COUPLED MICROMECHANICS-FINITE ELEMENT PROGRESSIVE FAILURE DYNAMIC ANALYSIS APPROACH: F-16 CANOPY CASE STUDY

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Abstract

This work presents a numerical approach for predicting damage evolution in aerospace structures subject to impact through the use of an explicit finite element code coupled with a micromechanics damage analysis module. Soft body impact, in the form of bird strike on an F-16 canopy, is simulated using this Progressive Failure Dynamic Analysis (PFDA) approach. First, bird impact on a canopy is studied for three finite element modeling approaches: (1) Lagrangian, (2) Arbitrary Lagrangian-Eulerian, and (3) Smoothed Particle Hydrodynamics. From these results, one method is chosen for incorporation into the PFDA methodology. Validation of results is performed by comparing against test data for the canopy deformation versus time and canopy failure at different bird impact velocities. The completed methodology clearly identifies impact failure mechanisms and their percent contribution to the multisite structural failure in order to guide aerospace design efforts.

1 Introduction

The impact of soft objects, such as birds and hail stones, with aircraft continues to pose great challenges in the design of safe aircraft components and systems. Existing numerical tools are often unable to predict how a structure will fail due to impact. Therefore, extensive physical testing is conducted to ensure a high level of crashworthiness for an aircraft design and conformance with certification standards.

Heavy reliance upon physical testing to assess the crashworthiness of aircraft components requires that fully functional parts be fabricated and destroyed. In addition to the high cost and long development time associated with this approach, difficulties arise in collecting data due to the short-duration of impact window, high impact forces, and potential for damage to structures and measuring equipment. Testing is further complicated by the need to study laminated and fiber-reinforced composite structures that are increasingly common in modern aircraft.

Fig. 1. Effect of bird strike on an aircraft canopy.

In an effort to reduce reliance on physical experiments, approaches that use the finite element method (FEM) are now employed for simulating soft impact [1-3]. However, these techniques are limited by the material models available for simulating the structural response and the available techniques for modeling soft objects. Accurate methods of predicting progressive damage in structures are still the subject of ongoing investigations. If failure is predicted, a thorough analysis of the stresses and strains present in a structure leading up to the predicted failure point can be conducted in an attempt to determine what conditions cause failure. For multiple failure modes, this process is extremely tedious, especially for dynamic impact problems. A more valuable modeling approach would be one that was capable of analyzing and determining specific failure mechanisms in a structure subject to impact so that further design decisions can be better informed.

This study aims to develop a platform for predicting soft impact-induced damage and failure for aerospace structures using a Progressive Failure Dynamic Analysis (PFDA) approach that allows specific failure mechanisms and their contribution to damage evolution in a structure to be easily determined. Such a tool can facilitate the design of complex aircraft components with robust crashworthy performance while decreasing design cycles and reducing reliance on physical tests. Numerical models were developed for bird strike on an F-16 canopy and compared with experimental data in order to demonstrate the methods viability. This work expands upon an earlier study to assess the crashworthiness of the F-16 canopy design in a bird strike event using numerical analysis and experiments in the pre- and post-design phases [4].

2 Failure Analysis Methodology

Modern aircraft employ materials with largely isotropic material properties, such a metals and plastics, and increasingly more complex laminated and fiber-reinforced composite materials with strongly direction-dependent properties and extremely complex failure mechanisms. In the analysis of composite aircraft components, it has been realized that FEM models are greatly challenged by the complexity of composite structures whose macroscale behavior is governed by the properties and interactions of microstructures with vastly different mechanical characteristics. Homogenization approaches rely on empirically derived equations of state that are in need of further validation for scale-up and fail to characterize damage accumulation and failure mechanisms.

To overcome the shortcomings of these approaches, micromechanics models have been developed which attempt to estimate individual stresses and strains in the heterogeneous microscale structures in order to predict fracture initiating at the microscale. These codes can be coupled with a finite element method to predict the behavior of composite structures with complex geometries. In one approach, an FEM code uses the effective constitutive properties of each element, whether isotropic or anisotropic, to determine nodal displacements that occur due to the problem conditions, such as forces induced by impact between parts with high relative velocity. Using these nodal displacements, the micromechanics code solves for the stresses and micro-stress from the macro-level down to the fiber-level to determine damage with each successive solution iteration.

