) meshless Lagrangian approach. The diagrams in Fig. 2-4 demonstrate how each method represents a soft object impacting a much stiffer structure. The meshless method typically employed is the Smoothed Particle Hydrodynamics (SPH) approach due to its wider availability in commercial FE codes, although others methods do exist [17].
2.2.2.1. Lagrangian

The Lagrangian FE approach represents a body using interconnected elements and nodes whose positions move with the material. The Lagrangian description of motion allows for easy tracking of object boundaries as nodal positions exactly match the location of corresponding material. This is appropriate for impact problems where accurate determination of the point of contact is critical.

Several investigators have modeled the bird using the Lagrangian approach. Niering [18] impacted a fixed metal fan blade with a Lagrangian bird. Vasko [19] managed to model a Lagrangian bird impacting an array of titanium fan blades using several separate bird portions corresponding to how the bird would be sliced by the fan blades. Yupu [20, 21] also managed to model bird impact on an array of fan blades.

A penalty-based contact algorithm is a common method of capturing interactions between Lagrangian parts. In this approach, the positions of nodes on the “slave” part are tracked relative to elements on the “master” part. If a slave node penetrates a master element, a spring-like force...
is applied to the slave node until the penetration is removed. A net equal force is also applied to all of the nodes belonging to the master element (see Fig. 2-5).

![Fig. 2-5. Penalty-based contact approach.](image)

The primary disadvantage of the Lagrangian approach is heavy element distortion due to the large deformations experienced by the soft impactor. Element distortion can lead to severe hourglassing, inaccurate results, contact difficulties, long analysis times, inverted elements, and error termination.

Ad hoc numerical techniques, such as element deletion, are required to model failure and allow portions of a body to separate, such as when a bird is broken into disjoint pieces by blade slicing. Element deletion can remove significant mass from the problem and induce nonphysical pressure oscillations during contact with an eroding part. Sometimes, the element mass is transferred to the nodes, and eroded nodes are maintained in the problem to continue interacting with the structure and conserve mass [22-24].

**2.2.2.2. Eulerian**

The Eulerian approach avoids issues of mesh distortion by utilizing a fixed mesh that carpets the entire bird trajectory. Material motion is tracked by calculating mass flux across elements. The resulting volume fraction of material in each element is determined at each time step. This technique is well-suited for problems involving large deformation. In addition, material separation can be effectively captured without the need for ad hoc techniques such as element
Solid structures are most often modeled using the Lagrangian approach, requiring a Coupled Eulerian-Lagrangian (CEL) technique if an Eulerian bird is used. Studies employing the Eulerian method often use a fixed grid, containing the bird model, surrounding a rotating Lagrangian fan assembly that the fan blades pass through. The CEL algorithm is activated when the bird nears the blades. Some studies have used a uniform mesh throughout the space [25, 26], while others tailored the mesh around the fan blades to promote accurate bird/blade interaction [27].

The computational cost of the fixed-grid Eulerian approach is very high for events occurring over a large space or where the projectile path is not well-known a priori, requiring a large grid to cover the entire space. In addition, a fine mesh must be used throughout the entire volume to accurately estimate material location and boundaries. Even with these measures, issues still arise with numerical dissipation, mass dispersion, and inaccurate contact prediction.

2.2.2.3. Arbitrary Lagrangian-Eulerian (ALE)

The ALE finite element approach combines aspects of both the pure Lagrangian and pure Eulerian methods by employing both a deformable mesh and material movement through the grid. The mesh can move with the bulk of the material and may deform with the body in order to track material motion as it expands.

The ALE method operates similarly to the Eulerian algorithm while improving upon some of its shortcomings. A moving mesh eliminates the need for a grid covering the entire projectile path, thereby requiring fewer total elements and significantly reducing computational cost. This also allows a higher mesh density within the ALE space, which improves contact behavior and reduces numerical dispersion effects. The ALE approach also avoids issues associated with the pure Lagrangian approach, namely element distortion difficulties and the need for ad hoc techniques, such as element deletion, to represent material failure.
Several authors have used a moving, non-deforming ALE grid that follows the rotation of the fan assembly. This domain may either completely surround the fan assembly [25], or the grid may only surround those fan blades where direct bird contact is expected. Other researchers have used a moving, deformable grid that tracks the center of mass of the bird and stretches to track most of the deformed material as it passes through the fan assembly [11].

It has been noted by several researchers that the pure Eulerian approach may produce less accurate results than the ALE approach while also incurring higher (often prohibitive) computational cost [28]. Olovsson and Souli [29] found that the deformable quality of the ALE mesh reduced mass flux across element boundaries as the bird deformed compared to the pure Eulerian approach. This reduced energy losses in the numerical model and allowed for a smaller element size without overloading computational resources. Most modern studies of bird impact appear to employ the ALE approach over the pure Eulerian method.

2.2.2.4. Smoothed Particle Hydrodynamics (SPH)

The SPH approach is a Lagrangian method that utilizes interactive particles to represent a body without the use of a structured mesh. The particle interactions encapsulate the material properties, and the particles move with the material. This Lagrangian description of motion allows easy tracking of material for impact contact. In addition, the particles can move far away from one another and even separate to the point that they no longer interact, allowing large deformations and material failure to be effectively captured.

Many researchers have taken advantage of the SPH method to model bird impact onto fan blades. Some have modeled a static, pre-stressed set of fan blades impacted by a bird, demonstrating the effectiveness of SPH in capturing the spread of bird material [30]. Others have shown that impact on a rotating array of blades or full fan assembly can be accurately captured with an SPH bird model [31-33].
The SPH approach is somewhat computationally expensive since the particle interaction distance and local particle interactivity are updated with each time step. Also, numerical instabilities inherent to the SPH formulation can occur as particles separate from one another, requiring numerical corrections that may add non-physical energy to the problem (see Chapter 4.2.3). Another issue is that the exact boundary of a modeled body is loosely represented by the smoothing length of the particles rather than being specifically defined by element surfaces, as in the Lagrangian approach.

Numerous studies have been performed analyzing the comparative strengths and weaknesses of Lagrangian, ALE, and SPH bird modeling, and different studies have found each of the approaches to be most accurate for certain applications [31, 34-37]. While seemingly more intensive computationally to analyze, ALE and SPH typically require less analysis time than the Lagrangian approach since element distortion in the latter method severely reduces the time step upon impact. In contrast, the SPH time step remains constant throughout the simulation regardless of the extent of particle displacement [28]. It is generally agreed that the SPH method requires less computing time than the ALE approach, but debate over which method is most accurate drives researchers to use both approaches.

2.2.3. Representative Geometry

The hemi-spherically capped cylinder geometry settled upon by Wilbeck (see Chapter 3.2) has been adopted for numerous FEA studies of bird ingestion. Other geometries, such as regular cylindrical, ellipsoidal, and spherical configurations have also been employed. In addition, some researchers have explored the merits of explicitly modeling the bird structures, such as distinct head, neck, and wing portions, for their effects on the pressure-time history response, change in structural response, and for comparison with experimental data. These geometries, and their approximate level of relative use in bird strike modeling, are shown in Fig. 2-6.
Fig. 2-6. Geometries commonly adopted for bird impact simulations.

Many studies have explored the effect of the representative geometry on the measured pressure when the bird impacts a relatively rigid target [38]. Others have explored the effects of the bird geometry on the normalized impact force on fan blade structures directly [1, 39]. These studies have concluded that the hemi-spherically capped cylinder shape produces the most accurate results. However, due to the significance of other parameters, such as material modeling and FE approach, which were not concurrently investigated, these studies cannot be considered definitive.

Most researchers have adopted the hemi-spherically capped cylinder or pure cylindrical geometry. In addition to studies indicating that these shapes can give adequate results, other reasons for adopting these shapes are for comparison with impact experiments in the literature (such as Wilbeck), geometric symmetry, and their relative simplicity to define in a finite element pre-processor (versus an ellipsoidal or realistic bird geometry).

2.2.4. Material Model

A simple fluid material model, referred to as the “null” model, has often been employed which only considers volumetric stiffness, hydrostatic stress (pressure), and viscous shearing,
while ignoring shear stiffness [11, 31, 34, 40, 41]. Deviatoric stresses are calculated purely as a function of strain rate if fluid viscosity is modeled. An elastic-plastic-hydrodynamic material model with extremely low shear stiffness has also been used, but with limited success [23]. Bird material properties are commonly derived from water with adjustments for porosity within the bird.

An equation of state (EOS) is often coupled with the material model either out of necessity (such as the null model) or to override the hydrostatic pressure calculations of the material model. This EOS relates the volumetric change of the object to hydrostatic pressure within the body. A linear polynomial equation with coefficients derived from linear Hugoniot relations [42], the Mie-Gruneisen equation [43], and other formulations [38] have all been employed to try to accurately reproduce the pressure-history profile of bird impact experiments. The EOS input parameters have string effect on the result, and the effective density of the bird is often adjusted to obtain an accurate result [44].

The null material model appears to be the most favored choice. While there are some other material models in commercial FE codes that could be applied, it appears that there are few appropriate fluid modeling options [45]. However, the null model produces adequate results when properly calibrated [11, 34]. The linear polynomial equation is the most popular EOS, and it has been reported that it produces better results than alternatives, such as the Mie-Gruneisen relation [38].

2.2.5. Other Physical and Numerical Parameters

Shmotin [32] modeled both Lagrangian and SPH birds impacting a fan assembly and explored the effect that friction has in the bird/blade contact. He concluded that zero friction produced the best correlation with experimental data.

Several parameters inherent to the numerical nature of the analyses are critical in determining
the final result. For an FE analysis, these include the choice of element formulation, hourglass control, bulk viscosity (important for the smoothing of shock discontinuities in the FE analysis), damping, and contact treatment. While these factors may be mentioned in passing, studies dedicated to quantifying their effect on the bird or the structure were not found in the literature.

2.3. Engine Impact Modeling

The forward section has been modeled with varying degrees of complexity for capturing the effects of bird strike. The choice of which components to include, from the fan blades to the casing, has played a critical role in determining the level of detail and the conclusions that can be drawn from an analysis.

2.3.1. Engine Components

Several investigators have modeled a single fan blade impacted by a bird in order to capture the blade’s independent response [1, 39, 46]. This was especially common in early studies when computational resources and modeling capabilities were limited. The primary goal of most of these studies was to match experimental results for impact on a single blade, compare the blade response for different bird models, or demonstrate viability of a blade or bird modeling method.

Others have modeled an array of fan blades, typically three or more, in order to capture bird impact across multiple points or interactions among blades [21, 30, 47]. Some of these studies modeled the motion of the blade(s), while others held them fixed at their bases and captured the correct relative bird/blade velocity through the bird motion.

A number of investigators have modeled half or the entire fan assembly in order to more realistically capture multiple fan blade interactions [19, 32, 33]. The fan assembly rotated with an initial velocity corresponding to the engine operating speed. Interactions between blades were usually captured as well [26]. These studies allowed the full range of initial bird impact damage to the fan assembly to be evaluated, along with additional damage from subsequent inter-blade
collisions.

The axle is rarely modeled in a bird strike analysis; most approaches rotate the fan assembly about a rigid axis. When included, the axle is able to deform as a result of the impact event and out-of-balance forces. The primary advantage is the ability to capture fan assembly unbalancing and the beginning of the vibratory response of the engine if blade loss occurs [48, 49].

It is also very rare for the casing to be included in a bird impact modeling strategy. However, models of “blade-out” events, in which a portion or an entire fan blade becomes detached from the hub and impacts the casing, frequently include both the casing and the axle [49-51]. The inclusion of the casing allows both impact damage and fan tip shearing to be captured [52, 53].

Very few researchers have extended their analysis to the compressor section. In one example, Frischbier [25] modeled the fan and low pressure compressor (LPC) inlet to estimate the amount of bird material entering the engine core. The measured mass was then used in a second analysis to estimate damage to the high pressure compressor (HPC) final stage blades. While this is an important consideration, this work has focused on predicting failure of the fan assembly where hard debris may be produced that could also be ingested by the engine core.

2.3.2. Hybrid/Composite Fan Blades

Fan blades incorporating composite materials have only recently become a practical and certifiable option for commercial aviation. As a result, the majority of studies found in the literature only consider modeling impact damage to solid or hollow metal fan blades. These analyses typically utilize material models incorporating plastic yield behavior and ductile failure criteria. Research into the use of composite fan blades has driven modern numerical studies for modeling impact upon these structures.

Several numerical studies have been conducted for bird strike upon a single stationary composite blade. Nishikawa [54] investigated the effectiveness of a composite material model to
capture the transition in damage modes from global bending, which induces matrix failure, to local shear perforation, corresponding to fiber failure, with increasing impact velocity. In addition, some analyses have included full composite fan assemblies subject to impact. Zammit et al. [31] compared bird impact on a composite fan assembly using both ALE and SPH bird models, observing lower impact forces with the ALE model yet greater fan assembly damage than the SPH model.

These above studies used composite material models incorporating fiber and matrix failure criteria, predicting progressive damage and final brittle failure of the part. Composite failure models typically use the state of stress and material properties of a ply to estimate damage (see Chapter 7.2).

In addition, micromechanics-based material models have also been used in the modeling of blade impact damage. In an early study, Chamis [55] couple a micromechanics code with an explicit FE code to predict fiber and matrix stress due to impact on a hybrid fan blade, obtaining reasonable results compared with experiments. Currently, micromechanics models are not readily available in many commercial FE codes, but can be incorporated though user-defined material models.

2.3.3. Fan Blade Pre-Stressing

It has been recognized since early studies that blades are pre-stressed due to rotation prior to impact, and centripetal loads must be applied to accurately assess the initial stress state in the blades [1, 18, 46]. Pre-loading is especially important in a dynamic analysis in which the fan blades are rotating. Without proper pre-loading, the instantaneous rotation will induce large, unrealistic loads (called “centrifugal shocks” [18]) in the blades prior to impact that are difficult to mitigate. Pre-loads are typically applied in a separate step before the impact analysis, using either an implicit static FE analysis or explicit dynamic relaxation FE scheme.
2.3.4. A Note About Air Flow Modeling

As air passes through the fan assembly, complex aerodynamic loads are exerted that vary across each blade. These loads are smaller than the centripetal forces, but nevertheless contribute to the total stress state of the blades. In addition, air flow is responsible for drawing bird material and detached blade fragments into the engine core or out through the bypass.

This complex fluid-structure interaction (FSI) is very challenging to model, particularly for 3-D, time-dependent problems involving complex geometries. In the literature, several approaches are found using coupled FE/CFD solutions [56, 57]. These methods are extremely computationally expensive, even for simple problems, and their efficacy has not yet been fully demonstrated [58]. In addition, these approaches do not typically incorporate material failure; in fact, the author has found no method in the literature for effectively capturing progressive material failure and the resulting fluid flow changes in a fully coupled solution.

In an alternative approach, Zammit et al. [31] attempted to include air flow effects by approximating the aerodynamic pressures on a fan blade during steady engine operation. Both aerodynamic and centripetal loads were applied to a composite blade model before impact with an SPH bird. This approach provided a more realistic approximation of the forces on the blade and lead to a reasonable estimate of damage throughout the composite blade. However, this technique may cause unrealistic behavior when failure occurs if the aerodynamic loads are not removed. For instance, upon failure, detached fragments will move toward the front of the engine rather than being swept downstream toward the rear.

In the absence of robust physics-based approaches, ad hoc numerical schemes have also been proposed for capturing air flow effects. Carney [49] employed global mass damping to the problem at the beginning of the dynamic simulation to approximate drag forces on the blades. This technique only roughly approximates aerodynamic loads, and it does not appear to have
been thoroughly studied.

While pressures due to flow over the fan blades would be most accurately resolved using a coupled FEA/CFD approach, the computational cost may be prohibitively high for large problems. Alternative simplified methods, such as the approaches by Zammit et al. and Carney described above, have not had their efficacy thoroughly verified and are likely inadequate.

2.4. Loading on Engine Structures

Loading on the blades occurs as a result of the high relative velocity between the bird and the rotating fan assembly. The two velocity components that determine the relative velocity are the (1) velocity of the incoming bird relative to the aircraft and (2) the linear velocity of the rotating fan blade at the point of impact. The first component can be approximated by the translational velocity of the aircraft. Because FOD most often occurs during takeoff or landing, the corresponding takeoff and landing speeds of the aircraft are suitable input values.

The second velocity component can be estimated using the equation

\[ v = 2\pi \omega r \quad (2.9) \]

The relative velocity varies along the length of the blade as the radius, \( r \), increases from the hub to the blade tip, as shown in Eq. (2.9). Consequently, impact with the blade tip will induce the highest impact forces.

Typical parameters for modern high-bypass ratio turbofan engines incorporating composite structures are given in Table 2-1. An analysis of the impact velocity using these values is shown in Fig. 2-7.
Table 2-1. Typical high-bypass ratio engine parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fan rotational velocity, ( \omega ) (rpm)</td>
<td>2550</td>
</tr>
<tr>
<td>Inner hub radius, ( r_i ) (m)</td>
<td>0.40</td>
</tr>
<tr>
<td>Mid-span radius, ( r_m ) (m)</td>
<td>0.94</td>
</tr>
<tr>
<td>Outer tip radius, ( r_o ) (m)</td>
<td>1.48</td>
</tr>
<tr>
<td>Aircraft takeoff speed, ( v_{\text{takeoff}} ) (m/s)</td>
<td>100</td>
</tr>
</tbody>
</table>

The velocities encountered lie in a transition region of the impact regime for composite structures in which both the local response and the larger global response of the structure are equally significant to capture [59]. Local damage may occur near the point of contact due to high impact loads, or it may occur away from the impact location, such as the blade root, due to global bending.

Goldberg [60] has shown that strain rate plays a significant role on CFRP composite material behavior, with higher rates leading to increased overall strength and stiffness. Isolated tests of the fiber properties show a mostly linear response up to the point of failure [61]. Therefore, ply- and laminate-level nonlinearity is attributed to the matrix contribution to the overall properties.

External loads acting on a fan blade impacted by a bird are shown in Fig. 2-8. Centripetal
loads are present throughout each blade prior to impact. The blade that first impacts the bird is subjected to high impact forces on the leading edge. Bird material will continue to flow over the blade and induce additional impact/pressure loads across its surface, expanding nonlinearly. If fan assembly unbalancing occurs, blades located opposite of the impact zone will be brought into contact with the casing, leading to forces that act normal to the edge, down the length of the blade, and shear loads on the blade tip.

If a portion of the blade fails, fragments will travel radially and impact the fan casing normal to its interior surface (Fig. 2-9). Shear contact with fan blades due to assembly unbalancing will lead to the creation of normal and shear stress fields.
All rotating components, including the fan blades and axle, will be subjected to centripetal loading. The axle may also experience bending loads as a result of out-of-balance forces in the fan assembly (Fig. 2-10). Forces on the axle also translate to forces on the bearings and other engine structures.

### 2.5. Remarks

Based on the review of the available literature, several conclusions can be drawn about bird ingestion analysis. Despite the number of studies aimed at developing optimal bird models for impact simulations, many factors are left unexplored. With only a few exceptions, there is no agreed upon best practice for bird modeling, and each new study must explore modeling
techniques for accurately capturing the bird strike event.

Lagrangian bird models can accurately capture the initial impact force imparted onto the structure by the bird. However, the accuracy of the method breaks down soon after the initial impact as large deformation occurs. Therefore, this method is not preferred. The ALE and SPH approaches can produce accurate results while easily capturing large deformation, and thus both are used. Issues with these methods include computational cost, ensuring proper contact coupling between the bird and the structure, and energy losses.

