

Bird Strike Impact Analysis of Vertical Stabilizer Structure Using Abaqus/Explicit

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Abstract: Directional stiffness property and ability to engineer the micro characteristics and ease of manufacture of complicated shapes has made composites a natural choice for aerospace industry. However their major drawback is its vulnerability against impact loads. As Bird impact is a major problem for an aircraft, the present work is take-up to study the effect of bird impact on vertical stabilizer made with composite materials.

To develop a required stiffness to resist bird impact, vertical stabilizer is designed using Glass and Aramid fibers. Stiffness requirement is further improved by using Aluminum sheet as first ply. Different methodologies for bird strike soft impactor modeling are the Lagrangian, Coupled Eulerian Lagrangian (CEL) and the Smooth Particle Hydrodynamics (SPH). Current investigation focuses on Lagrangian and CEL methods.

Bird strike numerical methodology and, bird material are verified with the Wilbeck and Walsh flat plate soft body impact experiments. Bird strike impact involves large deformation and simulating the same using the Lagrangian method is not accurate. But the CEL method which uses Eulerian elements to define the space around the impacted structure is more accurate and numerically efficient. This FE based analysis setup results in savings of time and cost for the manufacturer by limiting the number of experiments for bird strike impact study. Abaqus built-in progressive and damage model for fiber reinforced composite material is used in this study.

With this background, for our current study, several design for the vertical stabilizers that are to be resistant to bird strike, are developed. Design options include completely metallic, completely composite and hybrid structure of metallic and composite structure. Current work focuses on the design of aerospace structures for bird strike impact resistance using Abaqus/Explicit solver and methodologies.

Keywords: Soft Body Impact Analysis, Abaqus/Explicit, Lagrangian, Coupled Euler Lagrangian, Interlaminar fiber/Matrix failure, Damage Initiation/Evolution

1. Introduction

Foreign Object Damage (FOD) is one of the main concerns in design and maintenance of modern aircraft structures. A particular form of high velocity FOD is bird impact damage. A collision with a bird can lead to serious damage. There are other threats to exterior aircraft structures like hail, runway debris etc. But 90% of all incidences today are reported to be caused by bird strike [1]. All forward facing components, like engine fan blades and inlet, the wind shield, window frame, Radome and forward fuselage skin as well as the leading edges of the wings and empennage are prone to bird strike. Hence aviation certifying authorities require a certain level of bird strike resistance in certification tests before the aircraft parts are allowed for operational use. During the certification process, an aircraft must demonstrate its ability to land safely after being struck by a bird anywhere on the structure, at normal operating speeds [2]. In order to comply this requirement, aircraft manufactures need to test the aircraft structures experimentally. This physical validation is time consuming and very costly as this involves number of iterations. Hence in order to optimize the number of experiments required for certification, CAE/FEM methodology is implemented. With the advent of FEM dynamic explicit solvers like, Abaqus, bird strike simulation has become a reliable and cost effective tool.

Bird strike modeling has evolved remarkably since its first attempts, where a pressure pulse simulation on a rigid surface was done in FEM. Different methodologies for bird strike soft impactor modeling, are the Lagrangian, Coupled Eulerian Lagrangian (CEL) and the Smooth Particle Hydrodynamics (SPH) methods. Abaqus/Explicit general contact (penalty method) is used for the current analysis. Aerofoil structure is defined using shell elements, bird by Lagrangian solid elements or in CEL method by the Eulerian elements.

Isotropic material has a higher impact stiffness compared to composites. Manufacture of completely metallic aerofoil structure is complicated and in few instances is not feasible. Ease of manufacture makes composite a better choice and hence composites are extensively used in aerospace structures. But weak transverse stiffness of composite structure is a drawback. This design drawback can be overcome either by increasing the number of plies just for the bird strike impact loads or by using Fiber Metal / Laminate, or with the first ply as aluminum plate, a hybrid structure. The option of hybrid structure proves to be a good design. One of the design concept validated is the use of a metallic sheet on the fiber composite structure. The advantage being that this metallic sheet can be replaced or repaired on damage. Finally one or two design options need to be validated by physical detailed experiments. Current presentation validates the hybrid design of vertical stabilizer for bird impact. This hybrid material design can lead to huge savings on weight and will be more effective for impact resistance.