Due to the complex, direction-dependent nature of composite materials, micromechanics codes are inherently capable of determining damage sources and the directionality of the stresses or strains that induce damage. This is useful for identifying mechanisms that cause dynamic structural failure. In typical FEM approaches aimed at capturing structural damage, a failure theory or condition is defined by which elements are deleted when the condition is attained, such as a strain limit or stress value. Once one of the criteria is met, the element is removed without any information provided for which specific conditions caused the failure, such as stresses or strains in a particular direction. Micromechanics codes are able to provide the approximate orthogonal direction in which stresses or strains are present and the combination of individual mechanisms that induce failure. This information is extremely valuable as it provides insight into the cause of damage and may suggest specific design changes to prevent failure of a component.

Because of the advantages outlined above, a coupled micromechanics-explicit finite element algorithm was utilized to analyze and predict damage to an F-16 canopy subjected to soft impact in the form of bird strike. Because the canopy was an isotropic polycarbonate material, the part was modeled without fibers present in the formulation, meaning the canopy was only composed of matrix material with constitutive properties being the same in all directions. Further details about the model can be found in [5] and [6].

Damage mechanisms were captured by the analysis included:

1. tensile failure in the longitudinal and transverse directions (as determined by the local element coordinate system),
2. compressive failure in the longitudinal and transverse directions,
3. in-plane shear failure, and
4. failure determined by the Modified Distortion Energy (MDE) criterion.

Failure due to tensile, compressive, and in-plane shear stresses was defined to occur when the maximum principal stress in an element exceeded the polycarbonate ultimate strength, causing the element to fail.

The MDE criterion is a modified form of the von Mises failure criterion for predicting damage in anisotropic materials due to distortional effects. Differences in directional strength and material behavior are taken into account; however, when isotropic properties are used, the MDE criterion reduces to the original von Mises criterion [7].

3 Explicit FE Modeling

3.1 Canopy Model

Geometric data for an F-16 canopy and its polycarbonate material properties were obtained from Brockman [8]. Shell elements with an assigned thickness of 1.27 cm were used to represent the thin, curved structure. The failure analysis methodology described above was the material model employed for the canopy. Stiffness and directional strength properties of the plastic were inputs into the model.

3.2 Bird Model

Accurate modeling of soft bodies during impact is a complex challenge that is still the focus of ongoing research [9-11].

3.2.2 FE Modeling Approaches

Three bird models were given the same cylindrical geometry and dimensions. The Lagrangian and SPH models were simply generated by defining mesh node and particle locations, 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.