Modern forward section modeling employs a dynamic analysis where the motion of rotating engine components is explicitly captured. A static pre-loading phase is always used to initialize stresses and deformations in the rotating fan blades. However, the choice of which engine components to model in the analysis range from a single fan blade to the entire fan assembly, casing, and supporting structures.

The analysis of metal fan blades, other forward section components, and techniques used in these studies can be examined for their suitability in the analysis of composite fan blades and casings. However, there are only a small number of studies in the open literature of impact upon entire composite fan assemblies for capturing the full dynamic response. In addition, most bird impact studies assume the blade/casing interaction is minimal and do not aim to capture additional damage exerted onto the blades and casing from such impacts.
3. PROBLEM ANALYSIS

In this chapter, the physical and computational complexities of modeling bird strike on a jet engine incorporating hybrid structures, and the challenges that they present, are examined. Subsequently, a strategy is outlined for forming the comprehensive crashworthiness methodology.

3.1. Problem Complexities

The task of modeling the response and subsequent structural damage due to high velocity impact is very complex even for simple structures. The disturbed environment in which a damaged jet engine operates introduces yet more variables and physical phenomena that can contribute to the operation and further damage to the system.

3.1.1. Physical Complexities

Different aspects of the physics involved in bird strike onto an engine forward section incorporating hybrid structures are listed below. This list is by no means exhaustive, but highlights the most prominent physical phenomena in the problem.

a) Structural impact dynamics

b) Fiber-reinforced laminated composite mechanics

c) Soft impact mechanics

d) Composite damage and failure

e) Strain-rate dependent material behavior

f) Fluid-structure interaction (FSI)

Several of these phenomena, such as (a) and (b) above, have well-established theoretical bases, and related problems have recognized engineering solutions. Methods for predicting the dynamic impact response of a structure are widely available, at least for the elastic or elastic-plastic material regime with moderate deflections, and include analytical solutions for simple
structures. For thin composite structures, laminated plate theory and simple techniques for estimating orthotropic material properties provide good estimates for the structural response when failure is not present [61].

For other phenomena, namely (c) through (f) above, accurate solution approaches with wide acceptance are still the subject of ongoing investigation. The soft impact theory developed by Wilbeck (see Chapter 2.1) does not always match well with experiments, and adjustments are often made to the analytical solution input parameters, such as bird mass density, to achieve better correlation with impact data [7, 44]. Composite damage modeling techniques have been researched extensively for many years, resulting in numerous failure criteria [62, 63]. Despite these efforts, the complex behaviors of composites, such as failure at multiple length scales and sensitivity to impact loading, still present huge challenges to the development of an accurate, validated approach for predicting and representing damage in composites [64, 65]. Strain-rate dependent material models, especially for composites, are empirical in nature, and developments are challenged by temporally multi-scale effects in materials and the limits of experiments to capture critical details over the short duration impact window [66].

3.1.2. Numerical Complexities

In addition to the challenges posed by the physics of the problem, the nature of the numerical solution presents particular difficulties that must be considered as well. Modeling complexities associated with predicting damage and failure in a structural-hybrid jet engine subject to soft impact include the following:

a) 3-D, time-dependent impact analysis

Numerical codes for solving 3-D, non-linear, time-dependent impact problems have existed since the 1970’s. Most codes are based on explicit FEA. Time is discretized, and the problem must be solved progressively at finite time steps. For impact problems, the time step must be on
the order of 1 $\mu s$ or smaller to capture critical dynamic affects, such as stress wave propagation, which influence the structural response. Despite the efficiency of explicit FEA codes, the large number of solution steps required often limits the total simulation time to around 1 second or less for large problems. Therefore, only the impact event, usually on the order or 1-3 $ms$, and its immediate aftereffects can be reasonably analyzed in a time-dependent analysis.

b) Nonlinear numerical analysis

Nonlinearity is inherent to several aspects of impact simulations. Material models will necessarily include some form of nonlinearity in the stress-strain behavior, such as a lower stiffness after yielding or complete loss of stiffness at failure. Boundary conditions are highly nonlinear as contact continually changes between parts impacting at high velocity. Geometric nonlinearity must also be captured as structures undergo large deformation [67, 68].

Nonlinear numerical solutions require iterative routines that are variations of approximate solution techniques, such as the well-known Newton-Raphson method or alternatives like Broyden’s method [69]. These solutions can be sensitive to slight changes in problem parameters and initial conditions, hence the consistency of their results must be verified. For FE problems, the meshing scheme and initial conditions of elements and nodes are critical numerical parameters [69]. Since the aim is to accurately approximate a real problem through the underlying physics, it must be shown that these numerical parameters do not dominate the results. Therefore, investigations must check for the effects of such numerical variations and uncertainties in order to show their minimal effect on the solution.

As an example, mesh refinement, or convergence, studies should be conducted. First, the number of elements used in a problem, either globally or locally, can be increased to show that a sufficient level of detail is captured. This approached is referred to as $h$-refinement [67]. Second,
the number and position of the elements can be kept constant while the polynomial order of the element basis functions is progressively increased. For instance, first-order elements have constant stress throughout, while second- and third-order elements have linear and quadratic stress variation, allowing more detail of the problem to be captured across a single element. This is the $p$-refinement technique [67]. Lastly, the number of elements can be kept the same while nodal positions are changed to capture more detail around critical regions and observe the effect of different meshing configurations on the final solution. This is referred to as $r$-refinement [67]. When these mesh variation studies are automated with convergence criteria in a code, they are called $h$-, $p$-, and $r$-adaptive techniques [70]. At least one of these studies should be conducted, if not several, to verify that a solution is mesh-independent.

Several other numerical modeling choices can have a profound impact on a nonlinear FE solution, leading to uncertainties in the solution accuracy. The underlying mathematical formulation governing the behavior of each element is based on particular assumptions for the physical behavior of the structure being modeled [69]. For instance, some shell element formulations are based on Kirchhoff plate theory, which ignores out-of-plane shear deformation effects, while others employ first-order shear deformation plate theory. This difference could have major implications depending on the loads and deformations to which the structure is subjected. In addition, the choice of fully-integrated versus reduced-integration elements and the number of nodes per element affect the stiffness response of the element [67], and results, where these parameters are changed, can be drastically different.

The approximate representation of curved surfaces and boundaries using elements with flat edges and a linear polynomial function also introduce uncertainty, and small changes in the mesh for representing tight spaces can quickly change the solution [67]. A first order element may be
insufficient for capturing the necessary physics of a problem, requiring higher order elements. Mathematical round-off errors can also occur when using single precision calculations, extreme mesh transitions, and multiple materials with very different stiffness. Round-off errors induce non-physical effects that quickly propagate throughout a nonlinear solution \[67\].

Application of a crashworthiness assessment methodology in industry requires detailed quantification of the errors and inaccuracies of the results obtained and must implement measures to minimize sources of uncertainty. The specific goal of this study was to develop bridging methods that were devised for scattered structural techniques for small problems that were then brought together in a comprehensive methodology (with added complimenting features) to address the full system-sized problem of bird impact on complex advanced engine forward section. This is a major step forward towards facilitating the design and certification of future advanced propulsion designs. However, each bridging method requires a detailed assessment of the uncertainties present. Addressing sources of uncertainty stemming from the highly nonlinear analyses is the subject of future studies prior to adoption of the complete methodology as a validated industry design tool.

c) Multi-stage analysis

Multiple problem stages occur consecutively and with different loading conditions on the forward section. This work aims to capture the bird impact and short-term damage growth for a forward section. Pre-stressing of the fan blades must be included as well. This is best treated with a static analysis approach. In contrast, the bird impact and damage growth stages require a dynamic analysis, indicating that a static-to-dynamic method is needed. Care must be taken to ensure that the static analysis is converged before initiating the dynamic phase; otherwise, unrealistic behavior may be observed, such as large instantaneous loads and centripetal shocks.
3.2. Problem Approach

Experimental results for bird impact onto metal fan assemblies and other forward section structures composed primarily of metals are available in the open literature. However, experimental data for bird impact onto engine forward sections incorporating hybrid and composite structures is extremely limited.

Therefore, it was decided to develop a crashworthiness methodology by examining theoretical aspects and modeling strategies for separate aspects of the impact problem. Then, the developed methods were combined, and a comprehensive strategy was formed that can fully address the multi-faceted problem.

Due to the complexity of the bird strike event, a large variety of sub-problems could be investigated. The approaches and validations that were explored for this work were:

1. Bird impactor fluidic behavior
2. Forward section dynamic impact analysis
3. Composite ply damage and inter-ply delamination
4. Hybrid structure metal/composite de-bonding
In this work, FSI considerations for the influence of air on the forward section have not been included. Future work will aim to develop complementary methods for incorporating the effects of air disturbances on the dynamic impact analysis.
4. FUNDAMENTAL FORMULATIONS

This chapter outlines the mathematical bases for the analytical tools used in this work. Specifically, the mathematical basis for the explicit FE code utilized, the governing equations of the particle method used to represent the bird, and laminate theory for modeling composite structural behavior are reviewed.

4.1. Numerical Impact Analysis

FEA for impact problems involves special consideration for the finite element formulation, solution strategy, and ad hoc numerical techniques employed to capture the essential physics of the problem in a computationally stable and efficient manner. This section presents the underlying physical and mathematical principles governing the numerical method at the heart of the hybrid engine impact analysis methodology.

4.1.1. Governing Equations

For impact problems, the physical principle of most interest is the conservation of moment. The classical equation for conservation of linear momentum is

\[ \nabla \cdot \sigma_{ij} + \rho f_i = \rho \frac{dv_i}{dt}, \]  

(4.1)

where \( \nabla \) is the spatial divergence operator (3-D del operator) acting on \( \sigma_{ij} \), the 3-D stress tensor, \( f_i \) is the body force density, \( \rho \) is the current mass density, and \( v_i \) is the velocity vector.

As indicated by the del operator \( \nabla = \frac{\partial}{\partial x} + \frac{\partial}{\partial y} + \frac{\partial}{\partial z} \), the problem is a third-order partial differential equation, and the following three boundary conditions must be satisfied:

1. **Traction boundary condition on \( \Gamma_1 \):**

   \[ \sigma_{ij}n_i = t_i \]  

   (4.2)

2. **Displacement boundary condition on \( \Gamma_2 \):**

   \[ x_i(X_i,t) = D_i(t) \]  

   (4.3)
3. **Contact discontinuity boundary condition on \( \Gamma_3 \):**

\[
(\sigma^+_{ij} - \sigma^-_{ij})n_i = 0 \tag{4.4}
\]

Another elementary but important principle is conservation of mass, stated as

\[
\rho V = \rho_0 , \tag{4.5}
\]

where \( V \) is the relative volume and \( \rho_0 \) is the original mass density. Lastly, conservation of energy must also be satisfied, expressed as

\[
\dot{E} = Vs_{ij}\dot{\varepsilon}_{ij} - (p + q)V, \tag{4.6}
\]

where \( \dot{\varepsilon}_{ij} \) is the strain rate and stress has been decomposed into deviatoric stress, \( s_{ij} \), and hydrostatic pressure, \( p \). Bulk viscosity, \( q \), is a numerical pressure used to address shockwaves and is discussed more in section 4.1.5.

### 4.1.2. Finite Element Method

Finite element methods involve two main steps: (1) development of the weak form of the governing equations and (2) discretization of the problem domain.

#### 4.1.2.1. Weak Formulation

First, the momentum equation above is expressed as a homogenous equation. Each term is multiplied by the test function, \( \phi_i(x) \), and then integrated over the problem domain (the volume, \( V \), in this 3-D case). The resulting equation is

\[
\int_V \phi_i(\rho \dot{v}_i) dV - \int_V \phi_i(\nabla \cdot \sigma_{ij}) dV - \int_V \phi_i(\rho f_i) dV = 0. \tag{4.7}
\]

After performing several mathematical operations and substituting in the boundary conditions, Eq. (4.7) becomes
Each expression represents forces on the body. The description of each of these forces is listed below each term. After finding total acceleration force, the body’s mass can be used to determine its acceleration. In the next section, the body will be discretized into a finite number of connected masses, and the acceleration of each individual mass will be calculated.

4.1.2.2. Domain Discretization

To discretize the problem domain, a finite number of elements, \( m \), connected by a number of nodes, \( n \), is defined. The test function and trial solution for the velocity are expressed as

\[
v_i(x, t) = \sum_{l=1}^{n} v_i^l(t) \psi_i^l(x) = v_i^l \psi_i^l
\]

(4.9)

\[
\phi_i(x) = \sum_{k=1}^{n} c^k \psi_i^k(x) = c^k \psi_i^k
\]

(4.10)

Substituting back into Eq. (4.8), the following system of equations are derived:

\[
\dot{v}_i \left( \int \rho \psi_i^k \psi_i^l dV = \int \psi_i^k (\sigma_i \sigma_l n_l) d\Gamma + \int \psi_i^k (\rho f_i) dV - \int \sigma_i (\nabla \cdot \psi_i^k) dV \right)
\]

(4.11)

After choosing shape functions \( N_i^k \) and \( N_i^l \) over each element, corresponding to the basis functions \( \psi_i^k \) and \( \psi_i^l \), and building the global matrices and vectors, the resulting equation is

\[
Ma^n = P^n - F^n
\]

(4.12)

where \( M \) is the mass matrix, \( a^n \) is the nodal acceleration vector, \( P^n \) is the external force vector, and \( F^n \) is the internal force vector. The mass matrix is non-diagonal, meaning that the nodal
accelerations are coupled with the accelerations of other nearby nodes. \( F^n \) contains the element stiffness effects. The superscript \( n \) indicates that these vectors are time-varying.

### 4.1.3. Time Integration

To solve for the nodal accelerations, Eq. (4.12) is rearranged as

\[
a^n = M^{-1}(P^n - F^n)
\]

Once the accelerations are calculated, nodal velocities and displacements can be determined using finite difference approximations. The calculation for nodal velocities and displacements depends upon the time integration approach.

#### 4.1.3.1. Implicit Time Approach

In the fully implicit approach, the coupled system of equations in Eq. (4.13) is solved by inverting the mass matrix and carrying out the mathematical operations. The implicit approach is unconditionally stable, meaning that no numerical instability will occur as a result of the chosen time step. However, this does not guarantee that the solution will be accurate. If the time step is too large, important dynamic effects, such as wave propagation for impact problems, may be neglected. Without these effects, the predicted state of stress in a part will be extremely inaccurate, and useful conclusions about the part’s response and potential damage cannot be drawn from the analysis.

The primary disadvantage of the implicit approach is the high cost of inverting the mass matrix for solving a coupled system of equations. In order to capture dynamic effects in impact problems, the time step must be small, requiring repeated costly matrix inversions throughout the analysis. As a result, the implicit approach is typically not used for impact problems. However, some exceptions do exist, such as Noels et el. [71] who used a mixed implicit/explicit time integration scheme to simulate blade-out events.
4.1.3.2. Explicit Approach

In the explicit time integration approach, the mass matrix in Eq. (4.13) is lumped so that $M$ becomes a diagonal matrix. Numerous methods exist for the diagonalization operation [68]. This makes $M$ arbitrary to invert and uncouples the system of equations so that the acceleration of each node can be calculated quickly and independently of other nodes. This makes the explicit time integration approach very computationally efficient.

The downside of the explicit approach is that it is conditionally stable, requiring each time step to be below a certain threshold in order for the solution to remain stable. This stable time step limit is dependent on the wave speed and smallest element dimension. For 3-D, nonlinear problems, the time step limit is estimated using a calculation such as

$$\Delta t_{max} = a \cdot \min \left\{ \frac{L_1}{c_1}, \frac{L_2}{c_2}, \frac{L_3}{c_3}, \ldots, \frac{L_m}{c_m} \right\},$$  \hspace{1cm} (4.14)

where $L_e$ is the characteristic element length (for shells, the smallest dimension), $c_e$ is the element sound speed, and $a$ is a scale factor typically lower than unity, such as 0.9, for stability.

Along with the time step, a time-stepping algorithm must be selected for determining nodal velocities and displacements and advancing the solution time. The explicit FE code employed the central difference method [68].

For problems such as those addressed in this work, stable time limits were on the order of $1\times10^{-6}$ s or smaller. Impact problems require a small time step in order to properly capture the dynamics of the problem. Therefore, the explicit approach is naturally suited for short-duration impact analysis.

4.1.4. Hourglass Control

Most FE codes tailored toward impact modeling use under-integrated elements as the default formulation. These elements are very stable in large deformations. However, they can be subject
to spurious deformation modes that do not contribute to the internal energy in an element. Therefore, these distortions are not resisted by the element, and non-physical deformation can occur. When a number of elements become subject to this non-physical deformation, the shape they adopt appears similar to an hourglass. Therefore, this effect is called “hourglassing”. Hourglassing for 1-point integration shell elements are shown in (Fig. 4-1).

![Fig. 4-1. Shell element hourglassing.](image)

Fully-integrated elements do not possess hourglass deformation modes. However, these elements can become unstable in large deformations and can greatly increase the computational cost of a simulation. For 4-node shell elements, switching from under-integrated to fully-integrated elements can increase the number of computations fourfold [72].

An alternative is to employ hourglass control measures in which artificial forces are applied that resist the spurious deformations in the under-integrated elements. These forces are added to the right hand side of Eq. (4.12) in the solution.

\[ Ma^n = P^n - F^n + H^n \]  \hspace{1cm} (4.15)

Hourglass control adds non-physical energy to the problem by performing work at the nodes. It is important to monitor how much hourglass energy is added to a problem. Hourglass energy should be kept to a minimum, consisting of 10% or less of the total internal energy in the simulation.
4.1.5. Artificial Bulk Viscosity

Shock waves occur when the difference in the wave speed within a compressed bulk of material causes a traveling pressure wave to steepen sharply as it propagates. This leads to a nearly discontinuous jump in pressure. Upon impact with an aircraft, the bird is subjected to very high pressures that cause a shock wave to form around the point of contact.

The presence of shock waves can cause numerical instabilities in an FE solution. Strong shock discontinuities can cause drastically different pressures, energies, and velocities in elements directly next to one another. This can cause instabilities in the underlying governing equations that induce unrealistic pressure oscillations [73].

To address this issue, an artificial viscous pressure term is added to the total pressure calculation that effectively smears the shock discontinuity across several elements. This eliminates the problem posed by sharp pressure gradients in adjacent elements [72, 73]. Artificial bulk viscosity is applied automatically in most modern explicit FE codes, and it is used in solid elements, SPH particles, and sometimes shell elements [62].

Shock wave treatment in this work is most important for the bird. The viscous pressure added to the SPH particle pressure calculation is

\[ \Pi_{ij} = \frac{1}{\rho_{ij}} \left( -\alpha \mu_{ij} \bar{c}_{ij} + \beta \mu_{ij}^2 \right) . \]  (4.16)

where \( \alpha \) is the linear bulk viscosity coefficient, \( \beta \) is the quadratic bulk viscosity coefficient, \( \bar{c}_{ij} \) is the sound speed, and \( \mu_{ij} \) is calculated from the particle velocity and distance from neighboring particles.

4.2. Smoothed Particle Hydrodynamics (SPH)

Meshless FE methods are particularly applicable for problems involving large deformations, such as fluid flow or high velocity impact. Other traditional FE approaches, such as the
Lagrangian and Eulerian techniques, experience stability issues and prohibitively high computational cost when modeling these problems (see section 2.2.2).

The SPH approach is a meshless method with the capability to model parts undergoing heavy deformation. In this method, an object is discretized into a finite number of discrete particles that interact with each other based on a range of influence unique to each particle. These interactions can be visualized as intermolecular forces that hold the particles together and give the object its structure and overall properties. Each particle experiences fluid forces based on the number of surrounding particles and an equation, called the kernel, defining the strength of their interaction based on their distance from one another [72]. Closer particles exert more influence than those that are farther away.