1.1 Related Work

Earliest works on impact analysis by Wilbeck and Walsh [3], and Welsh [4] are experimental ones. Smojver et al discuss the methodologies related to bird modeling and the material failure modeling using Abaqus for both metallic and composite structures [5], [6] and [7]. Lagrangian formulation for bird behavior description has many drawbacks. Most important is that distortion of finite elements leading to drastic reduction of stable time increments of explicit time integration schemes or even premature analysis termination [8]. McCarthy et al [9, 10] carried out the analysis

on Fiber Metal Laminates (FML), a family of material consisting of alternating plies of thin aluminum and fiber/epoxy with high specific strength, using SPH method and PAM crash software. Abaqus based bird strike methodologies, guidelines [11] are well described in this work providing the numerical techniques for setting up the problem and also compares the Lagrangian and CEL methods with respect to the contact pressures. Erkan et al [13] discuss in detail the difference in the contact types, penalty and kinematic based techniques. Lavoie et al [14] discusses the various numerical modeling techniques, its advantages and disadvantages for bird strike analysis.

Earlier investigations in bird strike involved development of methodologies and were on metallic structures. Notable work on bird strike impact of composite aerospace structures using Abaqus/Explicit is done by Smojver [5], [6] and [7]. Few works involve aerospace structures made of CFRP and Aramid fibers of 32 plies [13]. Efforts are more concentrated in this area on analysis methodologies and validation with few discussions about the applications. SPH is another technique for the bird strike analysis, LS Dyna with SPH for bird strike analysis [14]. Investigation of composite aero structures behavior under impact loading is a major area of interest. Current work validates an alternative hybrid structure with metal as first ply and underlying composite plies as a feasible design.

2. Problem Definition

Soft body impact (Bird Strike) analysis is a multi physics problem as shown in fig.1. This involves dynamic analysis, which is transient, highly non-linear in both geometry and material, contact modeling normal non frictional and material modeling.

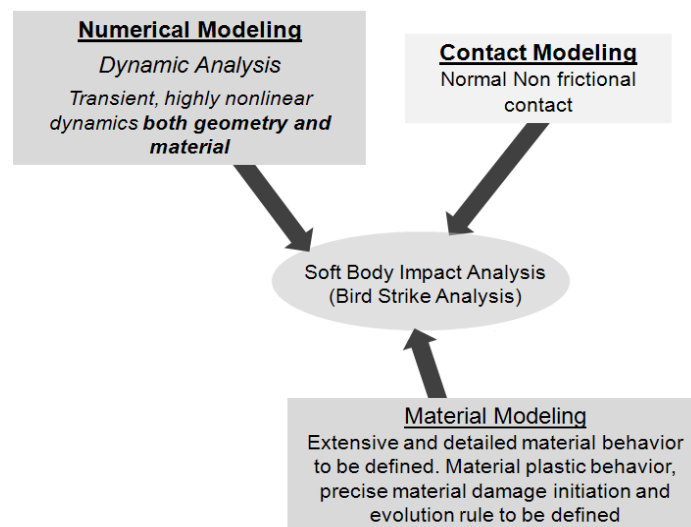
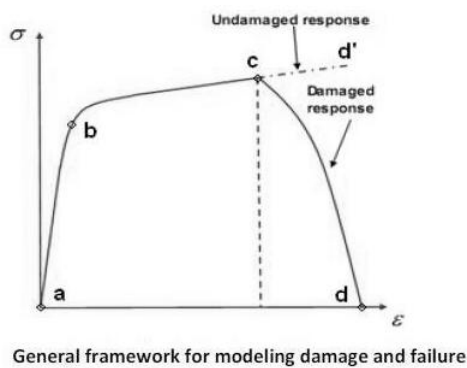


Figure 1: Components of bird strike analysis

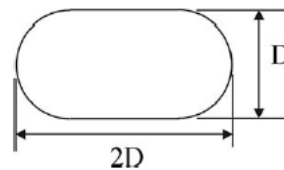
Target material (in this case the aerospace structure) is modeled giving the material elastic and plastic behavior, material damage initiation, damage evolution and failure. Target material can be isotropic, composites, or a hybrid structure of composites and metal. Each material model detail needs to be defined. Hooke's law is followed up to yield stress and in the plastic region, stress – strain curve is defined using Cowper Symonds Law [9, 10] as shown in fig 2. Damage initiation for this problem is shear criterion.