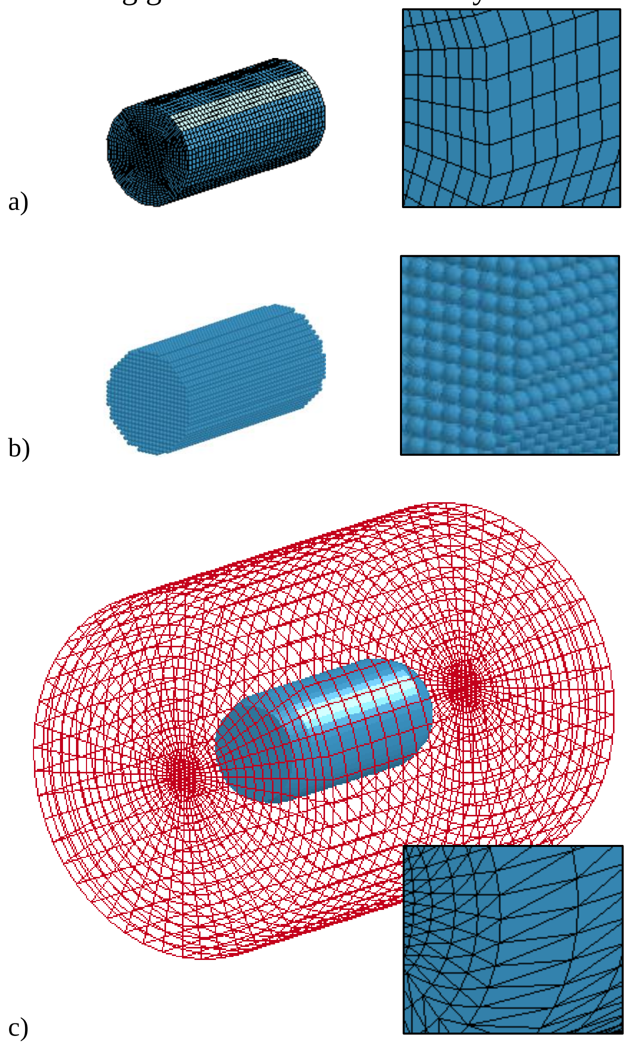


Fig. 2. Bird impact models (a) Lagrangian, (b) meshless Lagrangian, and (c) ALE (shown with moving grid).

The Lagrangian model was defined using 8-node solid elements. First, the null material model was implemented for the model. 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.

The ALE and SPH models utilized the null material model with an incorporated linear polynomial equation of state. No material failure parameters 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.

3.1.1 Material Models

Two material models appropriate for fluids were chosen for representing the bird. The first, called the "null" model, models fluid behavior by only applying volumetric stiffness and ignoring shear stiffness in an object. The pressure-volume relation in the body is governed by an equation of state (EOS), which in this study was chosen as the following polynomial function:

$$P = C_1\mu + C_2\mu^2 + C_3\mu^3 \tag{1}$$

The variable μ is defined by the equation

$$\mu = \frac{\rho}{\rho_0} - 1, \tag{2}$$

where ρ and ρ_0 are the current and initial mass density, respectively. The C's in Eq. (1) were material coefficients calculated as

$$\begin{gathered} C_1 = K \\ C_2 = (2k-1)C_1 \\ C_3 = (k-1)(3k-1)C_1 \end{gathered} \tag{3}$$