There are two major steps in implementing SPH: (1) the body must be represented as a cluster (lattice) of particles, then (2) a particle formulation that governs the particle interactions must be applied [74]. The first step, particle representation, can be achieved by any method that uses a part’s geometry to identify the space to fill with evenly spaced nodes. Each node represents a particle with physical properties such as mass, volume, and pressure.

The second step, particle formulation, is achieved by designating the behavior of each particle based on the kernel approximation and particle approximation described in the following sections.

4.2.1. Kernel Approximation

For a field variable, \( f(x) \), the SPH method calculates this as

\[
\langle f(x) \rangle = \int_{\Omega} f(x') W(x - x', h) \, dx',
\]

where \( \Omega \) is the domain containing \( x \), \( W \) is a ‘smoothing function’ specific to the meshless approach, \( h \) is the ‘smoothing length’, and \( x' \) is a variable of integration [74]. For a 3-D problem,
$dx'$ represents an infinitesimal volume. The bracketed form $\langle f(x) \rangle$ indicates that this is an approximation of the field variable rather than an exact solution.

The smoothing function, $W$, must satisfy the conditions given in Table 4-1. The variable $\kappa$ in the third row scales the smoothing length. Values outside the scaled smoothing length are equaled to zero. This condition is essential because it defines that only values within a local region will contribute to the approximation calculation [75]. A smoothing function will generally have a centrally peaked profile similar to that shown in Fig. 4-2.

### Table 4-1. Smoothing function conditions [74].

<table>
<thead>
<tr>
<th>Condition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\int_{\Omega} W(x - x', h)dx' = 1$</td>
<td>Unity condition</td>
</tr>
<tr>
<td>$\lim_{h \to 0} W(x - x', h) = \delta(x - x')$</td>
<td>Delta function property</td>
</tr>
<tr>
<td>$W(x - x', h) = 0$ when $</td>
<td>x - x'</td>
</tr>
</tbody>
</table>

![Fig. 4-2. Smoothing function calculation for particle $i$ based on the distance from particle $j$.](image)
4.2.2. Particle Approximation

In one common discretization, each particle $j$ is given a finite volume $V_j$ [74]. The term $dx'$ in Eq. (4.17) is then approximated by $\Delta V_j = m_j/\rho_j$. It is assumed that the field variable at a general location $x$ is restricted to particle locations. For a particle $i$, the particle approximation is written as

$$\langle f(x_i) \rangle = \sum_{j=1}^{N} f(x_j) W(x_i - x_j, h) \frac{m_j}{\rho_j}, \quad (4.18)$$

Therefore, the particle approximation converts the continuous Eq. (4.17) into a series of summations based on the number of particles within the scaled smoothing length $\kappa h$.

4.2.3. Kernel Function

A common kernel function is the cubic B-spline function defined by the equation

$$W(u, h) = \frac{c}{h} \begin{cases} 
1 - \frac{3}{2}u^2 + \frac{3}{4}u^3 & \text{for } |u| \leq 1 \\
\frac{1}{4}(2 - u)^3 & \text{for } 1 < |u| \leq 2 \\
0 & \text{for } |u| > 2
\end{cases}, \quad (4.19)$$

where $c$ is a normalizing constant and $u$ is the distance between the particle centers [74]. This particular kernel function was used in this work.

4.2.4. Tensile Instability

The above function has been shown to produce good results for a number of different applications. However, a mathematical instability occurs in the SPH formulation when particles have tensile strength as part of their behavior and are pulled away from one another in tension. This so-called tensile instability can result in blowup or clumping of the particles [74]. To combat this effect, numerical techniques are used, such as introducing artificial pressure that pushes clumped particles apart. This can add significant non-physical energy to the problem,
similar to the artificial energy added by hourglass control algorithms (see section 4.1.4). Therefore, it is important to monitor energy in the problem when using SPH and make modeling decisions that minimize non-physical energy gains or losses.

**4.2.5. Governing Navier-Stokes Equations for Fluid Formulation**

For fluidic objects, the particle behavior can be defined in terms of the Navier-Stokes (N-S) conservation equations, shown in Table 4-2. The superscripts $\alpha$, $\beta$, and $\gamma$ denote directions in a 3-D coordinate system. The particle approximations of the N-S equations are given in the right column of Table 4-2 [74].

<table>
<thead>
<tr>
<th>Conserved Quantity</th>
<th>N-S Conservation Equation</th>
<th>Particle Approximation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>( \frac{D\rho}{Dt} = -\rho \frac{\partial v^\beta}{\partial x^\beta} )</td>
<td>( \frac{D\rho_i}{Dt} = \sum_{j=1}^{N} m_j v_{ij}^\beta \cdot \frac{\partial W_{ij}}{\partial x_i^\beta} )</td>
</tr>
<tr>
<td>Momentum</td>
<td>( \frac{Dv^\alpha}{Dt} = \frac{1}{\rho} \frac{\partial \sigma_{\alpha \beta}}{\partial x^\beta} )</td>
<td>( \frac{Dv_{i}^{\alpha}}{Dt} = \sum_{j=1}^{N} m_j \left( \frac{\sigma_{\alpha i}^{\beta}}{\rho_i \rho_j} \cdot \frac{\partial W_{ij}}{\partial x_i^\beta} + \frac{\sigma_{\alpha j}^{\beta}}{\rho_i \rho_j} \cdot \frac{\partial W_{ji}}{\partial x_j^\beta} \right) )</td>
</tr>
<tr>
<td>Energy</td>
<td>( \frac{D e_{i}}{D t} = \frac{\sigma_{\alpha \beta}}{\rho} \frac{\partial v^\alpha}{\partial x^\beta} )</td>
<td>( \frac{D e_{i}}{D t} = \frac{1}{2} \sum_{j=1}^{N} m_j \left( \frac{p_i}{\rho_i^2} + \frac{p_j}{\rho_j^2} \right) v_{ij}^\beta \cdot \frac{\partial W_{ij}}{\partial x_i^\beta} + \frac{\mu_i}{2 \rho_i} \frac{\varepsilon_{ij}^{\alpha \beta}}{\varepsilon_i^{\alpha \beta}} )</td>
</tr>
</tbody>
</table>

For impact problems, the physical principle of most concern is the conservation of momentum. Therefore, the second line in Table 4-2 is very important to the accuracy of the SPH method. This formulation has been used successfully in previous studies of bird impact where the bird was modeled using SPH [76].

**4.3. Fiber-Reinforced Composite Analysis**

In this section, traditional micromechanics approaches for estimating individual ply properties are described. Next, laminated plate theories are presented that serve as the
macroscale model for composite structures. These laminated plate models form the basis for the shell finite element formulations and composite damage/failure theories discussed later in this work.

4.3.1. Anisotropic Material Properties

A key characteristic of FRP composite structures is that their behavior is highly anisotropic. The combined influence of multiple ply layers with various fiber layups and orientations allows for endless potential global properties. At the ply level, the properties of a unidirectional composite ply, in which all of the fibers are oriented in the same direction, are orthotropic. The fiber properties dominate in the longitudinal direction and the matrix properties dominate in the transverse directions (Fig. 4-3).

Several approaches exist for estimating the global properties of composites. If the fiber and matrix properties are known, a micromechanical model can be used to estimate the effective properties of each ply. Alternatively, the ply properties can be tested experimentally. Once the ply properties are known, a macromechanical model for the laminated plate can be used to estimate the global properties and evaluate deflections and stresses due to applied loads.
4.3.2. Classical Micromechanics Models

The behavior of composites at the structural level, with length scales typically in the centimeter to several meter range, depends on the mechanical properties and interactions of their constituent materials with dimensions at the micrometer length scale. Composite analysis is an inherently multiscale problem requiring distinct models for the constituent level, called the microscale, and the structural level, called the macroscale. The microscale model is used to estimate effective anisotropic material properties, which are then passed to the macroscale model. The macroscale model determines how a composite structure deforms and estimates effective stresses based on applied loads.

4.3.2.1. Strength-of-Materials Model

The strength-of-materials, or “rule-of-mixtures”, approach uses the mechanical properties of the fiber and matrix and their relative volume in the composite to estimate the effect that each constituent has on a ply’s properties. The contribution of each material is then combined to determine the effective ply properties, such as directional stiffnesses, Poisson’s ratios, and directional strengths. The stress and strain assumptions of this model are shown in Fig. 4-4.

![Diagram of Fiber and Matrix in Composite](Image)

**Fig. 4-4. Strength-of-materials model for fiber and matrix behavior.**

From these assumptions, expressions for the effective normal and shear properties of the material can be derived in terms of the fiber and matrix properties and the volume fraction of each in the ply. Several references exist for the derivation of these equations [61]. The in-plane
properties of a ply can be calculated using the following equations:

\[ E_1 = E_1^f V^f + E_1^m V^m \]  \hspace{1cm} (4.20)

\[ \nu_{12} = \nu_{12}^f V^f + \nu_{12}^m V^m \]  \hspace{1cm} (4.21)

\[ \frac{1}{E_2} = \frac{V^f}{E_2^f} + \frac{V^m}{E_2^m} \]  \hspace{1cm} (4.22)

\[ \frac{1}{G_{12}} = \frac{V^f}{G_{12}^f} + \frac{V^m}{G_{12}^m} \]  \hspace{1cm} (4.23)

### 4.3.2.2. Elasticity Models

The theory of elasticity and assumptions about the fiber and matrix shape and interaction can be used to derive ply-level properties. In contrast with the strength-of-materials model, elasticity solutions can account for the effects of fiber shape and inter-fiber interactions on the effective ply properties.

Several models are based on the Eshelby solution for a single ellipsoidal inclusion in an infinite domain, in which the inclusion is the fiber and the surrounding domain is the matrix. Another well-known elasticity-based solution is the Concentric Cylinders Model (CCM) that idealizes the fiber shape as an infinitely long cylinder surrounded by matrix material.

### 4.3.3. Classical Laminate Theory

In classical plate theory, the mechanical analysis of thin plates is reduced from a three-dimensional to a two-dimensional problem. A flat geometric mid-surface is used to represent the plate, and stresses and displacements are calculated about this mid-plane.

Classical lamination theory is an extension of classical plate theory that describes stresses and displacements throughout plates composed of layers of materials, with each layer potentially having unique anisotropic properties and orientations. Similar to plate theory, if the laminate
thickness is at least an order of magnitude smaller than the length and width dimensions and in-plane displacements are relatively small, then the use of classical lamination theory is valid. The same kinematic assumptions with additional constraints are made for perfect bonding between the plates with this theory.

The Kirchhoff hypothesis assumes the following for thin plates under deformation:

1. Straight lines normal to the mid-plane remain straight
2. Straight lines normal to the mid-plane remain normal
3. Plate thickness does not change

These principles are shown graphically in Fig. 4-6.

From these kinematic assumptions, strain-displacement relations can be derived, and a three-
A constitutive relation between the strains in a composite and the force and moment resultants can be expressed in matrix form as

\[
\begin{bmatrix} N_M \end{bmatrix} = \begin{bmatrix} A & B \end{bmatrix} \begin{bmatrix} \varepsilon^0_k \end{bmatrix}.
\]

The matrix at the heart of Eq. (4.27) is the classical ABD matrix. The inverse form of this matrix allows the in-plane strains at the reference mid-plane surface to be expressed in terms of
known forces and moments.

\[
\begin{bmatrix}
\varepsilon^0 \\
\kappa^0
\end{bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix}^{-1} \begin{bmatrix} N \\ M \end{bmatrix} \quad (4.28)
\]

The strain-displacement relations allow the strains through each ply to be determined as they vary with \(z\). Finally, the stresses through each ply can be found using the stress-strain relations as they vary with \(z\).

4.3.4. First Order Shear Deformation Laminate Theory

If the kinematic assumption from classical lamination theory that all normal lines remain normal is relaxed, then the out-of-plane shear stresses \(\tau_{13}\) and \(\tau_{23}\) can be estimated. The \(N\) vector, \(A\) matrix, and \(\varepsilon^0\) vector in the above equations are expanded to included shear stress, stiffness, and strain components, and the resulting system of equations has the same general form as Eq. (4.27) but with different matrix components.

\[
\begin{bmatrix} N \\ M \end{bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{bmatrix}\varepsilon^0 \\ \kappa^0\end{bmatrix} \quad (4.29)
\]

A constant through-thickness shear stress for each ply is obtained with this theory. Note that in a real laminate, the out-of-plane shear stresses vary through the thickness of each individual plate. For instance, the top and bottom surfaces of the laminate must have zero shear stress for equilibrium to hold, but shear stress through these plies is not necessarily zero everywhere else for most loading conditions. Despite these limitations, the theory provides improved results for laminate behavior and provides a useful estimate of out-of-plane shear stresses, which are believed to play a large role in composite delamination.
5. BIRD NUMERICAL MODEL

In this chapter, a bird modeling approach was developed that accurately reproduced the pressure characteristics of the bird/structure interaction, induced the correct responses in the structure, and approximated the fluidic post-impact behavior of the bird material.

Parametric studies are conducted for an SPH bird model in order to explore the effects of key modeling parameters, especially those not discussed in the literature. At the conclusion of these studies, a final bird model is developed for use in engine forward section impact simulations.

5.1. Modeling Approach

In order to determine which FE approach to employ, bird models were developed using three different methods: (1) Lagrangian, (2) ALE, and (3) SPH. It was desired to simulate bird impact onto a relatively simple structure and compare each model’s accuracy in producing the correct time-dependent deformation response. This tested each method’s ability to impose correct impact loads and transfer momentum to a target. Using a simple structure removed the difficulties posed by analyzing the response of a complex structure, such as a fan blade. Also, detailed test data capturing fan blade deformation during impact was not readily available in the literature.

To this end, a test case of bird strike on an F-16 canopy was chosen for comparing the numerical bird models. Experimental data was obtained in which intricate details of the deformed canopy shape was captured throughout the impact event. Modeling details and simulation results for this case study can be found in the Appendix.

It was observed that both the ALE and SPH bird models produced a very accurate deformation response for the canopy, as shown in Fig. A1-4. The Lagrangian bird model over-predicted the canopy deformation in comparison with the test data. The ALE model had used about 20,000 elements for the bird, while the SPH model used slightly more with 22,000 particles. Despite having approximately the same level of detail, the SPH model required 30%
less computation time than the ALE model. Lastly, the force-time history response of the SPH bird impact produced a smoother response that correlated better with observations from bird impact experiments on compliant targets [9]. From these results, it was chosen to develop an SPH approach as part of the crashworthiness methodology.

Reviewing the literature, few researchers have subjected SPH bird models to thorough convergence studies to verify that the impact pressure-time history response was independent of the number of particles employed. In addition, the influence of the cavitation pressure in the null material model had not been discussed in detail (see Chapter 2.2.4). Also, it has been noted that the SPH approach implemented in FE codes does not always produce energy-conservative results, but the exact reason of the energy loss is not defined. The influence of bird modeling parameters on the non-physical energy loss does not appear in the literature for the FE code used in this work.

5.2. Parametric Studies

With the above-mentioned deficiencies in the available literature, numerous bird models were developed to explore the effects of important modeling parameters for the SPH method and develop a suitable modeling approach. Bird impact onto a rigid plate was simulated for comparison with experimental results where birds were launched at fixed steel targets [8, 9].

5.2.1. Model Setup

A review of the literature showed the current trends in SPH bird modeling (see Chapter 2.2) and served as a starting point for the development of a base bird model for the parametric study. A hemi-spherically capped cylinder with a length-to-diameter ratio of 2 was chosen for the bird representative geometry (Fig. 5-1) [6]. Both numerical analyses and gelatin projectile experiments have obtained favorable results with this shape [7, 33, 40]. A 4 lb. bird (1.8 kg) was modeled in accordance with sizes required by FAR 33.76 for bird ingestion.
The null material model was chosen as it has been shown to provide favorable results in previous research \[34, 41, 77\]. A material density of 945 kg/m\(^3\) was adopted. This reflects the density of the bird material, approximately that of water, but with porous regions that decrease the effective density. This average bird density has been used successfully by previous investigators \[9, 44\]. The combination of density and length-to-diameter ratio defined the necessary bird geometric dimensions.

In addition, a polynomial EOS was used that defined the inverse relationship between the particle volume and pressure. Several studies have found this model to perform well for capturing the impact pressure due to soft impact \[33, 44\]. The EOS formulation is

\[
P = C_1 \mu + C_2 \mu^2 + C_3 \mu^3
\]

\[
\mu = \frac{\rho}{\rho_0} - 1
\]

\[
C_1 = K
\]

\[
C_2 = (2k - 1)C_1
\]

\[
C_3 = (k - 1)(3k - 1)C_1
\].

The constant \(\rho_0\) is the initial mass density, \(\rho\) is the current density, and \(K\) is the bulk modulus of the bird material. The bulk modulus of water (2.2 GPa) was substituted.
The variable $k$ is the compressibility constant of Eq. (2.5), the linear Hugoniot shockwave speed equation, reproduced here.

$$U_s = c_0 + kU_0$$

(5.2)

The variable $c_0$ is the speed of sound in the material, $k$ is the Hugoniot number, and $U_s$ and $U_0$ are the shockwave speed and initial velocity respectively, as defined previously. Prior studies have found that $k$ approximately equals 2 for biological materials, such as birds [13]. Additional properties of the base model are shown in Table 5-1.

<table>
<thead>
<tr>
<th>Table 5-1. Base bird model parameters [13].</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total mass, $m$ (kg)</td>
</tr>
<tr>
<td>Mass density, $\rho$ (kg/m$^3$)</td>
</tr>
<tr>
<td>Length-to-diameter ratio, $L/D$</td>
</tr>
<tr>
<td>Fluid viscosity, $\mu$ (Pa·s)</td>
</tr>
<tr>
<td>Bulk modulus, $K$ (GPa)</td>
</tr>
<tr>
<td>Compressibility constant, $k$</td>
</tr>
<tr>
<td>Initial velocity, $U_0$ (m/s)</td>
</tr>
</tbody>
</table>

Bird modeling parameters were varied in order to examine their effect on the pressure-time history at the center of the impact, where pressure is highest. Numerous energies in the solution, particularly the kinetic, internal, and total energy, were also carefully studied.

A typical example of the bird impact model results is shown in Fig. 5-2. It can be seen that a region of material at the front of the bird is quickly compressed. Particles begin shooting outward from the point of impact as high shock pressures occur. This correlates with a sharp rise and fall in pressure at the center of the impact. After the compressed material is released, a relatively smooth spread of the material can be observed throughout the duration of the impact.
5.2.2. Pressure Measurement Scheme

An important consideration when measuring the pressure-time history response is the manner in which pressure is calculated in the FE model. Johnson considered this by measuring forces over both a single element and the average pressure over 4 elements [42] near the bird impact center. It was found that different peak pressures can result. Heimbs [28] noted as recently as September, 2011 that these numerical details are rarely reported in the literature and have important consequences for accurate bird model validation and calibration. It was recommended that pressure be used at nodes covering an area equal to the contact area of the pressure transducers used in experiments; however, this information is often missing as well from the published works, including Wilbeck [6].

Pressure at the center of the bird/plate impact was measured in two schemes: (1) pressure at 1 node at the impact center, and (2) average of individual nodal pressures for 9 nodes radiating outward from the impact center.
Fig. 5-3. Pressure-time history at center of bird/rigid plate impact for two pressure measurement schemes.