For composite materials Abaqus offers the progressive damage and failure in fiber-reinforced composites, which uses the Hashin's failure initiation criterion and fracture energies for damage evolution [12]. This failure model accounts composites, fiber rupture in tension, fiber buckling, matrix cracking under transverse tension and shearing and matrix crushing under transverse compression and shearing.



a-b: Elastic region, b-c: Plastic region, c-d: Damage evolution law, d: Complete failure of material

Figure 2: Typical isotropic material modeling for impact analysis



D=114 mm for the 4 lb bird

Figure 3: Geometry of the bird

At the instance of Bird strike, bird material local stresses are higher compared to that of target material leading to the "flow" of bird material spreading the impact forces over a wide area, this phenomenon can be observed in fig. 10. The bird material strength can be neglected placing bird in the group of soft body impacts. The most suitable substitute material for bird was Gelatine with 10% porosity and a density of 950 kg/m^3 . The behavior of the bird is defined by the relationship between the shock velocity and particle velocity, which is referred as Linear Hugoniot relation. 4 lb. standard size bird as specified by aircraft regulatory certification agencies is used. The shape of the bird is represented as simple primitive geometry of cylinder with hemispherical ends as shown in fig.3.

Explicit solver calculates the state of a system at a later time from the state of the system at current time, while the implicit solvers calculate solutions using both current and the later stage. For problems with huge displacements, explicit solution is the preferred one. Since this is a contact problem, defining the contacts in Abaqus is made user friendly [11, 12]. Interaction between bird

and the aerospace structure is simulated using the general contact algorithms. This algorithm has been applied to impose the forces and pressures exerted during the impact. The critical design variable in this process is material of the target material. Large deformations leads to numerical instability which is a major issue for the Lagrangian approach bird modeling. Because of this-drawbacks, the initial stage analysis was done with the Lagrangian approach and rest of the analysis was done using CEL as the bird deformation is realistic in CEL.

In the Lagrangian methodology both the target and the bird are meshed using the Lagrangian elements. The target structure is modeled by quad elements, the bird by solid elements. In CEL method Eulerian space is represented by a stationary cube through which the Eulerian material moves and impacts on the Lagrangian structure. In the Lagrangian approach grid points are fixed to locations on the body being analyzed. As the body deforms, the grid points move with the material and the elements distort, which leads to destabilizing the numerical solvers. Whereas in Eulerian description the material flows through a mesh fixed in space and can avoid mesh distortion problems, as shown in fig. 4.