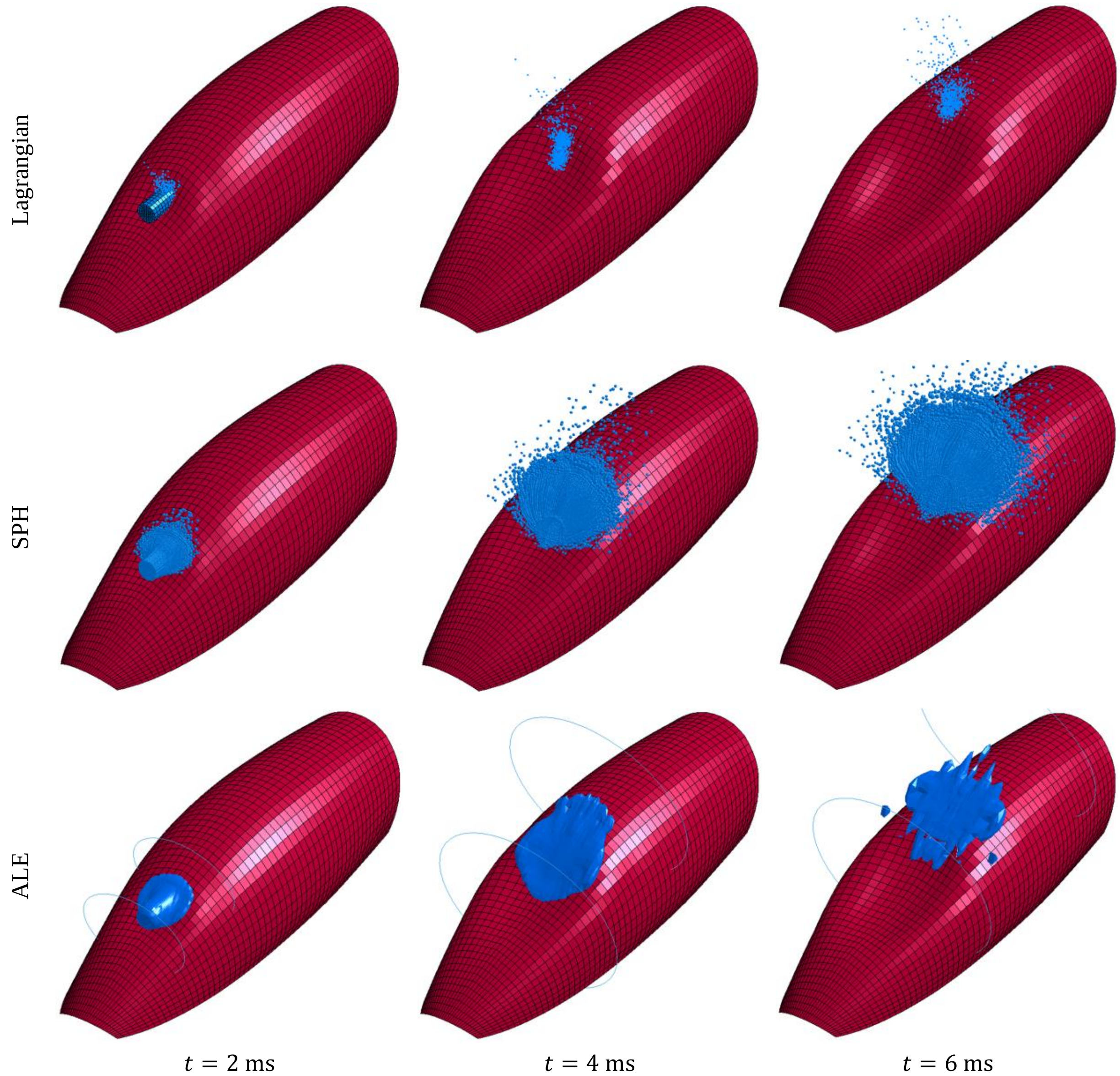


Fig. 3. Impact progression using each FE modeling approach for the bird.

where K and k are the bulk modulus and compressibility factor, respectively, of the material [11].

The other material model explored for the Lagrangian bird model was an elastic-plastic-hydrodynamic material model. This model was implemented with an added pressure-based failure criterion. 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. More details about this model can be found in reference [12]. Appropriate bird constitutive properties for this model were obtained from Brockman [8].

4 Impact Simulation and Validation

4.1 Bird Model Comparison

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

The ALE and SPH models spread out heavily as the simulation (Fig. 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.

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. 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 the most conservative.