Table 5-2. Peak pressure for different measurement schemes.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Pressure – 1 node (Pa)</td>
<td>$2.40 \times 10^8$</td>
</tr>
<tr>
<td>Peak Pressure – Avg. 9 nodes (Pa)</td>
<td>$3.29 \times 10^8$</td>
</tr>
<tr>
<td>Percent difference</td>
<td>27%</td>
</tr>
</tbody>
</table>

The average pressure over 9 nodes spreading out from the center of impact is 27% greater than the single node pressure at the center of impact. This matches the trends in pressure measurements reported by Johnson [42].

From this study, it was concluded that without information about the contact area of the pressure transducers used in bird impact experiments (as well as other experimental uncertainties) it was not valuable to attempt to match exactly the peak pressure loads from experimental pressure-time history data available in the literature. Instead, it was decided to match the general stages of the pressure response, namely the pressure rise, fall, steady, and final
tapering off.

5.2.3. Particle Density

The number of particles used to represent the bird was progressively increased and the pressure-time history at the center of impact was compared. This was done in order to verify that a sufficient particle density was used such that the bird behavior was independent of the number of particles used in the simulation (Fig. 5-4).

![Graphs showing pressure-time history for various numbers of particles](image)

**Fig. 5-4.** Pressure-time history for various numbers of particles used to represent the bird.
The recorded pressure was non-dimensionalized by dividing the results by the theoretical steady pressure given by Eq. (2.7). Time was also non-dimensionalized by dividing each time increment by the theoretical impact duration defined by Eq. (2.8).

Each graph was characterized by a short-duration sudden pressure rise, followed by an approximate steady pressure state, and a final region where the pressure decays to zero. For lower particle densities, shown in Fig. 5-4(a) and (b), the predicted pressure response included two peaks before settling to a steady pressure. As the number of particles was increased, the response changed such that the initial high pressure region was characterized by a single pressure rise rather than the two initially observed.

The reason for the two high pressure peaks with coarse models may be due to release waves. The particles at the front of the impact may be quickly ejected by high internal pressure while only exerting minimal influence on particles behind them. This essentially presents another surface of undisturbed particles that hits the target, resulting in two subsequent impacts. As the particle density increases, effects at the front of the bird may be more strongly coupled to the behavior behind the point of impact.

The relation between the peak pressure and number of particles used for the bird is shown in Fig. 5-5. Significant changes were seen when the particle count was increased from 10,000 up to around 35,000 to 40,000 particles. However, above this range, only minor changes were observed.
The particle count, and hence the particle density, was directly proportional to the computational expense of the bird model. In contrast, the number of particles used did not directly correlate to changes in the solution when larger numbers were used. This can is clear in Fig. 5-4, where the pressure-time history show little changes for higher particle counts, and in Fig. 5-5, in which the peak pressure shows convergence with increasing particle density. Therefore, an optimal particle density was the one with the minimum number of particles needed to still show a sufficient convergence peak pressure response.

When the particle count was increased to 35,000, the pressure-time history began reaching a consistent response. Further increases in the number of particles lead to minor refinements of the response with reduced oscillations and the overall response changing only slightly. The peak pressure value was also quite consistent with an approximate non-dimensionalized pressure of 10. This response was repeated in further analyses, up to around 150,000 particles.

It was concluded that when approximately 35,000 particles were used, the impact pressure response of the bird was sufficiently independent of the particle density. Therefore, a bird model
comprising around 35,000 particles was adopted in all subsequent bird impact models when the meshless approach was to be used.

This convergence study provided two important conclusions: (1) it demonstrated that the response of the particle model was convergent when the particle density was increased, and (2) it established an optimum particle density to be used for the birds in the 4 to 8 pound range of interest in this work. The first conclusion is important from a theoretical standpoint. If the number of particles influenced the solution but increasing the density did not converge the solution, then useful conclusions about the problem could not be drawn. The second point follows from the first and establishes the sufficient density when numerical effects are no longer substantial, and the governing physics and material models dominate the bird behavior.

Addressing the concern that the SPH approach may experience problems with energy conservation, the total energy in each of the models was examined.

![Fig. 5-6. Total energy-time history showing improved energy conservation with increasing particle density ($P_c = 0$).](image-url)
The total energy in the problem drastically drops as the impact begins and the bird is disintegrated. It is observed that the total energy drop decreases as particle density is increased, but nevertheless the energy drop remains large. All of the energy in the problem is contained in the bird as the plate is rigid and fixed in space.

Details about the cause of the energy drop could not be found in the literature, and it is not clear whether the energy is actually lost or if this is an issue of reporting the correct energy in the code output. However, one possible explanation is that non-physical forces added to the problem to combat the tensile instability issue (see Chapter 4.2.3) perform negative work on the bird as particles separate. The explicit FE code specifies that pressure in tension is negative [72]; therefore, applying an outward force to counter-act particle clumping would contribute negative work to the problem, thereby decreasing the total solution energy. Explanations for these effects will be sought in future work.

5.2.4. Cutoff Pressure

The tensile strength of objects can be incorporated into the null material model by defining a tensile cutoff pressure. When used in an SPH model, particles will resist separating from one another until the hydrostatic pressure exceeds the cutoff pressure.

This parameter has not been explored extensively in previous studies of bird impact. However, for a bird model, it is logical that the cutoff pressure corresponds to the tensile strength of the bird material. Values ranging from 0 to 100 MPa were tested for the cutoff pressure.

As the cutoff pressure was increased, different behaviors were observed in the spread of the particles. With no cavitation pressure, the particles spread out in a very dispersed, even pattern with little clumping of material (Fig. 5-7 (a)). When even a moderate cutoff was specified, some material remained locally bonded after the impact event (Fig. 5-7 (b)). For higher pressures, the material throughout the entire bird clung together in long strands of particles (Fig. 5-7 (c)).
Qualitatively, the extreme cases appeared less realistic than the moderate values in that bird material is neither vaporized by the impact, nor does the entire bird remain clumped together.

Fig. 5-7. Particle spread patterns for different cavitation pressures

The pressure-time history of the impact is shown in Fig. 5-8. Other than minor variations in pressure during the steady pressure phase, cavitation pressure does not appear to have a significant effect on the pressure-time history. Pressure here is non-dimensionalized

Fig. 5-8. Pressure-time history for various cutoff pressures (10400 particles).
However, as the cavitation pressure was increased, the energy loss phenomena became more prominent. This gives credence to the notion that measures to address the tensile instability issue, which is directly related to particle separation, may be the cause of the energy loss.

5.2.5. Artificial Bulk Viscosity

Several impact cases for different artificial viscosity coefficients were simulated. The equation for determining the applied artificial pressure contains both a linear coefficient, $\alpha$, and a quadratic coefficient, $\beta$. Equation (4.16), reproduced here, is used to calculate the applied pressure in SPH particles for addressing shocks.

$$\Pi_{ij} = \frac{1}{\rho_{ij}} \left( -\alpha \mu_{ij} \ddot{e}_{ij} + \beta \mu_{ij}^2 \right). \quad (5.3)$$

Default coefficients are provided within the explicit FE code used in this work. There are also recommended values for use with the SPH approach when using the fluid formulation (see Chapter 4.2.5) [72]. In order to observe the effects on the impact pressure and energy is the solution, both of these cases, plus a case where each coefficient is set to zero, were tested. The
coefficients used in each test case are summarized in Table 5-3.

<table>
<thead>
<tr>
<th>Test Case</th>
<th>$\alpha$</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Default</td>
<td>1.5</td>
<td>0.06</td>
</tr>
<tr>
<td>Recommended</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td>Zero</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

The default and recommended test cases produce essentially the same results for the pressure-time history. For the zero test case, a slightly lower peak pressure is observed, but otherwise the response is similar (Fig. 5-10).

![Fig. 5-10. Pressure-time history for various bulk viscosity coefficients (34,700 SPH particles).](image)

Again, the default and recommended test cases produced very close results for total energy throughout the analysis. Both cases have a similar trend of the total energy in the problem decreasing throughout the impact (discussed in section 5.2.3). By the end of the impact, only 67% of the original energy is present in the solution. In contrast, the zero test case shows significantly less energy loss by the end of the impact, with 89% of the original energy being maintained (Fig. 5-11).
Fig. 5-11. Total energy-time history for various bulk viscosity coefficients (34,700 SPH particle, $P_c = 0$).

Reducing the bulk viscosity in the SPH bird had minimal effect on the pressure-time history of the impact event. However, it substantially decreased the energy loss in the problem. While the exact nature of the energy loss in the problem was not identified, these results show that if stable, accurate results can be obtained with the bulk viscosity coefficients reduced to zero, then these parameters may be preferable in a bird model.

5.3. SPH Bird Models

At the conclusion of these studies, a general SPH bird modeling approach appropriate for large birds was outlined. The following table summarizes the material properties and modeling guidelines for a hemi-spherically capped cylinder SPH bird:
Table 5-4. SPH bird modeling properties.

<table>
<thead>
<tr>
<th>Material Properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass density, $\rho$ (kg/m$^3$)</td>
<td>945</td>
</tr>
<tr>
<td>Bulk modulus, $K$ (GPa)</td>
<td>2.2</td>
</tr>
<tr>
<td>Fluid viscosity, $\mu$ (Pa·s)</td>
<td>0.001</td>
</tr>
<tr>
<td>Compressibility constant, $k$</td>
<td>2</td>
</tr>
<tr>
<td>Cavitation Pressure, $p_c$ (kPa)</td>
<td>-500</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Geometric Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Length-to-diameter ratio, $L/D$</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Numerical Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Particles</td>
<td>~35,000</td>
</tr>
<tr>
<td>Linear Bulk Viscosity, $Q_1$</td>
<td>1.5</td>
</tr>
<tr>
<td>Quadratic Bulk Viscosity, $Q_2$</td>
<td>1</td>
</tr>
</tbody>
</table>
6. FORWARD SECTION IMPACT ANALYSIS

Rotating machinery, tight design tolerances, and complex interactions pose significant challenges for analyzing the structural response of engine components. The need for 3-D, time-dependent analysis for impact problems introduces further modeling complexity.

In this chapter, numerical methods are developed for properly capturing the structural response of engine forward section components in an impact event. First, an approach is developed for dynamically modeling a forward section under stable operating conditions. Then, a bird is incorporated using the techniques developed in Chapter 5 and the methodology is expanded to include the effects of soft impact.

In this stage of work, the problem was simplified by using only metal materials for the engine components. The added complexity of composite and hybrid structural response and progressive damage in jet engines is addressed in Chapters 7, 8, and 9.

6.1. Modeling Approach

It was determined that the key structures to be modeled were the fan blades, casing, fan hub, cone, inner axel, and bearings (Fig. 6-1). The stress distribution, deformation, and damage to the fan blades and casing were of primary interest. The central hub and cone are necessary features for connecting the fan blades and accurately representing the distribution of mass in the forward section. The inner axle and bearings support the fan assembly as it rotates and connect it to other portions of the engine. Modeling details for each of these components are provided in the following sections.
The bypass exhaust vanes were represented by a fixed boundary condition at the rear of the casing to capture their stiffening effect on the casing. Structures such as the inlet cowling and outer skin were not modeled due to their minimal effect on the crashworthiness of the engine. Other downstream engine components, such as the low pressure compressor stages, were not examined in this study; however, future work will aim to capture the response of these structures due to deformations and vibrations occurring in the forward section.

After the response under stable conditions was established (see section 6.6), a moving bird was introduced and impacted with the fan assembly.

6.2. Fan Blade Modeling

The choice of a suitable finite element depends on full consideration of the physical characteristics of the structure being modeled, while accounting for the expected loads and deformations to which the structure will be subjected. Jet engine fan blades can generally be regarded as thin plate structures as their thickness is much smaller than either their chord or span.
length. Shell finite elements governed by plate theory (see Chapter 4.3) are a logical first choice. These elements possess both membrane and bending stiffness analysis capabilities and are very computationally efficient.

6.2.1. Element Formulation

The twisting of the blade along its length presents some special attention. Shell element formulations are typically developed for flat geometries without considering twisting of the structure being modeled. Therefore, for complex shapes where twisting is prevalent, the response of the part to out-of-plane loads may be inaccurate.

With this consideration, the Belytschko-Wong-Chiang (BWC) shell element, governed by first-order shear deformation plate theory and incorporating warpage control, was used to represent the blades [72]. This has improved performance compared to the default Belytschko-Lin-Tsay (BLT) shell element provided in the FE code which does not incorporate warpage control. Only a slightly higher computational cost is incurred with the BWC shell element [72].

In Fig. 6-2, the results of a previous study are shown for an impulsive load on a twisted beam modeled with BLT and BWC elements. The BWC elements capture the correct vibration response due to the impact load, while the BLT elements deform unrealistically.

![Twisted beam problem](image from reference [72]).
Five (5) through-thickness integration points were assigned through the blades using the Lobatto integration rule, which places integration points at the top and bottom surface in order to accurately characterize the stresses and strains at these locations [62].

![Diagram of shell element integration points for the titanium fan blades model.](image)

**Fig. 6-3. Shell element integration points for the titanium fan blades model.**

6.2.2. Geometry

The fan blade shape initially selected was a general commercial aviation fan blade geometry consistent with several designs utilized in smaller turbofan engines (Fig. 6-4). Thirty-six (36) blades were modeled with their bases fixed using rigid connections constraining both translational and rotational motion relative to the central hub.
A uniform thickness of 3 mm was assigned to the shell elements to approximate the blade thickness for this analysis. This is in accordance with the average blade thickness in smaller turbofan engines, such as the one approximated in this model.

6.2.3. Material Model

An isotropic, elastic-plastic material model incorporating yield and failure was used to define aerospace grade titanium (Ti-6Al-4V, ASTM Grade 5) material properties for the blades. This is a common material in fan blade manufacturing due to its low density and high strength.

The stress-strain profile defined by the titanium model is shown in Fig. 6-5. After exceeding the yield strength, the lower post-yield stiffness, $E_t$, defined the material behavior. This produced a bilinear true stress-true strain curve approximating the ductile behavior of titanium.
Fig. 6-5. Stress-strain curve defined by elastic-plastic titanium model.

If the structure was unloaded after the yield strength, $S_y$, the material would follow the slope defined in the elastic region, but would exhibit permanent plastic deformation. If a part of the structure experience strain above the defined failure strain, $\varepsilon_f$, the material would fail. Once the failure occurred at all of the through-thickness integration points, the element was deleted, thus capturing material failure. This is a common metal material model that, properly calibrated, yields good results for the general behavior of thin metal structures. The input parameters for the titanium model are given in Table 6-1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, $\rho$ (kg/m$^3$)</td>
<td>4420</td>
</tr>
<tr>
<td>Elastic modulus, $E$ (GPa)</td>
<td>112.5</td>
</tr>
<tr>
<td>Poisson’s Ratio, $\nu$</td>
<td>0.31</td>
</tr>
<tr>
<td>Post-yield modulus, $E_y$ (GPa)</td>
<td>1.59</td>
</tr>
<tr>
<td>Yield Strength, $S_y$ (MPa)</td>
<td>980</td>
</tr>
<tr>
<td>Ultimate strain, $\varepsilon_f$</td>
<td>0.1</td>
</tr>
</tbody>
</table>

**6.3. Casing Modeling**

The aluminum casing was modeled as an open cylinder using BLT shell elements surrounding the fan section. Care was taken to fit the diameter of the casing very close to the fan
blade tips in accordance with the very small gap tolerances used in modern engines (Fig. 6-6). It was essential to allow a gap for the fan blades to deform radially as a result of pre-stressing in order to avoid initial penetrations between the blades and the casing. Fixed boundary conditions at the rear engine were used to represent structural supports for the casing, as well as stiffening provided by the exit guide vanes.

![Fig. 6-6. Casing FE model. Red points indicate fixed boundary conditions.](image)

The same isotropic, elastic-plastic material model was used to include yielding and failure. Material properties for aluminum used for the casing are given in the table below.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, $\rho$ (kg/m$^3$)</td>
<td>2810</td>
</tr>
<tr>
<td>Elastic modulus, $E$ (GPa)</td>
<td>71.7</td>
</tr>
<tr>
<td>Poisson’s Ratio, $\nu$</td>
<td>0.33</td>
</tr>
<tr>
<td>Post-yield modulus, $E_y$ (GPa)</td>
<td>7.2</td>
</tr>
<tr>
<td>Yield Strength, $S_y$ (MPa)</td>
<td>503</td>
</tr>
<tr>
<td>Ultimate strain, $\varepsilon_f$</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Aluminum engine casings usually have additional layers, such as a Kevlar composite wrap,
in order to increase their containment capabilities during a blade-off event. In the initial analysis, these additional features were not included.

6.4. Axle, Hub, and Bearings Modeling

The axle was modeled as a long cylinder using shell elements. Bearings were modeled using rigid cylindrical “sleeves” placed along the rotational axis where contact was used to hold the axle in place (Fig. 6-7). The bearings were free to rotate and pivot about their center of gravity, located at the center of each cylinder, but were restricted from rigid body translation. This arrangement provided a sufficient means to hold the axel in place while allowing it to bend in accordance with forces induced by oscillations in the forward section. An elastic-plastic material model was again specified to capture any permanent deformation of the steel axle, with properties given in Table 6-3.

![Axle, bearing, and hub FE models.](image)

**Table 6-3. Parameters for the steel axle.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, $\rho$ (kg/m$^3$)</td>
<td>7800</td>
</tr>
<tr>
<td>Elastic modulus, $E$ (GPa)</td>
<td>193</td>
</tr>
<tr>
<td>Poisson’s Ratio, $\nu$</td>
<td>0.305</td>
</tr>
<tr>
<td>Post-yield modulus, $E_y$ (GPa)</td>
<td>19</td>
</tr>
<tr>
<td>Yield Strength, $S_y$ (MPa)</td>
<td>690</td>
</tr>
<tr>
<td>Ultimate strain, $\varepsilon_f$</td>
<td>0.1</td>
</tr>
</tbody>
</table>
A central hub and connected to both the fan blades and the end of the axle, thus forming the entire rotating sub-structure. The hub is a relatively thick component that is not likely to experience damage or failure. Also, it is more likely that fan blades would fail before damaging loads were transferred to the hub. Therefore, it was determined that it was not necessary to characterize the hub stresses, and the part was assigned rigid steel material properties. Future studies in which the dovetail grooves are modeled, along with the corresponding blade dovetail roots, will likely aim to capture hub stresses within these regions in order to assess damage and failure of these restraining sub-structures.

6.5. Contact Modeling

For the case of a bird directly impacting the fan blades, it is critical to accurately capture the interactions between the

- bird and engine components,
- blades and casing,
- blades with other blades, and
- blades with themselves.

Contact between the bird and fan blades was effectively captured using the same node-to-surface penalty contact algorithm employed for Lagrangian contact (see section 2.2.2.1). Similar contact was also defined between the bird and casing should bird material be radially accelerated (or “centrifuged”) into the casing after passing through the fan assembly.

The impact of the bird with a blade induces reactions loads that act almost directly counter to the rotational direction of the blade. This can cause a blade to deform significantly to the point where it impacts adjacent blades. If the blade is deformed heavily enough or fractures, portions of the same blade may even come into contact with the remainder of the same blade.
6.6. Preloading Analysis

Centripetal forces acting on each fan blade pull it toward the hub center and maintain its circular path around the axis of rotation. This induces stresses that are greatest at the blade root and gradually decrease along the span of the blade, approaching zero at the tip. In order to accurately predict damage, it is necessary to assess stress and strain in the blades as a result of both the bird impact and the initial stress field caused by the fan assembly rotation.

The large diameter of the fan blades made preloading the structures a necessity. Other rotating components, such as the hub and axle, are stiffer and have a smaller maximum radius of rotation, making them less susceptible to deformation and high stresses due to rotation. Therefore, these parts were not included in the preloading analysis.