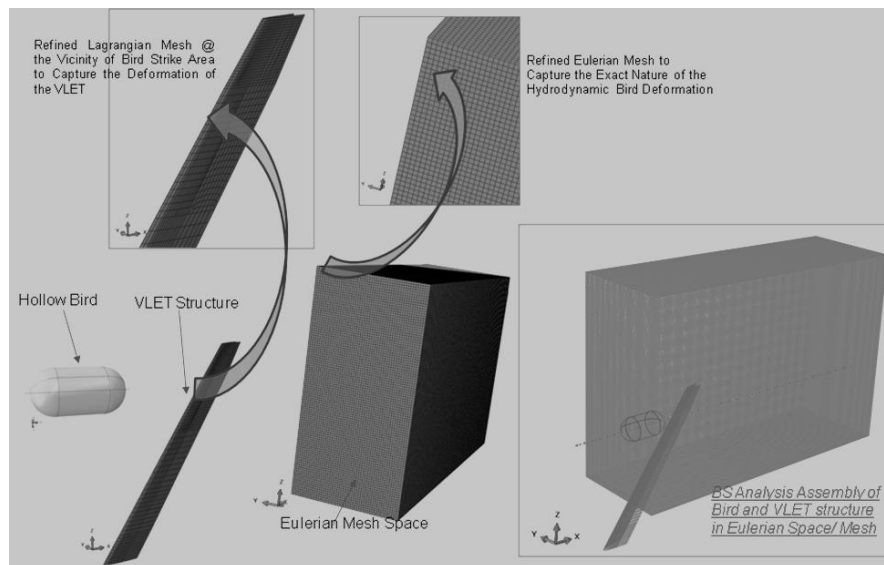


Figure 4: FEM CEL methodology

Meshing is simplified in the CEL approach as there is no need to mesh the soft projectile (bird). Eulerian space is constructed from Eulerian elements so that the projectile is fully contained within the mesh boundaries throughout the analysis. Material is tracked as it flows through the mesh by means of Eulerian Volume Fraction (EVF) [12]. The volume fraction tool creates a node set containing nodes in the area of the bird allowing assignment of initial conditions to the bird material [11, 12].

3. Analysis Procedure

First stage is the verification of the bird model and methodology. This is done by FEM model of Welsh experiment [4]. FE Analysis is setup as discussed in the previous section. Standard bird of 4 lb., speed of the bird of 150 m/s, target plate of Aluminum with dimensions 550x550x6.35mm. are considered in the present study. This plate is fixed at all ends. This evaluation is done for both the Lagrangian and CEL method.

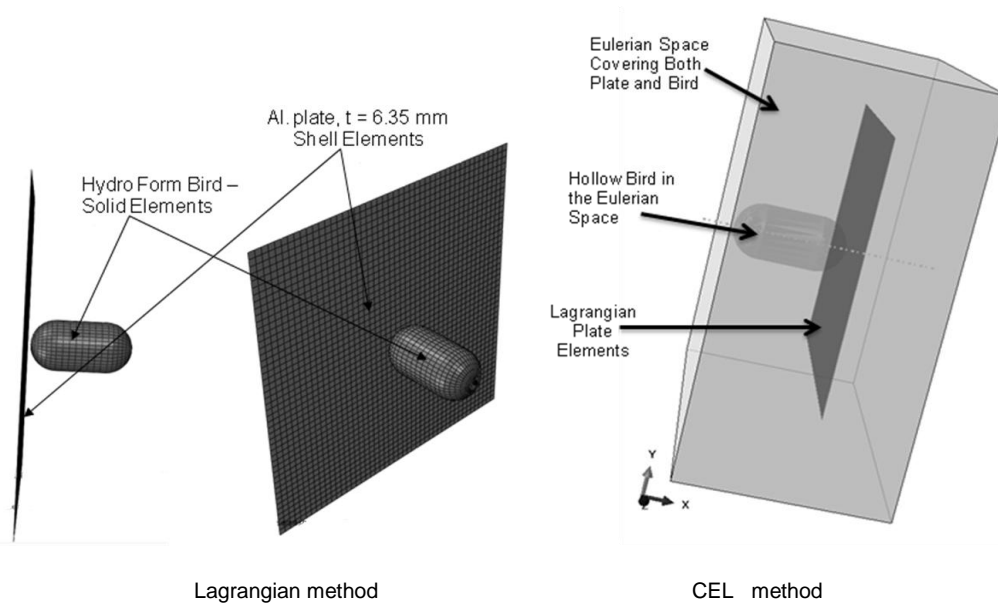


Figure 5: FEM validation of Lagrangian and CEL method [4]

Method	Max. displacement @ center (mm)
Experimental - Welsh 1986 [4]	41.30
Smojver [6] - Lagrangian method	38.54
Current analysis - Lagrangian method (refer fig. 6)	38.56
Current analysis - CEL method	36.44

Table 1: Comparison of displacement results with Welsh experiment [4]