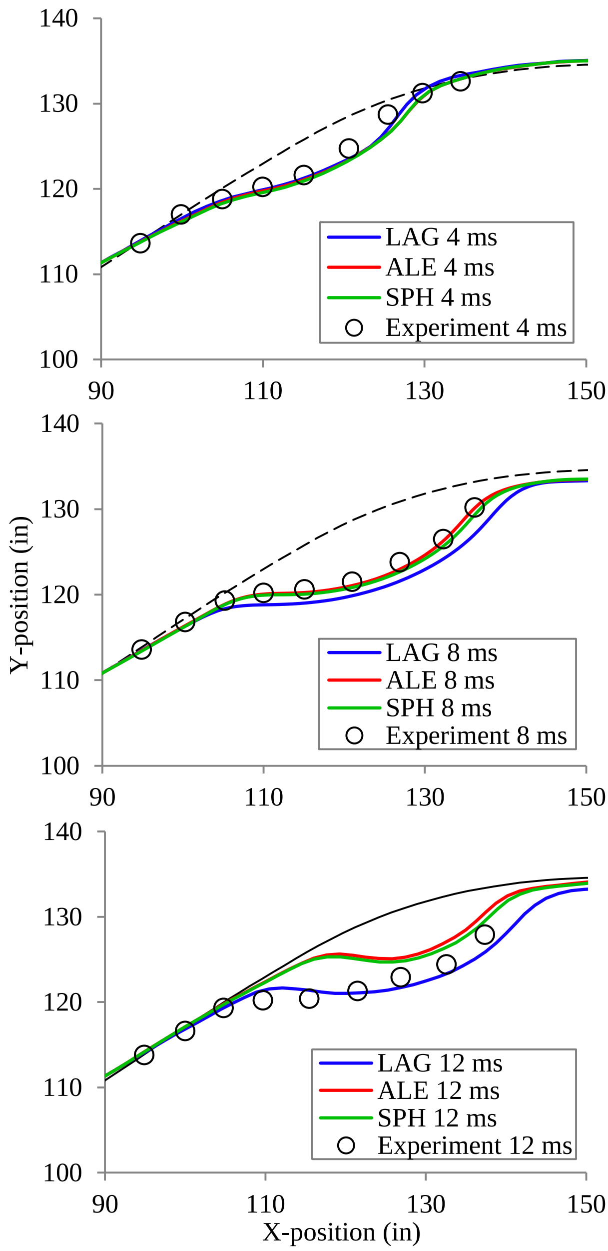


Fig. 4. Comparing simulation results to experimental data for the deformed canopy profile at different times.

The force-time history of the impact between the bird and the canopy is shown in Fig. 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 few elements are being used. In contrast, the SPH bird remains in contact throughout the impact.

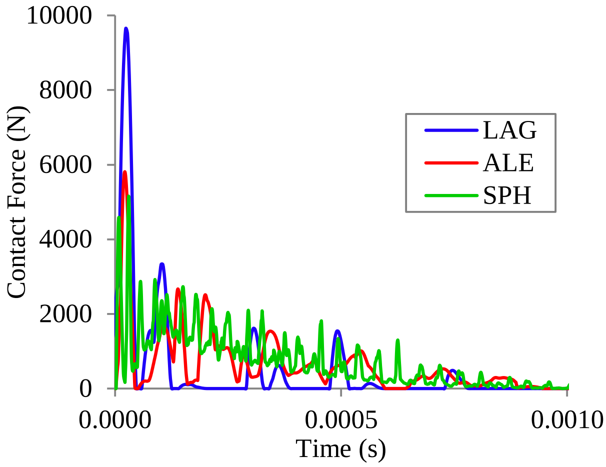


Fig. 5. Force-time history at initial impact point.

It was observed that both the ALE and SPH bird models produced a very accurate deformation response for the canopy, as shown in Fig. 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 [13]. From these results, it was chosen to develop a Lagrangian bird modeling approach as part of the crashworthiness methodology.

4.2 Large Deformation Response from Low Velocity Impact

An elastic-plastic-hydrodynamic material model incorporating yield behavior was assigned to the bird elements. Failure of the bird material was defined to occur once the von Mises stress exceeded the ultimate strength. Erosion of the bird was effectively captured by element deletion.

For the purposes of this study, an elastic-plastic-hydrodynamic material model for the bird was chosen because of its suitability for the problem and the success others have had implementing the model for studying impact on jet canopies [8]. The bird material properties are given in Table 1.

Table 1. Material properties of the bird model.

Density (kg/m^3)	950
Bulk modulus (MPa)	255.1
Shear modulus (MPa)	206.8
Plastic hardening modulus (MPa)	2.07
Ultimate strength (MPa)	20.68

Special attention was given to conserving mass in the solution when element failure occurred, particularly in the bird model. When an element failed, its mass was equally distributed to its corresponding nodes. If deletion left a node independent of any element, it continued to be present in the solution with its position being calculated based on its momentum. Interaction between eroded nodes and active elements was maintained throughout the analysis, allowing failed nodes from the bird to impact the canopy and cause further damage.

Due to the range of potential impact velocities encountered during flight, two initial bird velocity scenarios were modeled: (1) 180 m/s and (2) 230 m/s.

The bird collided with the canopy and began inducing large deformations in the structure. Elements at the front of the bird quickly experienced high stresses upon impact and failed. As subsequent elements of the bird impacted the canopy, they too experienced failure.

For the 180 m/s bird velocity case, the canopy was heavily deformed by the interaction, but did not experience stresses sufficient to cause failure. All bird elements failed as they impacted the canopy.

The position of each node along the centerline was used to create a profile shape throughout the simulation. This profile was compared with experimental data for the position of points along the canopy centerline at several instances in time, obtained from Brockman [8]. The deformed canopy profile shape from both the numerical and experimental data is superimposed in Fig. 6.