6.6.1. Explicit Dynamic Relaxation

An explicit FE method called dynamic relaxation (DR) was used to pre-stress the fan blades. In this method, forces imposed on the structure by a static or dynamically stable condition are applied to the initially un-deformed structure. As the structure deforms, nodal velocities are damped out at each time step by the addition of a damping term to the equilibrium equation [72]. Equation (4.15) is modified to obtain

\[ M a^n + C v^n = P^n - F^n + H^n , \]

where \( C v^n \) is the added damping term and \( C \) is the diagonalized damping matrix. The \( C \) matrix is determined by the calculation

\[ C = c \cdot M , \]

where \( c \) is a scaling factor. This parameter is estimated in order to obtain a critically damped system that eliminates the dominant frequencies in the structure when it is loaded.

First, the loads are gradually applied to the structure using a ramp from zero to the full loading condition. At the time that the full loads are applied, the maximum distortional KE will
be present in the structure. Then, the static loads are held constant, and the structure continues to deform. The kinetic energy of the structure decreases as the nodal velocities are continually damped.

The analysis continues until ratio of the current distortional KE to the maximum distortional KE of the structure drops below a preset threshold. This indicates that the structure is no longer deforming and is sufficiently preloaded. As the convergence threshold is decreased, the stresses and deformation of the structure is closer to the correct state for the given loading condition. However, this increased accuracy incurs higher computational cost as well.

After the preloading phase, a dynamic analysis is conducted with the structure subject to initial conditions matching those for which it was preloaded. If the structure is not sufficiently preloaded, it will not have the correct shape or nodal reaction forces to achieve a dynamically stable state under the initial conditions of the problem, leading to non-physical behavior and a potentially unstable solution.

6.6.2. Loading Conditions

Body forces due to centripetal loading were applied to the fan blade following the equation

$$b = \rho \omega^2 r \ ,$$

(6.3)

where $b$ is the body force density, $\rho$ is the mass density, $\omega$ is the angular velocity about the engine axis of rotation, and $r$ is a node’s distance from the axis of rotation. Density was determined from the blade material. The angular velocity was set to 5000 rpm, suitable for engines of the size in this problem. The volume used for calculating each nodal force is estimated within the FE code using the shell thickness and element connectivity.
6.6.3. *Determination of DR Parameters*

The main parameter to determine for the DR analysis was the convergence tolerance. The default convergence tolerance in the explicit FE code is 0.001.

The preloading results were evaluated by incorporating the blades into the rotating analysis for which they were preloaded and observing the stress and displacement variations within each blade.
It was found that lowering the convergence tolerance significantly improved the accuracy of the preloaded state. Finding the lowest ratio to which the problem can converge was a trial and error procedure. After much experimentation, a tolerance of $1.5 \times 10^{-5}$ was used. The results of the pre-stressing are shown in Fig. 6-11.

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**Fig. 6-10.** Convergence of DR analysis.

**Fig. 6-11.** Fan assembly stresses following the pre-stressing phase.
6.7. Bird Impact Modeling

Following the stress and displacement initialization phase, the bird impact was introduced into the simulation. The initial bird linear velocity, relative to the engine, was 100 m/s. This is consistent with takeoff speeds for commercial aircraft and velocities required by FAR 33.76 for bird ingestion certification. The initial rotational velocity of the fan assembly selected to be 525 rad/s, corresponding to a rotation of 5000 rpm, which is an appropriate speed given the inlet diameter of the forward section model. The bird was aimed at 60% of the mid-span of the blades; the minimum impact location required for bird ingestion certification is 50%, as per FAR 33.76. The bird was positioned close to the fan blades, just outside the penalty length, to reduce needless computation.

![Fig. 6-12. Forward section bird impact model setup.](image)

6.8. Impact Analysis

The bird was sliced by the first blade encountered and began deforming heavily as a result of the interaction. The result of the simulation early in the impact is shown at various times in Fig. 6-13. The stresses induced in the bird representing the shockwave are shown in Fig. 6-14.
Fig. 6-13. Progressive damage at selected time steps.

(a) $t = 1 \text{ ms}$
(b) $t = 5 \text{ ms}$
(c) $t = 9 \text{ ms}$
(d) $t = 13 \text{ ms}$

Fig. 6-14. Shockwave induced in the bird due to slicing impact with the fan blades.
The soft body was separated into multiple impactors by the slicing process, with portions of it coming into direct contact with three to four fan blades. The spread of the bird contributed to a larger contact area between the bird material and the rear face of each blade as the blades sliced through and then collided with clusters of particles. This larger contact area appeared to contribute to high deformation across the entire blade, inducing plastic strains across the blade and at its base. It was predicted that strains at the base of two or three blades, depending on specific modeling parameters used, exceeded the designated material limit. Material failure was effectively captured by the model in the form of element deletion along the length and base of the affected blades.

The force time history of the impact between the bird and the fan assembly over the duration of the impact is shown in Fig. 6-15. Multiple jumps in pressure are seen as the bird successively impacts multiple blades.

![Fig. 6-15. Impact force between bird and fan blades.](image)

Following the initial impact, several events occurred that contributed to extensive damage to other portions of the fan assembly. First, the detached blades impacted the engine casing and began to interact with other nearby blades. While the fan assembly rotated through one
revolution following the impact, the detached blades caused the fan assembly to move off center. This pushed the blades on the opposite side of the impact zone into the fan casing, resulting in high plastic strains and disintegration of the blade tips (Fig. 6-16).

![Fig. 6-16. Fan blade tips impacting and sliding against the casing across from the impact zone.](image)

As the unbalanced rotation continued, addition blades around the entire fan assembly made contact with the fan casing and experienced yielding and failure at the blade tips as well as along their length. The casing was heavily deformed due to the interaction, causing material failure and subsequent element deletion in several locations as a result of high strain levels (Fig. 6-17).

![Fig. 6-17. Plastic strain and failure of the engine casing as a result of blade-casing contact.](image)
6.8.1. Effect of Casing Modeling

Bird impact onto the fan assembly in the absence of the casing was modeled to establish the damage response of the fan assembly without interference from the fan casing. The bird directly impacted several blades and induced high stresses and strains that lead to material failure at the base of two of the blades.

From this analysis, deformation of the axle was used to establish the mode shape of the vibration response of the fan assembly due to mass unbalancing. The presence of the three non-translating sleeves holding the axle meant that there were three fixed points representing the real axle bearing locations within the propulsion system. The distributed mass between the sleeves and the large fan assembly constituted a system with three degrees of freedom. The mode shape diagram is given in Fig. 6-18. This mode shape corresponds with the first vibration mode of a three degree of freedom system.

![Fig. 6-18. Mode shape of the axel vibration resulting from mass unbalancing of the fan assembly.](image)

The results for the two modeling scenarios at progressive time steps are shown in Fig. 6-19. Without interaction with the casing, the fan blades only experienced damage due to direct impact from the bird and from interaction with other blades. Subsequently, only a few blades failed when the casing was not included, and the progression of damage was much slower.

In addition to different damage effects, the vibration response of the fan assembly was strongly affected by interaction with the casing. Orbit plots showing the displacement at the center of the fan assembly for each scenario are shown in Fig. 6-20. The fan assembly experienced quick changes in motion due to complex interactions between blades and the casing.
$t = 5\text{ ms}$

$\begin{array}{c}
\text{No Casing} \\
\text{With Casing}
\end{array}$

$\begin{array}{c}
t = 25\text{ ms} \\
t = 40\text{ ms}
\end{array}$

Fig. 6-19. Damage progression for casing versus no casing.
Additional simulations with the casing present were conducted in which the number of elements used to represent each fan blade was varied. This established the mesh dependence in fan blade damage assessment as well as the overall predicted damage. Figure 13 shows the results of three simulations utilizing different fan blade mesh densities immediately after the initial hit.

The low mesh density model predicted that the initial hit only caused detachment of one blade, while the medium and high density models predicted detachment of two blades. This
comparison indicated that a degree of fineness equal to or greater than the medium density model was necessary throughout the middle section of the blade to accurately characterize the bird/blade interaction between the meshless particles and the structured Lagrangian mesh used to construct the fan blades.

Figure 14 shows the results of the three simulations further in the analysis after several rotations of the fan assembly.

The coarse density blade mesh model predicted a lower rate of damage than the other models, indicating detachment of about half of the blades as predicted by the medium and high mesh density models at the same time step. The high density model determined a few more detached blades than the medium density model. All models predicted substantial damage to the tips of all blades as they sheared off against the casing.

The larger elements of the coarse mesh model failed at the blade tips as the simulation progressed, resulting in a large gap between the remaining blade material and the casing. This gap prevented further interaction between the blades and casing, which particularly lead to
prediction of less overall damage and fewer detached blades. The medium and high mesh density models experienced smaller gaps as elements at the blade tips failed, allowing further interaction between the blades and casing. Therefore, a level of mesh refinement equal to or greater than that of the medium density model was deemed necessary at the blade tips to accurately characterize damage in the entire forward fan section.

6.8.3. Comparison with Real Bird Strike Cases

These results of this analysis were compared with real cases of bird strike on engines with a similar inlet diameters and fan blade dimensions. Post-impact damage assessments for two cases were found where each engine ingested a large bird on the same order as the 4 lb bird in the analysis.

In Fig. 6-23, the real world impact case shows complete loss of almost all the fan blades. Those that remain are highly distorted, and it is observed that the blade tips are disintegrated by contact with the casing. These effects were captured in the model as most of the fan blades have impacted the casing by the end of the simulation and experience tip disintegration due to shearing against the casing prior to detachment. Permanent damage to the casing predicted by the analysis is also seen in the real world scenario.

The impact test case shown in Fig. 6-24 also displays loss of almost a quarter of the fan blades. Remaining blades are heavily damaged, and shearing of the blade tips against the casing is evident. Again, these effects were captured in the analysis. All of the fan blades experience heavy damage, and the casing experiences heavy damage.
Fig. 6-23. Comparison of simulation results versus real-life bird strike damage [78].

Fig. 6-24. Comparison of simulation results versus real-life bird strike damage.
7. COMPOSITE DAMAGE ANALYSIS

In this chapter, FE methods for modeling composite structures and capturing progressive damage and failure are developed. First, methods of representing FRP laminated composites using finite elements are reviewed. Then, a categorical approach to composite damage is discussed, and methods of predicting and representing ply and inter-ply composite damage and failure in a finite element context are presented. These methods are explored through case studies using FE simulations of impact onto simple structures, such as a composite plate.

For simple composite plate structures, the methods examined in Chapter 4.3 may be used to directly predict the mechanical response of the parts. For structures with complex geometry, these methods can be applied over discrete spaces via numerical techniques, such as the finite element method, to accurately model the structural behavior.

As damage occurs in a composite, the effective properties of the plies and laminate are degraded, and the displacement of the material is no longer fully reversible. Therefore, modeling progressive damage for a composite part is a nonlinear, inelastic problem, and the earlier elastic analysis methods must be augmented or replaced to address these damage effects.

7.1. Finite Element Approaches

Both shell elements and solid elements may be used to represent thin composite structures. The element formulation and general element use vary significantly with each approach.

7.1.1. Shell Elements

Shell finite elements are employed with their behavior typically governed by a higher order laminate theory, such as first-order shear deformation laminate theory (see Chapter 4.3.4). Integration points through the thickness of the shell represent the composite plies, where each layer may be represented by a different orthotropic material model and a unique local material orientation. The combined properties of each layer define the average orthotropic laminate
properties, which are then assigned to the flat shell element.

Fig. 7-1. Shell finite element showing through-thickness integration point locations.

The shell is usually located at the mid-plane of the composite structure, and calculations are performed about this reference location. Nodal displacements and rotations are used to calculate unique membrane and bending stresses at each integration point via the laminate formulation, allowing the bending stiffness to be accurately represented using just one element.

7.1.2. Solid Elements

Solid elements with an orthotropic material model may also be used to represent composite structures. Most often, one-point integration solid elements are employed in time-dependent, explicit FE solutions due to their stability under large deformations. However, one integration point means that the stress state is constant throughout the element. Therefore, to properly capture the stress variation through the thickness of a thin composite, multiple layers of solid elements must be used.

Solid elements perform best when all of their dimensions are approximately equal to one another. If one dimension is much smaller than the other two, the element may give inaccurate results or encounter stability issues. To avoid these issues when modeling composites, the dimensions of each element must be reduced such that they are on the order of the ply thickness.
This adds considerable computational cost due to large number of elements needed.

There are, however, some advantages to explicitly modeling each composite layer. If delamination is modeled in the analysis, then the effects of relative motion between plies on the laminate stiffness and the influence of sliding inter-ply friction after delamination can be effectively captured.

### 7.2. Composite Damage Modeling

Damage in composites is often broadly categorized into two main classes: (1) ply damage, and (2) inter-ply delamination. These effects occur simultaneously and interactively to influence the overall progression of damage in the composite structure. If both are deemed significant for an analysis, models are necessary for each class of damage and must be coupled to form an overall failure analysis approach.

Within each of these damage classes, specific damage mechanisms can be identified. For composite plies, unique matrix and fiber failure mechanisms, such as fiber tensile failure or matrix compressive failure, can be discerned. The most commonly defined ply failure modes are:

1) Fiber tensile failure
2) Fiber compressive failure
3) Matrix tensile failure
4) Matrix compressive failure

The method of predicting these failure modes and how their affects are represented varies with each composite model.

For delamination, local failure due to normal and shear stresses can be identified. In laminated composites, delamination commonly occurs between ply layers where the difference in ply orientations is great.
7.3. Ply Damage Models

Numerous criteria have been proposed for predicting damage and failure in composite materials using the in-plane ply stress state. Composite failure theories commonly define ply strengths relative to the longitudinal (along the fiber) and transverse (perpendicular to the fiber) directions [63, 64, 79-81].

![Diagram showing longitudinal and transverse orientations.](image)

**Fig. 7-2. Diagram showing longitudinal and transverse orientations.**

Tensile and compressive strengths for the matrix and fibers can be different by an order of magnitude or greater; therefore, both must be defined. Also, their effects must be represented differently in the subsequent ply degradation. In-plane shear strength is also important. Common failure theories, such as those of Chang-Chang and Tsai-Wu, demonstrate how these properties are used to predict and incorporate the effects of matrix and fiber failure.

7.3.1. Chang-Chang Failure Model

The fibers have the largest effect on the ply properties in the longitudinal direction. Therefore, stresses present in the longitudinal direction, namely $\sigma_{11}$ and $\sigma_{12}$, will play the biggest role in determining if the fiber fails. The same relation exists between the stresses in the transverse direction, $\sigma_{22}$ and $\sigma_{12}$, and matrix failure. This is demonstrated in the governing equations below.
**Tensile fiber failure** ($\sigma_{11} > 0$):

$$e_{f,t}^2 = \left( \frac{\sigma_{11}}{X_t} \right)^2 + \beta \left( \frac{\sigma_{12}}{S_c} \right) - 1 \begin{cases} < 0 & \text{elastic} \\ \geq 0 & \text{failed} \end{cases} \quad (7.1)$$

**Compressive fiber failure** ($\sigma_{11} < 0$):

$$e_{f,c}^2 = \left( \frac{\sigma_{11}}{X_c} \right)^2 - 1 \begin{cases} \geq 0 & \text{failed} \\ < 0 & \text{elastic} \end{cases} \quad (7.2)$$

**Tensile matrix failure** ($\sigma_{22} > 0$):

$$e_{m,t}^2 = \left( \frac{\sigma_{22}}{Y_t} \right)^2 + \left( \frac{\sigma_{12}}{S_c} \right)^2 - 1 \begin{cases} < 0 & \text{elastic} \\ \geq 0 & \text{failed} \end{cases} \quad (7.3)$$

**Compressive matrix failure** ($\sigma_{22} < 0$):

$$e_{m,c}^2 = \left( \frac{\sigma_{22}}{2S_c} \right)^2 + \left[ \left( \frac{Y_c}{2S_c} \right)^2 - 1 \right] \frac{\sigma_{22}}{Y_c} + \left( \frac{\sigma_{12}}{S_c} \right)^2 - 1 \begin{cases} < 0 & \text{elastic} \\ \geq 0 & \text{failed} \end{cases} \quad (7.4)$$

Note that fiber or matrix failure may depend on both the strength in the longitudinal and transverse directions, respectively, and the shear strength.

Table 7-1 shows the ply property degradations following the detection of each failure mechanism. Note that compressive matrix failure leads to a reduction of the residual compressive fiber failure using a scaling factor, YCFAC. Numerical parameters such as these are used to calibrate simulation predictions with experimental results.

<table>
<thead>
<tr>
<th>Failure Mechanism</th>
<th>Degraded Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Fiber Failure</td>
<td>All properties = 0</td>
</tr>
<tr>
<td>Compressive Fiber Failure</td>
<td>$E_{11} = v_{12} = \nu_{21} = 0$</td>
</tr>
<tr>
<td></td>
<td>$X_c = YCFAC \times Y_c$</td>
</tr>
<tr>
<td>Tensile Matrix Failure</td>
<td>$E_{22} = G_{12} = \nu_{21} = 0$</td>
</tr>
<tr>
<td>Compressive Matrix Failure</td>
<td>$E_{22} = G_{12} = \nu_{12} = \nu_{21} = 0$</td>
</tr>
</tbody>
</table>

Once fiber failure is detected for a ply and all properties are degraded, the ply is considered failed and cannot support any load. Loads are redistributed throughout to the other intact
composite layers. The element properties are recalculated using laminate theory with the failed ply ignored, resulting in reduced stiffness and lower residual strength.

Once all plies have failed, the element is deleted, representing complete failure of the composite in a local area.

Note that strain-based failure criteria may also be incorporated, and often must be defined in order to accurately capture brittle failure of the composite.

7.3.2. Tsai-Wu Failure Model

The tensile and compressive fiber criteria are the same for the Tsai-Wu model as the Chang-Chang model. Tensile and compressive matrix failures are both assessed using the following equation:

Matrix failure:

$$
e^2_{m,c} = \frac{\sigma^2_{22}}{Y_c Y_t} + \left(\frac{\sigma_{12}}{S_c}\right)^2 + \frac{(Y_c - Y_t)\sigma_{22}}{Y_c Y_t} - 1 \begin{cases} < 0 \text{ elastic} \\ \geq 0 \text{ failed} \end{cases} \quad (7.5)$$

Ply properties are degraded similarly to the Chang-Chang model. Despite the similarity of the two models, this small difference in the matrix failure calculation can have a significant effect on the predicted damage for a composite structure.

7.3.3. A Note About Composite Failure Model Accuracy

Numerous studies have examined the wealth of available composite failure models in an effort to determine the most accurate, robust method. In an extensive investigation spanning a decade, Hinton et al. [63, 79] conducted the World Wide Failure Exercise testing and comparing 19 composite failure theories for their ability to match experimental results for 14 different biaxial loading cases. At the end of these studies, the most accurate models were only able to predict final failure loads within ±50% of experimental results 75% of the time [64, 80].

With these considerations, it was determined that assessment of the most accurate composite
failure model for the crashworthiness methodology was beyond the scope of this study. The goal of this work has been to develop a flexible modeling approach that can implement a wide variety of failure models.

7.4. Delamination Models

A critical damage mode for both composite and hybrid structures is the separation of individual subcomponents, such as the delamination of composite plies or the de-bonding of the metal leading edge in a hybrid blade.