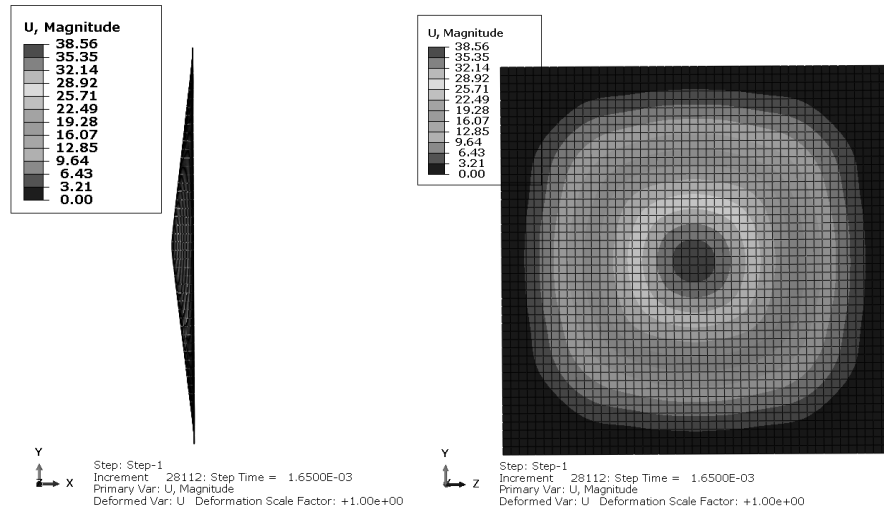


Figure 6: Metallic structure Lagrangian approach analysis displacements results

Initially a 1.5 mm metallic vertical stabilizer structure is used for the Lagrangian method analysis. In the Lagrangian approach the bird is meshed and the material properties assigned. Bird density and the Equation of State (EOS), tensile failure criteria, and low damage initiation are defined for the bird. For the target material of Al, metallic isotropic properties in elastic, plastic, damage evolution and initiation are defined. For the plastic region "Power Cowper Symonds Law" based stress strain relation which includes transverse shear effects and the strain rate [9] is used. Cowper Symonds Law calculates a dynamic yield stress by scaling the static yield stress by accounting the strain rate effect. This law combines the plastic strain and strain rates to obtain dynamic yield stress.

$$\sigma_{py} = (A + b\varepsilon_p^n) \left(1 + \left(\frac{\dot{\varepsilon}_r}{C}\right)^{1/p}\right)$$

"A" = 277 N/mm², "b" = 485 N/mm² and "n" = 0.55 for Aluminum alloy ε_p = Plastic Strain

A - static yield stress, C= 6500/s, p = 5 and $\dot{\varepsilon}_r$ = strain rate. For this analysis, strain rates considered are 0.0, 0.01, 0.1, 1.0, 10.0, 25.0, 100 and 250. Values "A", "b", "n", "C" and "p" are obtained from experimental results [9].

Damage criteria for the removal of elements is defined shear failure and this criteria is 18% or 0.18 strain. vertical stabilizer is fixed at the bottom and simply supported at all the edges. At the cap end of the vertical stabilizer (horizontal edge), nodes are connected by MPC. (See fig. 7) Bird speed is defined as nodal velocity of V=150000 mm/s.