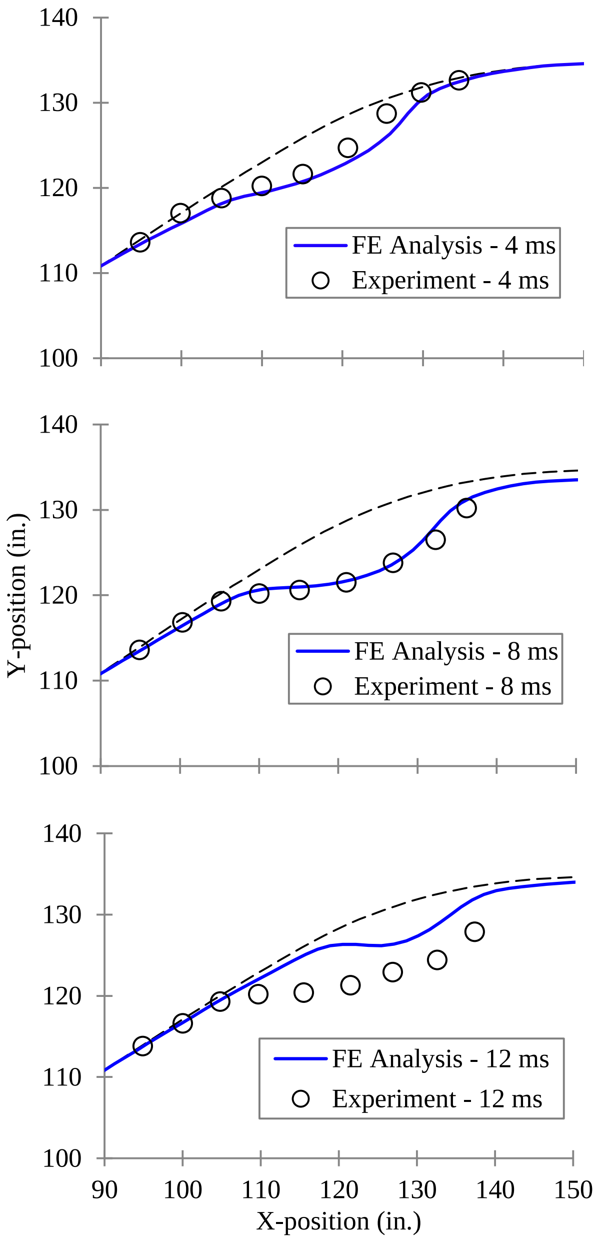
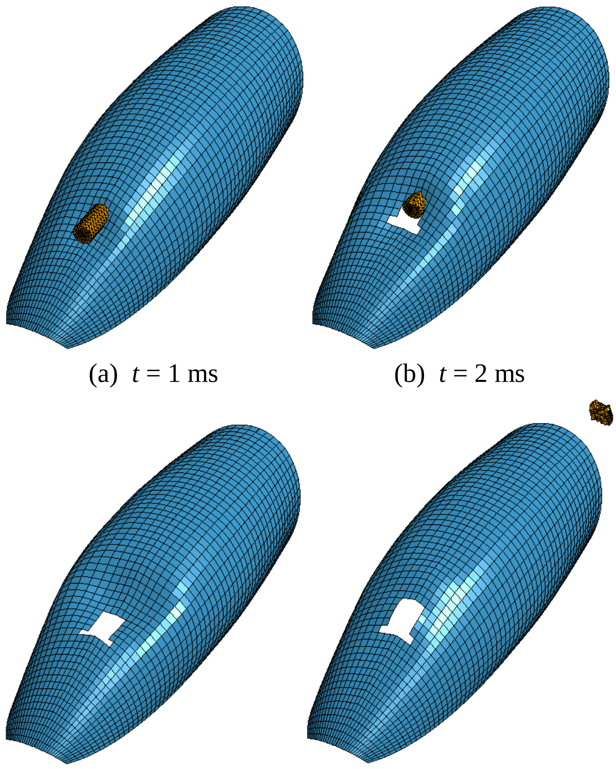


Fig. 6. Deformed canopy centerline comparison between numerical and experimental results.