7.4.1. Out-of-Plane Shear Strength

Several theories propose the use of an out-of-plane shear strength for a stress-based delamination criterion. When the stress exceeds the predefined out-of-plane shear strength, stiffness properties are degraded in a similar manner to the ply damage models. For instance, the Langlie-Cheng model predicts delamination using the following equations

*Out-of-plane shear, longitudinal direction* \((\sigma_{11} > 0)\):

\[
F_{13,s} = \left( \frac{\sigma_{11}}{S_{1,T}} \right)^2 + \left( \frac{\tau_{13}}{S_{13}} \right)^2 \begin{cases} < 1 \text{ elastic} \\ \geq 1 \text{ failed} \end{cases}
\] (7.6)

*Out-of-plane shear, transverse direction* \((\sigma_{22} > 0)\):

\[
F_{23,s} = \left( \frac{\sigma_{22}}{S_{2,T}} \right)^2 + \left( \frac{\tau_{23}}{S_{23}} \right)^2 \begin{cases} < 1 \text{ elastic} \\ \geq 1 \text{ failed} \end{cases}
\] (7.7)

Table 7-2 shows the degraded ply properties for each delamination mode. Essentially, the ply can no longer support any load along the fiber (longitudinal failure) or through the matrix (transverse direction), depending on the failure mode. In addition, both cases cause the ply to no longer possess in-plane or out-of-plane shear stiffness.
Table 7-2. Delamination mechanisms and related ply property degradations.

<table>
<thead>
<tr>
<th>Delamination Mechanism</th>
<th>Degraded Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Out-of-plane shear, longitudinal direction</td>
<td>$\sigma_{11} = 0, \ G_{12} = G_{13} = G_{23} = 0$</td>
</tr>
<tr>
<td>Out-of-plane shear, transverse direction</td>
<td>$\sigma_{22} = 0, \ G_{12} = G_{13} = G_{23} = 0$</td>
</tr>
</tbody>
</table>

Theoretically, it should be possible to implement this models, and others like it, in any finite element where out of plane shear stresses, $\sigma_{13}$ and $\sigma_{23}$, are captured. Solid elements inherently capture these stresses in their behavior. Shell elements with first-order shear deformation plate theory, such as the BLT or BWC element, also capture these stresses. However, in practice, material models in commercial FE codes do not always have the ability to be used in any element. For instance, the explicit FE code used in this work, the Langlie-Chang delamination model can only be implemented in solid elements. In fact, only two material models in the code can capture delamination using shell elements, and these models require additional licenses to access, signifying their value [72]. A user-defined material may be developed in order to implement a material model in an FE code.

7.4.2. Cohesive Formulation

The cohesive modeling approach aims to explicitly capture delamination by connecting two parts using spring-like bonds in the normal and shear directions. This is a fracture mechanics-based approach that uses the strain energy release rate during the formation of new fracture surfaces in a material to define the conditions that will produce a new crack surface (in this case deamination). The strain energy release rate for a laminated composite under different loading conditions can be determined by experiment [82]. Cohesive connections have both a prescribed strength that determines the onset of bond softening and a strain energy maximum that governs failure.
A mixed-mode bilinear stress-displacement cohesive law was explored within the FE code, shown in Fig. 7-3. In this model, the bond between surfaces is represented as linear springs in the normal and tangential directions. As the surfaces move away and/or slide relative to one another, the normal and shear stresses between the surfaces follow a linear elastic path.

\[ G_{IC} = \frac{1}{2} T \cdot \delta_N^F \quad , \]

\[ G_{IIIC} = \frac{1}{2} S \cdot \delta_S^F \quad , \]

The displacement at which softening begins was determined by the equation

\[ \delta^0 = \delta^0_I \delta^0_H \frac{1 + \beta^2}{(\delta^0_H)^2 + (\beta \delta^0_I)^2} \quad \delta^0_I = \frac{T}{E_N} \quad \delta^0_H = \frac{S}{E_T} \quad , \]

where \( \delta^0 \) is the displacement for onset of softening, \( \delta^0_I \) and \( \delta^0_H \) are the mode I and mode II onset of delamination, \( \beta \) is the mode mixity, \( T \) is the normal strength, \( S \) is the tangential strength, and \( E_N \) and \( E_T \) are the cohesive normal and tangential stiffness, respectively.

The displacement at which failure occurs was determined by the equation
\[ \delta^F = \frac{2(1 + \beta)^2}{\delta^0} \left[ \left( \frac{E_N}{G_{IC}} \right)^{\alpha} + \left( \frac{E_T}{G_{IIc}} \beta^2 \right)^{\alpha} \right]^{-\frac{1}{\alpha}}, \] (7.11)

where \( \delta^F \) is the ultimate displacement, \( G_{IC} \) and \( G_{IIc} \) are the mode I and II strain energy release rates, and \( \alpha \) is the mixed-mode exponent.

If the interface stresses exceed the strength of the bond, further loading decreases the stiffness and residual strength along a linear path (Fig. 7-4). Upon reloading, the new reduced stiffness load path will be followed. Once the relative displacement between parts causes the stored energy to exceed the maximum strain energy, the bond fails, thus capturing delamination between plies.

![Diagram](image)

**Fig. 7-4. Progressive softening of the cohesive bond up to the point of failure.**

When this model is used to capture composite delamination, physical strengths and strain energies can be readily obtained from double cantilever beam and end load split tests for pure mode I and mode II delamination. However, the bond stiffnesses, \( E_N \) and \( E_T \), are numerical parameters, for which it is more difficult to determine suitable values. While it may appear that the material stiffness should be substituted, this leads to physically unrealistic values for the softening and failure displacements. A review of the literature indicates that when this model was used in the FE code, arbitrarily high values for the stiffness are selected in order to obtain a close-to-perfect bond among the nodes of each ply [82].
7.4.2.1. Implementation in the FE Code

The above cohesive formulation has been implemented in the explicit FE code using both 8-node brick elements and tied constraints between nodes. In the former method, the cohesive properties, such as the stiffnesses, are incorporated into the element behavior, and the element is deleted once the failure condition has been reached. In the latter method, a penalty-based contact formulation is used to tie slave nodes to master elements. The tied constraint is deactivated once the failure criterion is met.

The cohesive element approach requires the bonded parts to have identical mesh patterns on their bonded surfaces so that the cohesive elements can be matched to each part. In contrast, the tied constraint approach is well-suited for bonding two parts with dissimilar meshes since elements do not have to be matched. Nodes of the slave parts will be tied to master elements based on proximity, and there is no limit to how many nodes may be tied to a single element.

7.5. Cohesive Model Development

The mixed-mode bilinear cohesive formulation was incorporated into a detailed numerical analysis of delamination due to normal surface impact on a composite. Experimental data published by Ilyas et al. [82] for a case of rigid impact on a laminated composite plate provided a detailed characterization of the resulting delamination damage using an ultrasonic scanning method. This test case was replicated in a dynamic FE analysis, and an accurate cohesive element-based delamination model for a composite structure was developed.

7.5.1. Model Setup

A laminate consisting of 10 carbon-fiber reinforced composite plies with a \([+45/-45/0_2/90]_s\) layup was modeled. Each ply was represented using one layer of solid elements, as displayed in Fig. 7-5. The outer 5 cm of the plate edge were fixed to simulate a clamped boundary condition. The impactor was a rigid ball with a mass of 2.32 kg and an initial velocity of about 3 m/s, giving
the ball an initial kinetic energy of 10.3 $J$.

![Image of a rigid ball impacting a composite plate. Cohesive elements are incorporated between the ply layers (highlighted in red).]

A single layer of cohesive elements was placed between each adjacent ply layer shown at the right in Fig. 7-5. The cohesive element thickness can be very small or even zero. Unlike regular finite elements, this does not cause numerical errors or degrade the cohesive element’s performance.

The Chang-Chang failure model (see section 7.3.1) was implemented for each ply layer. The reported material properties for the composite layers were used as input into the model [82]. The composite material properties are listed in Table 7-3, and the cohesive properties are given in Table 7-4.

<table>
<thead>
<tr>
<th>$\rho$ (kg/m$^3$)</th>
<th>$E_{11}$ (GPa)</th>
<th>$E_{22}$ (GPa)</th>
<th>$E_{33}$ (GPa)</th>
<th>$G_{12}$ (GPa)</th>
<th>$G_{23}$ (GPa)</th>
<th>$G_{13}$ (GPa)</th>
<th>$\nu_{12}$</th>
<th>$\nu_{23}$</th>
<th>$\nu_{13}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1272</td>
<td>157</td>
<td>8.5</td>
<td>0.22</td>
<td>4.2</td>
<td>2.2</td>
<td>4.2</td>
<td>0.35</td>
<td>0.53</td>
<td>0.35</td>
</tr>
<tr>
<td>$S_{11,T}$ (GPa)</td>
<td>$S_{11,c}$ (GPa)</td>
<td>$S_{22,T}$ (GPa)</td>
<td>$S_{22,c}$ (GPa)</td>
<td>$S_{12,S}$ (GPa)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.62</td>
<td>2.76</td>
<td>1.62</td>
<td>0.56</td>
<td>0.62</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 7-4. Cohesive parameters for the delamination model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_{IC}$</td>
<td>765 J/m$^2$</td>
</tr>
<tr>
<td>$G_{IIIC}$</td>
<td>1250 J/m$^2$</td>
</tr>
<tr>
<td>$T$ (MPa)</td>
<td>60</td>
</tr>
<tr>
<td>$S$ (MPa)</td>
<td>60</td>
</tr>
<tr>
<td>$E_N$ (N/mm$^3$)</td>
<td>4.2</td>
</tr>
<tr>
<td>$E_T$ (N/mm$^3$)</td>
<td>2.2</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>1</td>
</tr>
</tbody>
</table>

7.5.2. Impact Results

The progressive impact at selected time steps in Fig. 7-6 clearly shows the presence of both local effects, as indicated by the local indentation of the ball into the plate, and the global reaction of the structure, in which the entire plate is observed to dip down with the impact. Delamination is initiated early into the impact, and separation between plies can be clearly observed at the peak of the plate deflection shown in Fig. 7-6(c).

![Fig. 7-6. Section view of the rigid ball impacting the composite plate. Delamination can be seen between many of the plies.](image-url)
Sliding between delaminated plies is also prevalent and is shown in detail in Fig. 7-7. In-plane deformation can also be seen as the elements no longer have uniform dimensions.

![Fig. 7-7. Sliding between delaminated plies (a) early and (b) later in the impact.](image)

Delamination first appears between plies where the fiber orientation changes from 0° to 90° and vice versa. This is due to the high degree of directional stiffness mismatch by the plies that causes high tangential stresses at their interface. The growth of delaminations in the laminate is shown in Fig. 7-8. The delamination patterns are somewhat peanut shaped and are oriented in the direction of the lower ply fiber orientation. This is consistent with behavior seen in many composite impact experiments [82, 83].

![Fig. 7-8. Delamination growth in a composite plate impact model.](image)

\[ t = 0.5 \text{ ms} \quad t = 1 \text{ ms} \quad t = 2 \text{ ms} \]
All of the plies have delaminated in the area directly underneath the ball. This can be regarded as the major delamination region. In addition, delamination extends outward from the impact zone for several plies. This is a secondary delamination region.

![Diagram showing major and secondary delaminated regions]

**Fig. 7-9. Major and secondary delaminated regions.**

The energy-time history of the impact event is shown in Fig. 7-10. Kinetic energy in the model is primarily the kinetic energy of the impactor. Since the ball is rigid, internal energy is only located within the plate model. The hourglass energy is less than 10% of the internal energy for any point in time and is thus within tolerable limits. Minimal hourglassing effects were observed in the analysis, indicating that hourglass control was effective.

![Energy-time history plots for composite plate impact]

**Fig. 7-10. Energy-time history plots for composite plate impact.**
Fiber damage was minor throughout the plies. However, matrix tensile failure was observed in each of the plies near the point of impact (Fig. 7-11). The affected area grew larger in the lower plies, consistent with the expected higher tensile forces as the plate was subjected to global bending by the impact.

![Matrix tensile failure throughout the composite plies.](image)

Total energy in the model is constant, indicating energy is well-preserved. Eroded internal energy (IE) is strain energy in an element prior to its deletion. For instance, when a cohesive element contains internal energy due to relative displacement of the plies and is then deleted once satisfying the failure criterion, its dissipated energy is included in the eroded IE. The strain energy of intact elements, plus eroded IE of failed elements, equals the total internal energy.

\[
\text{Internal Energy} = \text{Strain Energy} + \text{Eroded IE} \tag{7.12}
\]
7.5.3. Comparison with Experiment

The total delaminated area was compared with the experimental results by Ilyas et al. [82] where delamination was evaluated using a sonic c-scan method (Fig. 7-12). The experiment displayed a major delaminated region in which the majority of plies were completely delaminated. The numerical model very closely predicted the area and shape of this region. The FE model over-predicted the major delaminated area by 5.85%.

![Fig. 7-12. Comparison of delaminated area with experiment c-scan results from Ilyas [82].](image)

The FE model also predicted a secondary region in which only one or two plies delamination were present through the thickness of the composite. These additional delaminations were either not reported or were not detected by the sonic scan. With the additional area, the FE model over-estimated the delaminated region by 13.6%. However, the lower extent of delamination amongst the total number of ply bonds in their region suggests these will have a lower effect on the plate response than the major delaminated region. These results are tabulated in Table 7-5.

<table>
<thead>
<tr>
<th>Table 7-5. Comparing delamination from FE model and experiment.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Delamination</td>
</tr>
<tr>
<td>Experiment (m²)</td>
</tr>
<tr>
<td>Major plus Secondary Delamination</td>
</tr>
<tr>
<td>498.1</td>
</tr>
</tbody>
</table>

7.5.4. Investigation of Bonding Response

The bonding response was also evaluated experimentally and numerically (Fig. 7-13). The bonding response was influenced by the delaminated area. The FE model predicted the delaminated area more closely than the bonding response. However, the FE model over-estimated the bonding response by 2.7% for the major delaminated area and 16.6% for the major plus secondary delaminated area.

![Fig. 7-13. Comparison of bonding response with experiment c-scan results from Ilyas [82].](image)
Overall, the FE model results compare well with the experimental results. The major delaminated area observed in the experiment was predicted within less than 6% by the numerical model. With the addition of the secondary delaminated area, the FE model over-predicts the delaminated zone to a larger extend. Nevertheless, this demonstrates that the developed numerical method is able to provide accurate, if not slightly conservative, estimates of the delaminated area in a thin composite structure subject to impact.

7.5.4. Mesh Dependence Study

It was determined that the impact region would require a relatively fine mesh to capture intricate damage details. In order to reduce analysis time, the total element count was decreased by employing a coarser mesh away from the impact zone. To accomplish this, two meshing schemes were investigated (Fig. 7-13):

1) a transition mesh with abrupt mesh density changes, and

2) a scaled mesh with element dimensions extended outward in the x- and y-directions.

In order to focus on the effect of mesh density on delamination, a purely elastic ply model with no damage effects was employed (see the discussion in section 7.5.5). Elastic properties were the same as those given in the top row of Table 7-3.
First, the transition mesh technique was studied. It was found that despite refinements of the inner and overall mesh, the sharp change in element density caused the impact effects to be focused within the dense inner mesh zone (Fig. 7-14). Stresses were focused within this central area and around the mesh transitions zones. In case this was due to using to coarse of a mesh, the transition mesh was refined. However, the same stress effect and widespread delamination throughout the fine mesh region were both observed in every case regardless of the level of overall mesh refinement (Fig. 7-15).
Stresses in the top ply of the composite are shown in Fig. 7-16. The mesh transition did not appear to have a significant effect on the stress response of the composite regardless of the mesh refinement level. This is evident in that the stress pattern that developed did not experience a sudden drop or cutting off of the response at the transition from one mesh region to another. In addition, the delamination damage responded to further mesh refinement, and a mesh convergence study was carried out.
(a) Low mesh density
(b) High mesh density

Fig. 7-16. von Mises stresses within the composite plate showing that the transition region does not strongly affect the stress response.

To check for mesh convergence, the widths of the elements in the x- and y-directions were progressively reduced. The z-direction thickness remained the same for all configurations. Therefore, a useful non-dimensional measure of the mesh density was selected to be the “width-to-thickness ratio”.

The total delamination for several different width-to-thickness ratios are shown in Fig. 7-17. Each figure is from the same vantage point and orientation in the model. Therefore, the width-to-thickness ratio not only affected the area of delamination, but the pattern as well. Despite differences in the shapes, the delaminated areas are similar for the 2.5:1 and 2:1 ratio models.

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>3:1</td>
<td>0.0044 m²</td>
</tr>
<tr>
<td>2.5:1</td>
<td>0.0022 m²</td>
</tr>
<tr>
<td>2:1</td>
<td>0.0021 m²</td>
</tr>
</tbody>
</table>

Fig. 7-17. Total delaminated area for different ply element width-to-thickness ratios.
As the width-to-thickness ratio was reduced, area of delamination began to show little change with further mesh refinements (Fig. 7-18). This signified that the mesh choice was having a progressive lesser influence on the response, indicating a converged solution. Once the ratio reached 2:1, further mesh refinements showed little change in the delaminated area. Therefore, a ratio of 2:1 was chosen for subsequent analyses.

![Graph showing delaminated area versus width-to-thickness ratio]

**Fig. 7-18. Total delaminated area in all layers versus element width-to-thickness ratio.**

### 7.5.5. Influence of Ply Damage

Weakening of the plies due to internal damage can influence the progression and total extent of delamination, and vice versa. In order to evaluate the effect this damage had on ply delamination, an elastic composite material model without damage was compared to the above case when damage was taken into account.

In the elastic case, the delamination pattern is much more uniform and even appears to have lines of symmetry within each layer of delamination (Fig. 7-19). Also, the total delaminated area is larger for the elastic case than the damage case. This indicates that impact energy is being dissipated via delamination rather than ply failure.

For the damage case, the delamination pattern possesses some features that are similar to the
elastic case. Overall, however, the pattern is much more complex, and local ply failure appears to constrain the delamination growth to a smaller area. More layers become delaminated within the confined area.

![Elastic Ply Model vs Damage Ply Model](image)

**Fig. 7-19.** Comparison of delamination growth between a model with ply damage and without ply damage.

The energies present in each model are given in Fig. 7-20. The elastic model produced very smooth results over the impact event. In contrast, the damage case displayed jumps in the energies, especially around 1.3 ms, as ply damage and delamination grew.

The ball was stopped by the plate at around 2 ms, indicated by zero kinetic energy. Up to this point, the results of the two models are very similar except that the eroded IE of the elastic model
was approximately 22% lower than that of the damage model.

Fig. 7-20. Comparison between energies with ply damage and without ply damage.

As the ball and plate rebound, the energies in the two models show significant differences, with the damage case containing more internal energy in the plate and imparting less kinetic energy to the ball by the conclusion of the impact. This indicates that the plate incorporating ply damage has dissipated more energy through damage, whether by ply or delamination local failure, than the elastic plate. Table 7-6 shows these results and shows that greatest difference seen by incorporating ply damage was the increase in eroded IE by 24.3%.

Table 7-6. Final energies for the pure elastic and damage ply model cases.

<table>
<thead>
<tr>
<th>Final Impact Energies</th>
<th>Elastic Ply Model</th>
<th>Damage Ply Model</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic Energy (J)</td>
<td>7.11</td>
<td>6.48</td>
<td>-9.7%</td>
</tr>
<tr>
<td>Internal Energy (J)</td>
<td>3.27</td>
<td>3.82</td>
<td>+14.3%</td>
</tr>
<tr>
<td>Eroded IE (J)</td>
<td>1.17</td>
<td>1.54</td>
<td>+24.3%</td>
</tr>
<tr>
<td>Internal / Eroded IE Ratio</td>
<td>35.7%</td>
<td>40.4%</td>
<td>+13.3%</td>
</tr>
</tbody>
</table>

The force-time history for the damage ply model indicates that a lower peak force is
experience by the composite plate. This is a result of the plies weakening as they are damaged, and thereby both dissipating energy and offering less resistance to the impactor.