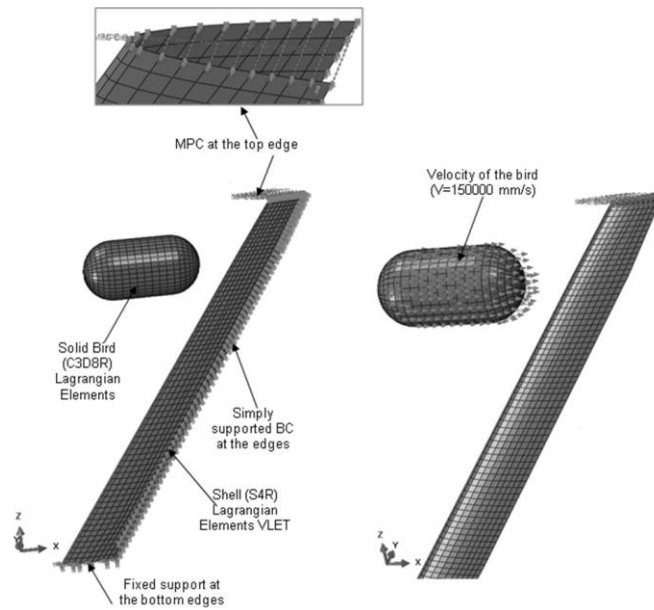


Figure 7: Analysis force and boundary conditions

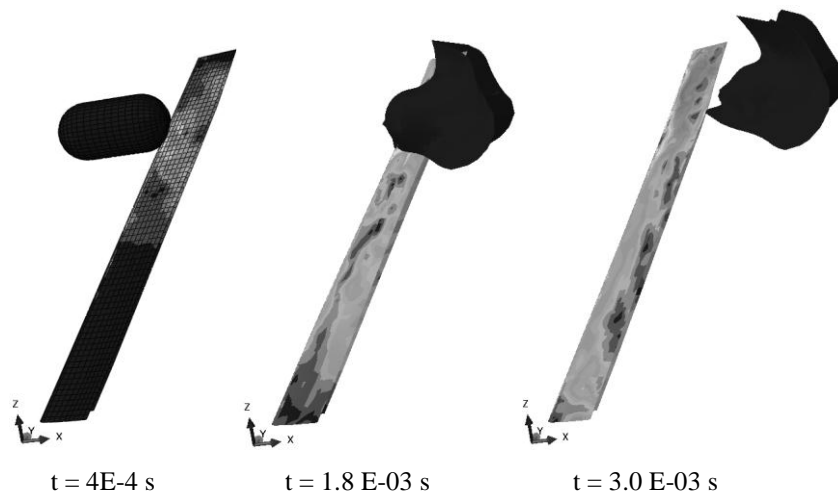


Figure 8: Vertical stabilizer metallic structure Lagrangian approach bird deformation plot

Lagrangian results for the vertical stabilizer made of Aluminum, with thickness of 2.5 mm are shown in fig. 8. This figure shows the non-conforming behavior of the fluid like bird deformations with Lagrangian method.

For the same metallic vertical stabilizer structure, $t=1.5$ mm we see that CEL approach shows more realistic behavior of structure and bird. (See fig. 9a)

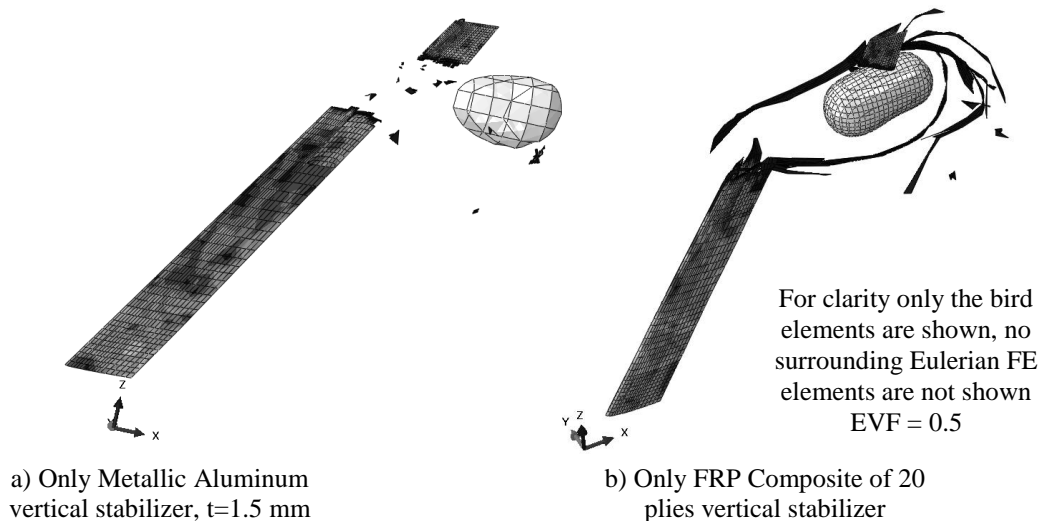


Figure 9: CEL approach analysis results

Based on the aircraft loads acting, vertical stabilizer was designed to have 20 plies of composites, with glass and Aramid plies quasi isotropic layup. Only composite of 20 plies also fails. (See fig. 9b)

For the hybrid material having 20 plies of composite glass and Aramid plies, with the first ply of Al, $t=0.9$ mm is observed to be a safe design.