At 4 and 8 ms, the analysis matched the experiment very well, accurately capturing the complex deformation across the entire canopy. The analysis at 12 ms showed greater deviation from the experimental results, predicting a more rapid elastic "spring back" to the original canopy shape. Overall, the character of the deformed canopy was captured very well.

4.3 Progressive Canopy Failure from High Velocity Impact

For the 230 m/s initial bird velocity case, the canopy experienced failure soon after the impact occurred. This corresponded with the experimental results that also identified damage at the same impact velocity [8]. Elements at the front of the bird failed prior to penetrating the canopy. Once damage grew, the remaining bird material passed through the canopy (Fig. 7).



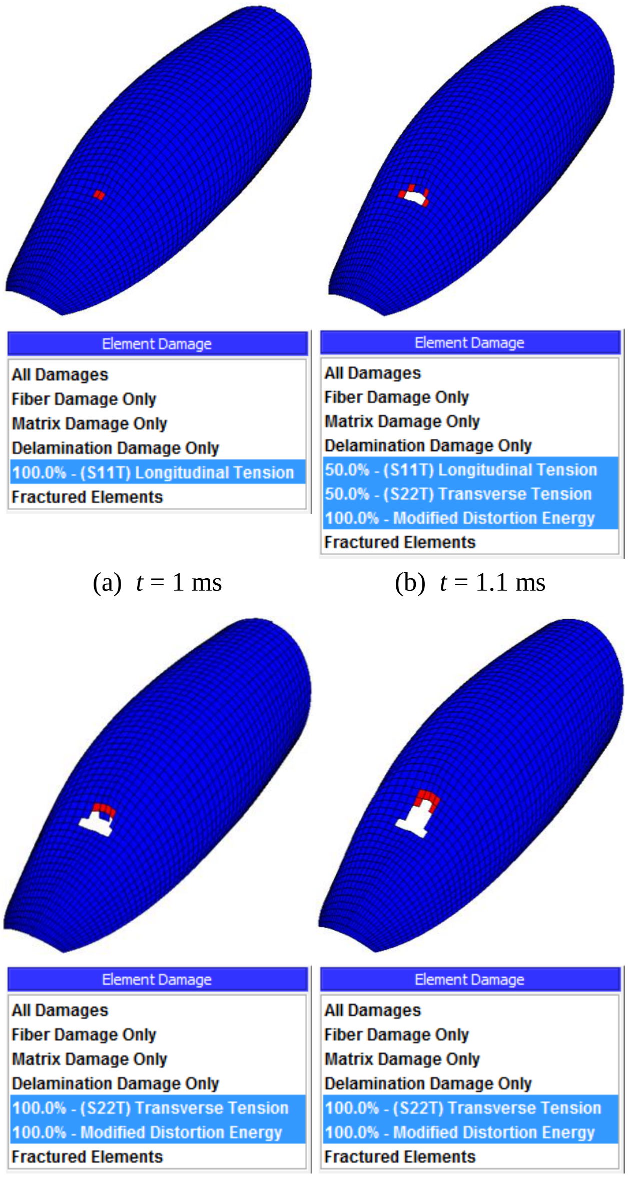
(a) t = 1 ms (b) t = 2 ms

(c) t = 7.5 ms (d) t = 11 ms

Fig. 7. Bird impact at 230 m/s onto an F-16 polycarbonate canopy.

Stresses leading to the dynamic failure behavior were determined by the micromechanics code coupled with the finite element solution. The code allowed the specific source of the damage to be identified and showed the evolution of the damage throughout the simulation. Damage to the canopy at various time steps is shown in Fig. 8.

The table associated with the model lists damage sources present in the simulation, with the percentage indicating the fraction of damaged elements subject to a particular failure mechanism. Failure due to longitudinal tension, transverse tension, and the distortion energy criteria were predicted at different times throughout the analysis, as highlighted below each figure.