![Graph showing force-time history for plate with and without ply damage.](image)

**Fig. 7-21.** Comparing force-time history for plate with and without ply damage.
8. HYBRID FAN BLADE DAMAGE ANALYSIS

Hybrid fan blades are manufactured using unidirectional carbon fiber-reinforced epoxy pre-preg material [84]. Layers of the material are arranged and built up on preforms before being bonded together to create the fan blade structure. Metal reinforcements, such as a titanium sheath that wraps around the leading edge of a composite blade, are then added to improve the part’s impact resistance. The resulting part is referred to as a hybrid structure.

In this section, details of the composite model for each blade are presented. Next, the leading edge modeling approach and the implementation of the cohesive formulation for representing bonding (and de-bonding) of the titanium component is detailed. Finally, test cases for bird impact on an array of hybrid fan blades are presented to demonstrate the viability of the methodology developed.

8.1. Composite Blade Modeling

While it would be optimal to model both ply and delamination failure, it was determined that capturing ply failure was sufficient given that ply failure is more severe than delamination to the blade. In addition, the computational cost of having cohesive bonds throughout all of the blades was extremely high. Numerical stability issues were also encountered with cohesive elements during the blade pre-stressing analysis. Additionally, studies have found that long, simply supported beams or plates, which fan blades could be considered, are more prone to ply failure than delamination failure [85]. Therefore, a laminated shell element approach was used to model the composite portion of the fan.

8.1.1. Element Formulation

In addition to in-plane loads, hybrid blades are subject to untwisting and torsional loads during pre-stressing and impact. Therefore, the BWC shell elements based on 1st order shear laminated plate theory and with warpage control (see Chapter 6.2) were again utilized.
8.1.2. Material Model

Many studies have aimed to assess the accuracy of various composite failure models and rank them against one another [63, 81, 86]. Different models possess unique strengths and weaknesses based on the particular loading conditions, part geometries, material properties, and numerous other parameters. In the end, there is no agreement for which is the “best” model or how to select the most appropriate model, requiring investigators to conduct exhaustive studies for each new problem.

The goal of this work was not to determine an optimal material model for composite fan blades, but rather demonstrate that these models can be implemented in an explicit FE platform in order to form a unique and comprehensive crashworthiness methodology. Detailed studies to determine the most appropriate model for soft impact scenarios may be conducted in future work.

With these considerations, the Chang-Chang model with strength- and strain-based failure criterion was used for the composite portion of each blade (see model details in Chapter 7.3.1). It should be noted, however, that many other composite failure models, such as the Tsai-Wu model mentioned previously, can be activated in the developed methodology.

Ply failure was determined by calculating generalized stresses in each orthogonal material direction for each layer. If the state of stress and strain met any of the matrix or fiber failure criteria, the load-carrying capacity of the layer was removed from the calculation, thus capturing damage through the reduced stiffness and strength properties in a portion of the composite. Once each layer satisfied the failure criterion, the element was removed, thus identifying local failure within the composite.

Detailed information about the layup used for existing hybrid blades was not available at the time of this work. A composite layup of [0°/+45°/-45°/0°] was used, with the 0° fiber orientation
directed along the length of the blade. This provided a blade with high bending stiffness and strength in the radial direction while still affording significant rigidity in the transverse direction. The thickness was smoothly varied across the blade from 6.35 mm (0.25 in) at the tip and 25.4 mm (1 in) at the base, which is consistent with descriptions of hybrid fan blades [84]. Material properties for IM7/8551-7 graphite fiber composite were used for the material definition, shown in Table 8-1.

Table 8-1. Composite material model parameters for hybrid fan blade model.

<table>
<thead>
<tr>
<th>$\rho$ (kg/m$^3$)</th>
<th>$E_{11}$ (GPa)</th>
<th>$E_{22}$ (GPa)</th>
<th>$G_{12}$ (GPa)</th>
<th>$G_{23}$ (GPa)</th>
<th>$G_{13}$ (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1272</td>
<td>157</td>
<td>8.5</td>
<td>4.2</td>
<td>2.2</td>
<td>4.2</td>
</tr>
<tr>
<td>$S_{11,T}$ (GPa)</td>
<td>$S_{11,C}$ (GPa)</td>
<td>$S_{22,T}$ (GPa)</td>
<td>$S_{22,C}$ (GPa)</td>
<td>$\varepsilon_m$</td>
<td>$\varepsilon_s$</td>
</tr>
<tr>
<td>1.62</td>
<td>2.76</td>
<td>1.62</td>
<td>0.56</td>
<td>0.62</td>
<td>0.01</td>
</tr>
</tbody>
</table>

8.2. Leading Edge Modeling

The leading edge was represented using shell elements that wrapped around the end of the composite blade. Elements of the leading edge were offset to the approximate location of the upper and lower surfaces of the composite. The complete blade model showing the thickness variation across the composite portion and the placement of the metal edge are shown in Fig. 8-1.
Fig. 8-1. Hybrid fan blade model showing (a) thickness variation, (b) leading edge metal reinforcement bonded using a tied cohesive model.

The titanium leading edge was modeled using an elastic-plastic material model with a strain-based failure criterion. Properties for Ti-Al6-4V ASTM Grade 5 titanium alloy were used to define the leading edge behavior.

Table 8-2. Titanium leading edge material parameters for hybrid fan blade model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$ (kg/m$^3$)</td>
<td>4420</td>
</tr>
<tr>
<td>$E$ (GPa)</td>
<td>112.5</td>
</tr>
<tr>
<td>$\nu_{12}$</td>
<td>0.31</td>
</tr>
<tr>
<td>$S_{\text{yield}}$ (GPa)</td>
<td>0.98</td>
</tr>
<tr>
<td>$E_{\text{yield}}$ (GPa)</td>
<td>1.59</td>
</tr>
<tr>
<td>$\varepsilon_{f\text{ail}}$</td>
<td>0.22</td>
</tr>
</tbody>
</table>

8.3. Cohesive Modeling

The same cohesive formulation used in Chapter 7 for capturing ply delamination was explored for modeling de-bonding of the leading edge. In this case, the tied constraint approach was used to bond the titanium leading edge to the composite edge. With this approach, parts
being coupled do not need to share similar geometries or meshes. This provides a convenient method of defining cohesive behavior between parts with very different shapes and meshes.

Cohesive parameters for the composite/metal bond were not available at the time of this study. As an approximation of the peak stress and the mode I and II energy release rates, properties from carbon-fiber composite delamination experimental studies were obtained from the literature and decreased by half before being applied, with the assumption that the composite/metal bond would form a weaker interface than bonding between similar materials.

<table>
<thead>
<tr>
<th>Table 8-3. Cohesive parameters for the hybrid fan blade model.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_N$ (MPa)</td>
</tr>
<tr>
<td>60</td>
</tr>
</tbody>
</table>

8.4. Preloading Analysis

The same dynamic relaxation analysis used in Chapter 6.6 was employed to pre-stress the hybrid blade prior to impact (Fig. 8-2). The cohesive tied connection successfully captured the bonding between the leading edge and the composite while it was brought to the correct stress state for the dynamic rotation analysis phase.

The stress state throughout the blade was more complex than the previous metal blade analysis. In addition to the more complex geometry, the orthotropic material layers support the load unevenly, with the fiber direction providing the most structural support.
8.5. Hybrid Fan Assembly Impact

The fan assembly was formed using an array of hybrid fan blades configured based on a modern turbofan design arranged around a central hub and connected via rigid constraints at their bases. Half of the fan assembly was modeled with a total of 9 blades. The fan assembly was set rotating with an initial speed of 2400 rpm, a typical speed for similar high bypass ratio turbofans with wide-chord fan blades.

A bird with a relative velocity of 100 m/s was incorporated into the model to impact the fan assembly at about 60% of the span of the blades away from the hub. FAA regulations require impact at minimum 50% mid-span for certification. The model approximated the validation tests in that the bird was launched straight into the fan blade with a velocity perpendicular to the fan assembly plane of rotation. It should be noted, however, that more damaging angles could be obtained by aiming the bird at the fan blades to increase the incidence angle of the impact [87].
The model setup is shown in Fig. 8-3. Each blade is numbered for easy referencing. The bird first collides with blade 2.

**Fig. 8-3. Explicit FE model of a bird strike case on a hybrid fan assembly**

8.5.1. Analysis Results

The bird was sliced into two parts upon impact with the first blade. Part of the bird material remained in contact with the blade, while the remaining material continued to impact additional structures. The soft body was separated into multiple impactors due to slicing by subsequent blades, with portions coming into direct contact with four fan blades. Contact between the structures and the bird involved both a slicing action with the blade edge and a blunt impact with the rear face of the blade. The impact event is shown in Fig. 8-5.

**Fig. 8-4. Bird sliced by impact with the hybrid fan assembly.**
None of the hybrid blades experienced failure in any part of the structure as a result of the impact. However, critical damage mechanisms were captured throughout several of the blades impacted by the bird. The damage analysis showed fiber tensile failure occurring at the base of two blades as a result of high stress at their respective roots, as shown in Fig. 8-6.
In addition, matrix failure was predicted within each of the blades, especially where the bird impacted the face of the blade rather than the leading edge. This resulting damage is shown in Fig. 8-7.

![Fig. 8-7. Matrix tensile damage throughout the impacted fan blades.](image)

Leading edge delamination was predicted in several blades. These de-bonded regions are shown as red in Fig. 8-8, while blue represents those bonds that are still mostly intact.

![Fig. 8-8. Leading edge de-bonding due to bird impact (blue = bonded, red de-bonded).](image)

The force-time history of the bird impact with several blades is shown in Fig. 8-9.
In order to observe the effect that the leading edge has in preventing the onset of damage and failure in the hybrid blade, additional simulations were carried out in which the leading edge was
not present, reducing the construction to a plain set of composite blades. Impact on such a fan assembly is shown in Fig. 8-11.

Fig. 8-11. Bird impact on a composite fan assembly without metal leading edge reinforcements (von Mises stresses shown).

Fiber tensile failure was predicted in the same locations for the plain composite fan assembly as the one with incorporated leading edge. A comparison of the final matrix damage state for each fan assembly is shown in Fig. 8-12.
A plain composite blade experiences significantly higher stresses and damage as the bird impacts the side of the blade, folding over a section of it and inducing failure in several other parts of the blade. Damage initiates near the leading edge as expected, but also near the blade tip. This may suggest why many hybrid blade designs also include an additional L-shaped metal reinforcement that stiffens the blade tip and trailing edge.
9. COMPREHENSIVE HYBRID ENGINE ANALYSIS

An all-encompassing modeling approach that captures all of the dominant damage mechanisms in a hybrid engine subject to bird impact is a powerful tool.

The methods developed in the previous sections for modeling birds, jet engines, and composite structures are combined and expanded to form a successful and comprehensive methodology for modeling advanced hybrid jet engine forward sections subject to bird strike. Details of the methodology are recapped, and a general set of design parameters are outlined.

9.1. Modeling Approach

The methods developed for the analysis of traditional forward sections in Chapter 6 were adopted for modeling advanced engine designs incorporating composite materials and hybrid structures. The hybrid fan blades, composite casing, fan hub, cone, inner axle, and axle bearings were again identified as necessary minimum details to be modeled in explicit FEA-based methodology.

The FE approaches developed in Chapter 7 for modeling the response and damage of composite structures were utilized to model the composite casing. This allowed ply damage and delamination to be captured.

Finally, the novel hybrid fan blade modeling technique detailed in Chapter 8 was used to model the full fan assembly. The bird was also modeled using the conclusions from Chapter 5.

9.2. Bird Modeling

The final SPH bird model detailed in Chapter 6 was used in the full hybrid engine analysis. Two models, a 4 lb. bird and an 8 lb. bird, were developed with the same length-to-diameter ratio for use in impact analysis. Each model possesses the same number of particles, material properties, and numerical properties.
9.3. Axle, Hub, and Bearings Modeling

The axle was modeled using shell elements with an elastic-plastic material model using aluminum material properties.

The hub, nosecone, and other forward components were modeled as rigid parts. Several features of the low pressure compressor, such as the rotor disks and supporting structures, were modeled in order to more realistically capture the distribution of mass in the forward section.

The bearings were represented using rigid “sleeves” that held the axle in place via a contact definition. Each sleeve was able to rotate about any axis, allowing the axle to flex if needed, but remained fixed at their center of mass.

Fig. 9-1. 4 lb. and 8 lb. SPH bird models (35,000 particles each).

Fig. 9-2. Axle, hub, cone, and bearings utilized in model.
9.4. Hybrid Fan Blade Modeling

The hybrid fan blade modeling approach developed in Chapter 8 was used to model a full hybrid fan assembly incorporating 18 fan blades. This arrangement is consistent with modern designs for high bypass wide-chord fans using hybrid structures. The hybrid blades were connected to the central hub by rigid translational and rotational constraints on the nodes at the base of the blades.

The composite material properties, metal properties, and cohesive parameters were equivalent to those used in sections 8.1, 8.2, and 8.3.

![Connections between hub and base of each hybrid blade (connections in red).](image)

9.5. Composite Casing Modeling

It was determined that delamination was important to capture within the casing due to the high out-of-plane forces to which it would be subjected if any blade fragments impacted its inner surface. Delamination dissipates the impact energy and helps the casing contain blade fragments. If a region is delaminated, it may also be less effective at surviving subsequent fragment impact
as energy must now be dissipated purely by ply failure, which can lead to penetration. To capture delamination, the solid/cohesive composite modeling approach developed in Chapter 7.5 was used to model the casing.

9.5.1. Layer Representation

The casing design explored in this work was a unidirectional carbon-fiber reinforced composite. The casing had three different regions through the thickness in which material was oriented in the 0° direction, the 90° direction, and finally the 0° direction again. The 0° direction was oriented in the circumferential direction of the casing.

An actual fan casing requires thousands of thin layers of composite material in order to build up the necessary thickness needed to have sufficient containment properties. Modeling thousands of layers throughout the entire structure would be prohibitively expensive, even using a layered shell approach. One method of maintaining accuracy while decreasing computational cost is to model layers with identical material properties and fiber orientations as single layers.

Using this tactic, the casing was modeled as a [0°/90°/0°] composite layup, and each layer...
was modeled using a layer of solid elements. Three layers through the thickness also provided a minimally sufficient number of data points for accurately capturing the bending stiffness of the casing. A fine mesh was used around the fan blades.

![Composite casing model. Red points indicate fixed boundary conditions.](image)

**Fig. 9-5.** Composite casing model. Red points indicate fixed boundary conditions.

### 9.5.2. Damage Modeling

Ply damage and delamination were anticipated near the front of the casing where it may interact with the fan blades. However, at the rear of the casing, damage may not be present or may be less critical to capture. The operations needed to check for damage and delamination and update residual element properties. Therefore, computational time may significantly increase, especially over the time scales considered in this analysis.

In an effort to reduce computational cost, the rear portion of the casing utilized solid elements incorporating an elastic material model with the same orthotropic properties of the composite at each layer. No cohesive layers were placed between these elements.

In the front of the casing, a composite damage model was incorporated into each element.
Cohesive elements were placed between each of these layers, thus allowing delamination to be captured (Fig. 9-6). The conclusions drawn from the mesh dependence study in Chapter 7.5.3 were applied to the casing model. The dimensions of the elements in the plane of the composite were chosen such that they had a 2:1 relation with the thickness of each layer.

**Fig. 9-6. Modeling features for the front and rear portions of the composite casing.**
Fig. 9-7. Full hybrid forward section model for bird impact.
The mesh density of the casing away from the fan assembly was decreased since less damage detail was required in this region. The reduction was achieved by scaling the elements outwards from the fan region using a similar scheme used in the Chapter 7.5 in the cohesive model development. In the rear of the casing, the mesh density was reduced significantly.

The models of the composite casing, hybrid blades, and other engines components were combined to form the full engine hybrid forward section model. The bird was incorporated into the model and located at about the half-span of the fan blades.

9.6. Contact Modeling

It was necessary to capture interactions between the

a) bird and engine components (fan blades and casing)

b) blades and casing

c) blades and other blades

d) blades with themselves

Upon impact with the fan blades, the body undergoes very large deformation and spreads nonlinerly from the point of impact. This was identified as a debris region that would vary with the speed of the rotating fan assembly (Fig. 9-8). Bird debris is radially accelerated into the fan casing. The bird’s momentum carries it through the fan region until the majority of the material exits the forward section. Contact was defined between the bird and only those blades it would directly impact (in this case, five blades) before passing through the fan. A region was defined around the bird debris zone in which contact was established between the bird and the casing (Fig. 9-9).
In addition, the time for the bird material to pass through the forward section was estimated using the initial bird velocity and the casing dimensions. At this time, all bird contact was terminated. These measures reduced computational time associated with the contact in the simulation.

A numbering convention was adopted for the blades in the contact definition since these blades were subjected to the highest forces and were the most likely to experience damage and
failure. The numbers assigned to each blade are listed in Fig. 9-10.

![Numbering convention for blades involved bird/blades contact.](image)

**Fig. 9-10. Numbering convention for blades involved bird/blades contact.**

### 9.7. SPH Calculations

The operations performed for governing particle behavior in the SPH approach are relatively expensive computationally. A volume was defined around the fan assembly in which SPH calculations were performed while the bird nodes were within the region. Outside of this zone, the particle calculations were ceased, and the bird nodes were treated as independent point masses (Fig. 9-11). This allowed the bird material behavior to be accurately modeled during the blade impact but reduced the model accuracy when it was unnecessary. This minimized needless computation and thereby saved analysis time.
9.8. Pre-loading Analysis

The same dynamic relaxation analysis used in Chapters 6.6 and 8.4 was employed for pre-stressing the hybrid blade prior to impact.

Fig. 9-11. SPH calculation zone.

Fig. 9-12. Hybrid fan assembly stresses following the pre-loading phase.
9.9. Impact Analysis

The fan assembly was set rotating with an initial speed of 2400 rpm. A bird with a relative velocity of 100 m/s was incorporated into the model to impact the fan assembly at about mid span of the blades. Both of the bird models developed, 4 lb. and 8 lb., were tested separately.

9.9.1. 4 lb. Bird

Impact with the 4 lb. bird induced high stresses and damage throughout the blades with which the bird material came into direct contact. However, none of the blades experienced any complete failure or fragmentation due to the impact.

Fiber and matrix failures were effectively predicted by the composite failure model. Reduced stiffness was observed in in the blade where damage was predicted, and the blade was heavily deformed. As expected, matrix failure was much more widespread that fiber failure throughout the plies. The percentage of damaged plies within each element is shown in Fig. 9-15.
Fig. 9-13. Impact onto hybrid fan assembly by an 4 lb. bird (von Mises stresses shown).
Fig. 9-14. Force-time history of the 4 lb. bird/blades contact (filtered).

Fig. 9-15. Composite failure modes throughout hybrid blades impacted by a 4 lb. bird.
It was observed that damage was more prevalent in the outer plies. The outer plies are subjected to higher normal strains and stresses when subjected to bending caused by the bird impact. This tendency towards outer ply damage is shown in Fig. 9-16.

Fig. 9-16. Composite damage to hybrid blade 3 due to the 4 lb. bird impact.
The dominant energies in the problem are shown in Fig. 9-17. All other energies were zero or negligible, including internal energy. It is clear that a significant portion of the fan kinetic energy was transferred to the bird as a result of the impact.