The first ply in the hybrid layup, is the ply where maximum damage is observed. Composite modelling for impact loads should cover all possible impact related failure models involving inter-laminar fiber / matrix damage and delaminations. Composites Hashin's criteria is used to determine the failures which was discussed earlier. A value of greater than one, is considered to be failure. Fig. 11 shows the Hashin's criteria for fiber tension (0.85) and fiber compression (0.71). Hashin's criteria with different damage scenarios, numerical value reflect the damage state of composites, a value ranging from 0 to 1, 1 being completely damaged. In the current configuration of the study both the values are less than 1, which implies the underlying fiber composite is safe.

The Von-Mises stress recorded at the Aluminum sheet is greater than the tensile ultimate allowable implying a failure of the aluminum sheet. But the maximum composite Hashin's criteria failure is recorded for the tensile fiber failure has a value of 0.85. Even though the first ply facing the impact, aluminum sheet has failed it has left the underlying composite structure safe. With a

replacement technique for the metallic cover, the present design for bird strike will be an economic and safe option.

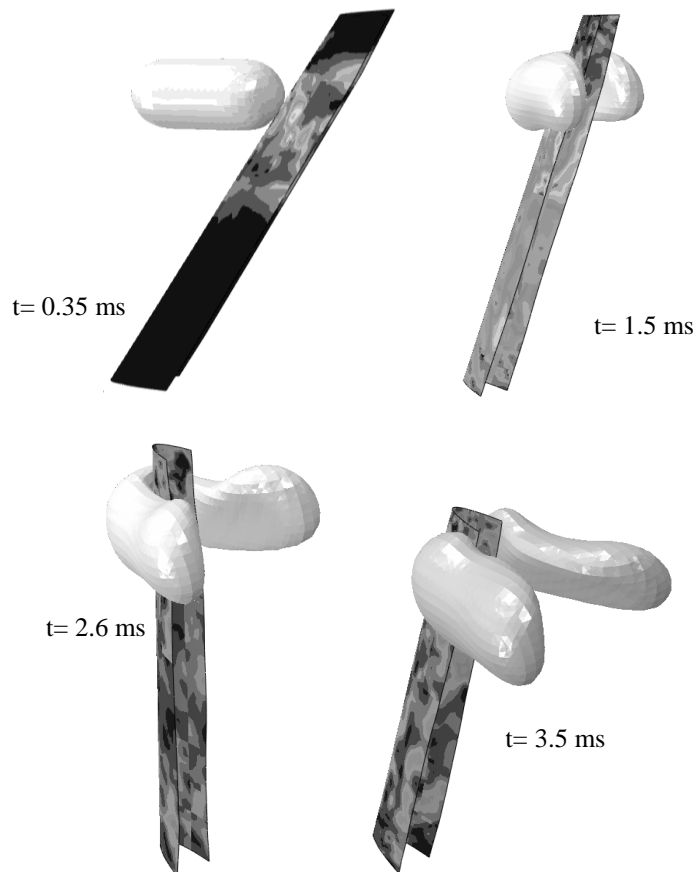


Figure 10: Impact of 4 lb bird on the vertical stabilizer model-Hybrid design

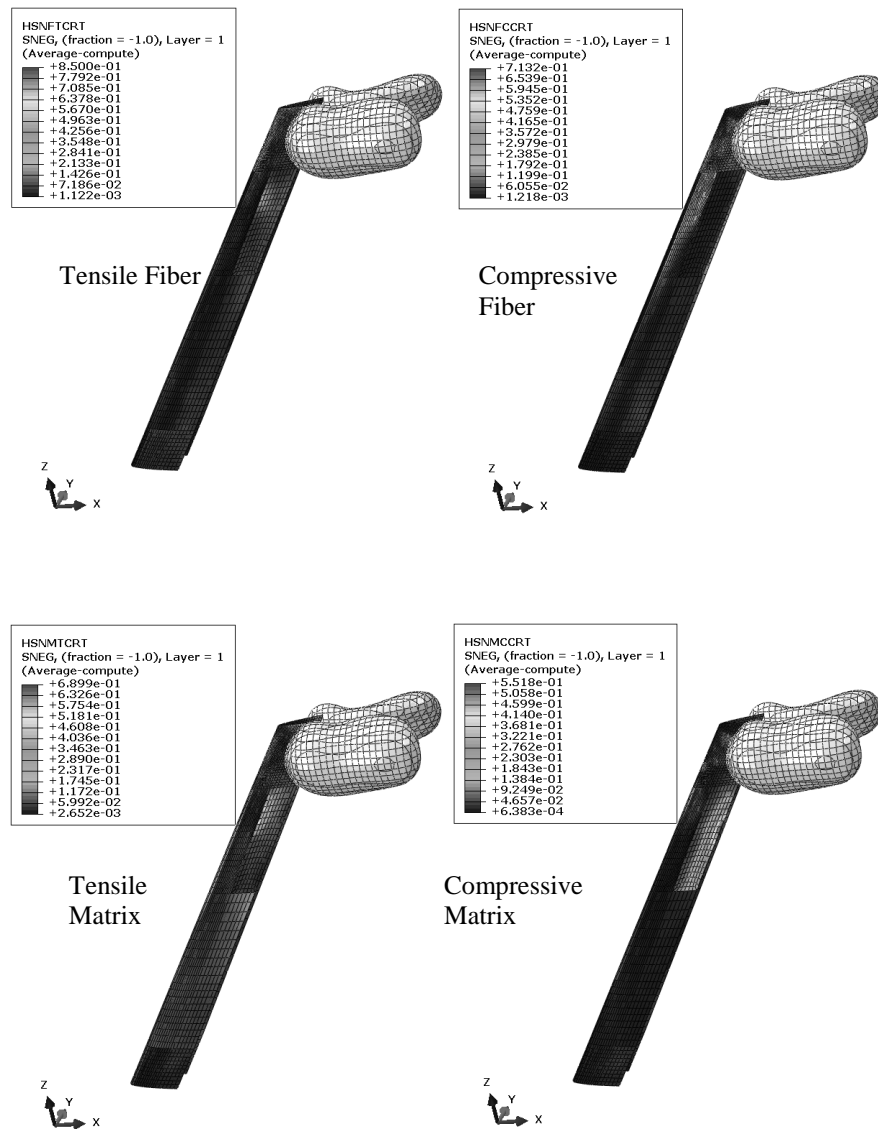


Figure 11: Hashin's Criteria for vertical stabilizer model-Hybrid design

4. Conclusions and future work

Most of the bird strike prone area on aircraft is considered to be aerofoil surface, with lower thickness plates. Composites are widely used in aircraft structures. But the major drawback is the

impact stiffness in the lateral direction is poor. In order to meet the bird strike requirements the number of plies will be very large. To overcome this problem, the current investigation and design proposals open up a new option for the bird strike design of aircraft structures. With this new option, the top metallic layer can be replaced in the case of damage with no or minimal impact damage to the underlying structure.

It is observed that the CEL approach proves to be the better option than Lagrangian. Fully metallic with a $t=1.5\text{mm}$ and only composite structure with total plies of 20 (3.5176 mm) fail. In order to achieve a non failing structure, only composite model with more than 30 plies and only metallic Aluminum layer with $t=0.21\text{mm}$ is required to comply with the bird strike requirements. In composites, the dominant failure mode is tensile fiber and matrix failure. Hybrid structure having an Aluminum plate of 0.9mm thick as the first ply and 20 plies of composite is found to be impact resistant. (total thickness= 4.3176 mm)

Future work can include the study of bond line between the fiber composites and the aluminum plate, to validate the bonding between them. Current study uses the experimentally available data for fracture energies, whereas VUMAT Abaqus subroutine can be used to calculate the failure of composites, from the stresses and strains developed during the analysis as alternative analysis failure criteria. SPH as an analysis methodology for the bird strike can be adopted.

5. References

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