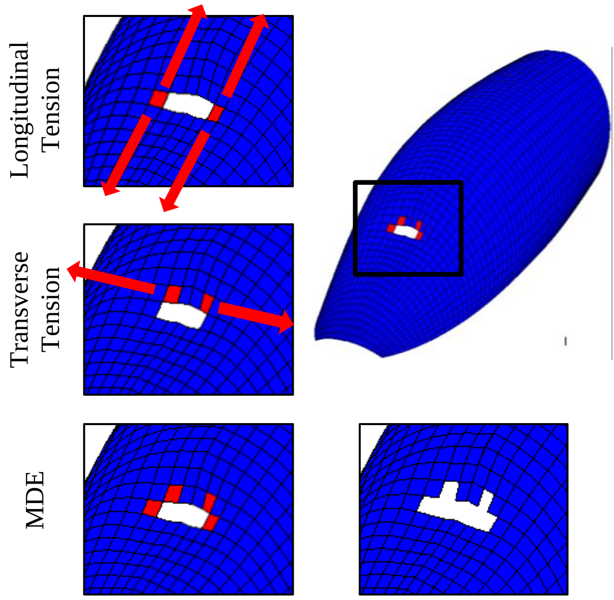
(a) $t = 1$ ms (b) $t = 1.1$ ms

(c) $t = 1.3$ ms (d) $t = 2.4$ ms

Fig. 8. Progressive failure of a canopy impacted by a bird at 230 m/s. Red elements indicate damage, with the damage source(s) indicated below the model.

Fig. 8(a) shows the initial onset of damage in the canopy. The table below the model indicates that tension in the longitudinal direction, approximately the global x-direction, exceeded the ultimate strength of the canopy. The code then removed the element in the next solution iteration and continued the analysis with the failure captured.

Fig. 8(b) indicates that several failure mechanisms were presents at 1.1 ms into the impact event. The code allowed the specific elements subject to each damage mechanism to be identified, as shown in Fig. 9. The value of 50% listed next to Longitudinal Tension indicated that half of the damaged elements at the time (2 in total) were subject to failure due to longitudinal tension (Fig. 9(a)). The same was true for damage due to transverse tension. At the same time, 100% of the damaged elements were subject to failure determined by the MDE criterion, indicating that multiple failure mechanisms could be present in a single element. Over the next two solution iterations, the damaged elements were removed in order to model the canopy failure (Fig. 9(b)).



(a) $t = 1.1$ ms, iteration 13 (b) $t = 1.2$ ms, iteration 15

Fig. 9. (a) Damage mechanisms predicted by micromechanics analysis and (b) subsequent material failure in the form of element deletion.

Further damage with multiple damage sources present are shown at later time steps in Fig. 8(c) and (d). Tensile damage in the transverse direction appeared to be dominant following the initial onset of failure.

These results provide valuable information for aerospace engineers designing crashworthy components to withstand bird strike. Decisions for modifying the design to improve its performance can be better directed by having knowledge of the sources of damage initiation and progression in a component subject to bird impact. For instance, in order to delay or prevent the initial onset of failure to the canopy, redesign efforts could be aimed towards increasing the canopy's strength or reducing the stresses it experiences in the longitudinal direction. Alternatively, the canopy strength in the transverse direction could be increased in order to prevent propagation of damage following the initial onset of failure. Further numerical analyses are necessary to ensure that the solution has converged in order to accurately describe the damage behavior. Detailed information about the specific source of damage in an advanced structural component subject to soft impact is not readily obtainable through experimental methods. Therefore, this numerical tool provides a new level of detailed information that will allow engineers to design advanced aerospace parts with superior safety and performance.

6 Conclusion

A coupled micromechanics-explicit finite element modeling approach was developed that allowed specific failure mechanisms and their contribution to dynamic damage in a structure to be determined for soft impact scenarios. Numerical models employing this approach were developed for bird strike on an F-16 polycarbonate canopy. The solution results for different initial bird velocities compared very well with experimental data. The code predicted the sources of in-situ damage, initial canopy failure, and further dynamic damage progression throughout the analysis that provided insight for future design changes in order to create more fracture-resistant components. The development of an analytical approach for identifying specific damage mechanisms in structures subject to soft impact will facilitate the design of complex aircraft components with robust crashworthy performance, while reducing the reliance on physical tests and their associated time and cost.

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