![Energy-time history of the 4 lb. bird impact.](image)

9.9.2. 8 lb. Bird

Impact with the 8 lb. bird induced caused immediate failure to blade 3. Subsequent impact between the detached blade fragments and one of the adjacent blades prompted further damage to the forward section.
Fig. 9-18. Impact onto hybrid fan assembly by an 8 lb. bird (von Mises stresses shown).
Fig. 9-19. Detached fragments from blade 3 causing failure to blades 4 and 5.

As a large portion of blade 3 impacted the casing, delamination of the casing layers was effectively captured by the cohesive model. Delamination first initiated between the innermost layers before the outer layers were affected, as shown in Fig. 9-20. As the fan assembly became unbalanced and further contact occurred between the casing and the fan blades, delamination was
initiated in several locations around the casing (Fig. 9-21).

The delamination response appeared to be influenced by the casing mesh. Also, delamination extended to the edge of the cohesive zone in several locations. Future work will aim to refine the mesh and extend the cohesive zone if necessary to capture the full delamination response.

Fig. 9-20. Progressive delamination from blade 2 detachment.

Fig. 9-21. Final casing delamination.
Fig. 9-22. Force-time history of the 8 lb. bird/blades contact (filtered).

Fig. 9-23. Energy-time history of the 8 lb. bird impact.
9.10. Closing Remarks

In this chapter, all of the methods developed throughout this work were applied to the task of modeling bird impact onto an advanced jet engine forward section design incorporating modern hybrid fan blades and a composite casing. These methods included techniques for accurately modeling a bird, an engine forward section, composite structures, and hybrid aerospace structures during in an impact event. It has been shown that when these methods are combined into a single modeling approach, they provide a robust and accurate methodology for assessing the full extent of damage to modern advanced propulsion designs impacted by a soft object.

Critical information about the location, extent, and mode of damage in complex jet engine hybrid and composite structures is provided. The progression of damage throughout the forward section and the influence of complex dynamic interactions are readily captured. Moreover, this is provided in a single analytical approach without making simplifications for the significant structures to be captured.
This work has presented a detailed predictive modeling methodology for comprehensive analysis of bird strike and post-impact damage assessment in jet engine forward sections containing hybrid and composite structures. The developed approach shows promise for accurately capturing the full range of multifaceted failure mechanisms in hybrid and composite structures, including specific fiber and matrix failure modes, ply delamination, and hybrid structure de-bonding, as they evolve throughout the forward section. The methodology for assessing the complete extent of damage in a single, concise numerical analysis is a breakthrough for the modeling of advanced modern forward sections that can contribute greatly to the future design and analysis of these systems.

Strategies for accurately modeling different aspects of the problem were developed separately and then combined to form the full methodology. Effective methods had to be developed for modeling the bird, engine forward section, composite delamination, and hybrid structural damage. Significant contributions were made to science and application of numerical solutions in each of these areas, as well as the overall crashworthiness analysis of advanced forward sections.

10.1. Contributions

10.1.1. Bird Modeling Using SPH

An effective meshless Lagrangian particle approach bird modeling approach based on the SPH method was developed, and the influence of critical modeling parameters on the solution was thoroughly explored. The cutoff pressure, a physical parameter for simulating material tensile strength, was shown to have minimal influence on the resulting impact pressure, but contributed to numerical energy losses.

The particle density and artificial bulk viscosity, both important numerical parameters for the
SPH method, were varied in order to study their effect on the solution. Particle density had a profound effect on the peak impact pressure, and it was demonstrated that refinement of the particle density lead to a converged impact response and decreased numerical energy losses. Despite the importance of artificial bulk viscosity in the treatment of shockwaves, reducing this numerical parameter had little effect on the impact pressure-time history. These parametric studies explored crucial modeling variables that are not thoroughly discussed in the literature.

10.1.2. Forward Section Modeling for Bird Strike

A two-stage analysis approach was formed for modeling a forward section subject to foreign object impact. The analysis steps included (1) pre-stressing rotating components in a static analysis, then (2) initiating the bird impact event in a dynamic analysis. Impact with the bird and complex interactions among engine components were captured effectively.

The effect of the fan blade mesh density on the predicted damage was explored. It was shown that as the fan blade mesh density increased, interactions between the blade tips and casing were more accurately captured, and the extent of damage and failure changed less with increasing mesh density. It was also shown that analyses lacking this detail will not only fail to characterize damage and potential shearing of the casing, but will also significantly underestimate the extent of damage to the fan assembly.

10.1.3. Composite Delamination Using Cohesive Elements

A composite damage modeling technique was formed for capturing inter-ply delamination, as well as intra-ply damage, in composites. Delamination was modeled using this fracture mechanics-based cohesive formulation. A test case of impact onto a composite plate was simulated using the method, and the numerical results were found to be in good agreement with the experimental data.

A mesh dependence study was then conducted to assess the behavior of cohesive elements
for different meshing schemes and densities. The results indicated that the sharp mesh transitions amplify the predicted delamination to an unrealistic extent. It was also shown that with a smooth scaled mesh transition, the overall mesh density could be refined such that the delamination response converged to a specific size and pattern.

10.1.4. Novel Hybrid Structure Modeling Approach

A novel hybrid structure modeling strategy was developed for capturing progressive failure of the composite blade, the metal leading edge, and de-bonding of the two sub-structures simultaneously in a single analysis. A physics-based cohesive formulation was implemented to bond the two components together, and progressive weakening and local failure of the bond due to bird impact was successfully captured.

In addition, the method was able to incorporate a composite material model where ply damage mechanisms were predicted, and the resulting degradation of the structural properties was captured. This original modeling approach provides new capabilities for assessing the unique failure modes of hybrid structures not present in previous analytical tools.

10.1.5. Comprehensive Crashworthiness Methodology

Finally, an innovative crashworthiness methodology for advanced propulsion systems was created by combining these individual modeling strategies. A full forward section incorporating hybrid fan blades and a composite engine casing was modeled for impact by a range of soft impactors. Strategies to substantially reduce the calculation time were introduced, such as limiting bird contact to a small debris region and deactivating the SPH formulation when the bird exits the engine compartment.

For the 4 lb. bird impact, the model captured de-bonding of the leading edge from several of the blades most strongly impacted by the bird. Fiber and matrix damage was captured throughout the composite portion of the blade. This scenario demonstrated that the methodology could
successfully characterize complex hybrid damage below the threshold for complete failure.

For the 8 lb. bird impact, failure was captured in one of the blades, and the detached portion impacted the casing. This initiated extensive delamination between each of the layers of the composite casing. Blade fragments encountered other nearby blades, triggering further blade damage, casing delamination, and casing ply damage. This impact scenario demonstrated the methodology’s ability to effectively model part failure and subsequent engine component interactions, along with the full range of complex ply damage, delamination failure, and part fragmentation stemming from engine component interactions.

10.2. Future Outlook

In this work, modeling methods have been developed using results from small-scale experiments, such as bird impact upon a steel plate and delamination in a flat composite plate. Future investigations are required to validate and further develop these modeling methods by matching more complex impact scenarios, such as actual cases of bird strike on a rotating composite fan blade or impact on a curved plate with similar dimensions to an actual engine casing, where these or other similar experimental results are available. Ideally, a well-documented case of bird impact onto an engine incorporating hybrid and composite structures can be used for validation.

One particular enhancement will be the incorporation of delamination modeling for the composite portion of the hybrid fan blades. Strategies for overcoming the stability issues observed when incorporating cohesive elements will be researched. Alternatively, material models incorporating delamination that do not explicitly capture ply separation may be explored for their accuracy and implemented.

Throughout this work, mesh refinement studies have been performed to demonstrate that a sufficient level of detail has been used and that the analysis results converge as the mesh density
increases. This is compliant with the $h$-refinement approach for investigating mesh independence (see Chapter 3.1.2). However, the high nonlinearity and complexity of the problem demand that additional studies be performed to show suitable independence of the solution from numerical effects. Alternative meshing schemes and refinement techniques will be studied to verify the viability of the completed methodology.

The long-term ambition of this work is to incorporate the mature, validated methodology into a full multi-disciplinary design environment. Novel design techniques are desired by engine manufacturers that combine fluid, combustion, controls, manufacturing, and structural analysis into a complete system-wide engine performance analysis. One such attempt at this is the NASA-initiated development of Numerical Propulsion System Simulation (NPSS) using coupled multi-physics tools to analyze engine performance at both the component and system levels [88]. So far, 3-D structural analysis of individual parts does not appear to have been successfully coupled with the larger engine performance analysis [89], which is the stated goal [88]. Even if coupling and computational multi-physics challenges are overcome, the analysis is only as good as the methodologies applied to study each associated physical domain. Prior to this undertaking, the available literature identified numerous shortcomings in development of potential comprehensive methodologies capable of dynamic damage assessment of hybrid structure forward sections. In this work, the aim has been to devise an accurate crashworthiness methodology to fill that gap. Following future development and validation, the methodology proposed here will constitute an effective tool for capturing complex hybrid and composite propulsion forward section damage, either as an independent tool or as a key component of the structural analysis in a larger multidisciplinary methodology.

An accurate methodology for predicting damage and failure in advanced propulsion systems
subject to soft impact will be a critical tool allowing for the development of robust, crashworthy
designs. Hence, the methodology introduced here is a major step towards realizing the goal of
developing an efficient multi-disciplinary analysis design and certification platform that can
assess total engine performance and dynamic structural behavior resulting from soft impact.

10.3. Closing Remarks

Overall, it was aimed to create a comprehensive analysis method for assessment of hybrid
engine designs that will reduce reliance on physical tests and can support rapid future
developments of advanced aerospace propulsion systems. The full dynamic damage prognosis
capabilities demonstrated by this methodology encompass aspects, such as hybrid structural
damage, leading edge de-bonding, blade-out failure, and subsequent engine casing delamination,
which remain mainly unaddressed in previous studies of bird strike analysis.

The development of a relatively “fast” aerospace propulsion design tool for evaluating the
crashworthiness of future advanced structural engines has been one of the long-term objectives
of this study. While physical testing of jet engines may never be eliminated, a validated
numerical crashworthiness methodology can limit physical testing to final certification in an
endeavor remove it from the design phase. Such a tool is critical for future advancements where
the added complexities presented by advanced composite and hybrid structures will make
physical testing exceedingly costly and burdensome. This work has taken a novel approach
towards developing such a numerical methodology and has taken a great leap toward making this
concept a reality.
APPENDIX I: CASE STUDY – BIRD IMPACT ON THE F-16 CANOPY

The goal of this case study was to compare Lagrangian, ALE, and SPH numerical approaches for modeling a bird in cases of high velocity impact and benchmark their performances against experimental data for bird strike on an F-16 canopy. Specifically, it was desired to observe which approach produced the most accurate deformation structural response.

A1.1. Experiment

Experimental results for bird impact on an F-16 canopy were obtained from Brockman [22]. The 0.5 in thick canopy was made of simple isotropic polycarbonate material. The bird was impacted along the centerline of the canopy at 180 m/s. The shape of the deformed centerline canopy profile was precisely measured for several time instances. This test case was simulated using each of the three FE bird models.

![Fig. A1-1. F-16 canopy bird strike testing (image from Brockman [23]).](image)

A1.2. FE Models

The three bird models were given the same cylindrical geometry and dimensions (Fig. A1-2). The Lagrangian and SPH models were simply generated the location of their mesh or particles location, respectively. The ALE model was created by defining a cylindrical grid (shown in red) and assigning cells at the center to be filled with bird material in a cylindrical pattern. The remaining grid cells were void of any material.
Fig. A1-2. Bird impact models (a) Lagrangian, (b) ALE (shown with moving grid), and (c) SPH.

The Lagrangian model was defined using 8-node solid elements. First, the null material model was implemented for the model (see Chapter 5). However, large deformation and heavy mesh distortion terminated the analysis in an error. To counteract these effects, a strain-based failure criteria was activated to attempt to delete the heavily distorted elements. This eliminated the errors, but resulted in very poor results.

Alternatively, an elastic-plastic-hydrodynamic material model was implemented with an added pressure-based failure criterion. Details about this model can be found in reference [72]. When pressure within an element caused it to failed, its mass was transferred to its connected nodes, and these nodes remained in the simulation as discrete point masses. This is one method of conserving mass in the problem with the Lagrangian approach. Appropriate bird constitutive properties for this model were obtained from Brockman [22].
The ALE and SPH models utilized the null material model with an incorporated linear polynomial equation of state (see Chapter 5). No failure criteria are required with these approaches. All three models had an initial velocity of 180 m/s, a length of 22.5 cm, and a radius of 10.6 cm. The material properties for each bird model are given in Table A1-1.

<table>
<thead>
<tr>
<th>FE Model</th>
<th>Material Model</th>
<th>Density (kg/m$^3$)</th>
<th>Shear Modulus (MPa)</th>
<th>Yield Stress (MPa)</th>
<th>Hardening Modulus (MPa)</th>
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<td>ALE Null</td>
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<td>2.2</td>
<td>5.03</td>
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<tr>
<td>SPH Null</td>
<td>950</td>
<td>2.2</td>
<td>5.03</td>
<td>13.9</td>
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<td></td>
</tr>
</tbody>
</table>

The canopy was modeled using shell elements incorporating an elastic-plastic material model with a strength-based failure criterion. The material properties for the canopy model are given in Table A1-2.

<table>
<thead>
<tr>
<th>Polycarbonate canopy material properties.</th>
<th>$\rho$ (kg/m$^3$)</th>
<th>$E$ (MPa)</th>
<th>$E_{\text{yield}}$ (MPa)</th>
<th>$S_{\text{yield}}$ (MPa)</th>
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<td>224</td>
<td>49.22</td>
<td>75.84</td>
<td></td>
</tr>
</tbody>
</table>

A1.3. Results

The impact event for each FE bird model is shown at various time steps in Fig. A1-3. In each model, the bird induces heavy deformation in the canopy. Despite the large motions of the canopy, no plastic deformation or failure is predicted.

The ALE and SPH models spread out heavily as the simulation progresses (Fig. A1-3). The general behavior of each model was similar. The Lagrangian model behaves much differently,
however. Upon impact, bird elements are subjected to high pressures that delete elements at the front of the bird. The nodes of the failed elements were kept in the model and continue to impact the canopy. By the end of the impact, they were all that remain as the bird material completely failed.

![Impact progression using each FE modeling approach.](image)

The bird material in the Lagrangian model does not spread out as the other models predict. This is because the eroded nodes can no longer interact with other nodes or element. Therefore,
no internal pressure is generated to push the nodes away from one another.

The ALE and SPH simulations predicted a canopy response that closely matched experimental data of the deformed canopy profile over the impact window. Simulations using the Lagrangian bird model predicted an overall greater deformation of the canopy than the experimental data (Fig. A1-4). All of the models are generally conservative, meaning that the predicted deformation exceeds the experimental data and implies that canopy damage would be predicted earlier than observed in physical experiments. In this sense, the Lagrangian bird model is most conservative, but least accurate.

![Graph comparing simulation results to experimental data for the deformed canopy profile.](image)

**Fig. A1-4.** Comparing simulation results to experimental data for the deformed canopy profile.

The force-time history of the impact between the bird and the canopy is shown in Fig. A1-5. Both the Lagrangian and ALE models predict loss of contact force at various times throughout the impact. This may suggest contact difficulties or that too fewer elements are being used. In contrast, the SPH bird remains in contact throughout the impact.
It was observed that both the ALE and SPH bird models produced a very accurate deformation response for the canopy, as shown in Fig. A1-4. The Lagrangian bird model over-predicted the canopy deformation in comparison with the test data. Despite having approximately the same level of detail, the SPH model required 30% less computation time than the ALE model. Lastly, the force-time history response of the SPH bird impact produced a smoother response that correlated better with observations from bird impact experiments on compliant targets [9]. From these results, it was chosen to develop an SPH approach as part of the crashworthiness methodology.

A1.4. Conclusions

Fig. A1-5. Force-time history at initial impact point.
Utilization of several processors in parallel, each with its own memory, to solve numerical problems has the potential to reduce computation time compared to typical shared memory processing platforms. However, special considerations are necessary for parallel processing solutions due to the splitting of the memory, requiring tactics such as passing messages between processors to maintain consistent solutions.

The goal of this study was to compare solutions obtained from the standard shared memory processing (SMP) and the massively parallel processing (MPP) versions of the explicit FE code utilized throughout this work for bird impact on a hybrid fan assembly. This study is not extensive; however, it is meant to highlight the differences that can be observed between SMP and MPP solutions.

A2.1. FE Model and Decomposition

The hybrid fan assembly model examined in Chapter 8.5 was used in this case study (Fig. A2-1). The bird impacted the rotating fan assembly with an initial velocity of 100 m/s.

An important consideration for parallel processing solutions of FE problems is how to decompose the domain for treatment by each processor. The FE code contained a default
algorithm for dividing the problem based on the initial velocities present in the model and the number of processors utilized. The decomposition when using the default algorithm for 8 processors is shown in Fig. A2-2. Each unique color represents a part of the problem that will be solved by a single processor.

As can be seen in Fig. A2-2, the problem has been poorly decomposed. The large blue region indicates that one processor is responsible for performing calculations over approximately 80% of the problem. The narrow bands of color show that the other processors are likely being under-utilized.

**A2.2. Solution Comparison**

The original analysis discussed in Chapter 8.5 was the SMP solution. The MPP solution was run and compared to the SMP solution. The MPP solution was solved using 8 processors partitioned in the same manner shown in Fig. A2-2. The default settings in the code for the MPP analysis were used.

Overall, each analysis showed the same relative response as the bird impacted and subsequently came into contact with several fan blades (see Chapter 8.5). However, significant differences were seen in the predicted patterns of damage throughout the blades. One significant
difference, the predicted matrix tensile damage, is shown in Fig. A2-3 for two of the blades most heavily impacted by the bird. Red indicates regions where matrix tensile failure has occurred throughout the laminate, while blue shows areas not experiencing matrix tensile failure. Overall, the extent of matrix tensile damage predicted by the MPP solution is much less than that predicted by the SMP solution.

![Fig. A2-3. Matrix tensile damage for SMP and MPP solutions.](image)

The energies in the SMP and MPP solutions are shown in Fig. A2-4 and Fig. A2-5, respectively. The energy-time history of the MPP solution is much different than the SMP solution and shows apparent nonphysical energy jumps and negative energy values. Despite the fact that the MPP solution appeared reasonable in the observed behavior of the model, this examination of the energies in the problem revealed critical shortcomings of this particular analysis.

One reason for the odd energy phenomena may be the uneven decomposition of the problem. Another possibility is that the default settings for the MPP analysis are insufficient for a problem of this complexity and may require adjustment. For instance, the default procedure for passing
information from one processor, including nodal positions and forces, to the others throughout the analysis may need to be enhanced to ensure proper coupling between each sub-problem.

A2.3. Future Considerations

The decomposition of the MPP analysis obtained with the default algorithm was likely inefficient in its distribution of the solution across processors and may be the source of different results and irregular energies present in the problem. A better decomposition would spread the
calculations more evenly across processors. For examples, one possible decomposition for the
fan assembly that will be attempted in future work is shown in Fig. A2-6.

![Fig. A2-6. Alternative problem decomposition.](image)

**A2.4. Conclusion**

Significant differences can occur between problems solved using an SMP platform versus
and MPP computational platform. While a solution may appear reasonable, investigation of
critical values, such as damage and energy in the problem, is necessary to determine if an
analysis has yielded valuable results. Care must be taken when using MPP platforms as they
cannot be considered easy answers to the analysis of large dynamic and fully non-linear FE
problems.
REFERENCES


