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Numerical bird strike impact simulation of aircraft composite structure

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***ABSTRACT*: *The work presented in this paper deals with application of explicit finite element analysis in order to predict the bird-strike induced impact damage on fuselage part of typical transport aircraft. A methodology has been developed to support the bird-strike certification of the metallic materials made with aluminum alloy2024-T4, 7075-T6. The numerically explicit LS-DYNA codes were used to simulate the arbitray Lagrangian Euler (ALE) bird model. An important part of the bird strike modeling procedure is the application of a bird replacement material with constitutive response which replicates the forces induced by an impact of a real bird. The bird material is modelled by an equation of state, with properties that match the pressure–density relations of water and air mixtures. The input parameters for the simulation have been selected as to simulate a bird strike used to verify the compliance with damage tolerance certification requirements. The ability of this work is leading to improved design efficiency and safety, while significantly reducing certification cost.*

Keywords- *Bird Strike, Certification. Aluminum Alloy Structures, Explicit Analysis LS-DYNA, Structural Impact.*

I. INTRODUCTION

Bird-strike is a potentially serious and damaging event that must be accounted for in the design of flight critical aircraft components. The problem goes back to the dawn of modern aviation, when the Wright Brothers recorded the first bird -strike on 7 September 1905[1]. Although definitive figures are hard to obtain due to variations in reporting requirements, it is estimated that bird -strike events occur at least once every 2000 flights. In civil aviation, more than 50 planes and over 223 lives are reported to have been lost since 1912 due to bird-strike. The cost to the worldwide aviation industry is estimated to be over USD 1 billion per-year [2].The collisions between birds and aircraft are known to cause substantial losses to the aviation industry in terms of damage and delays every year.

The ability of critical structure to withstand bird-strike events is regulated under the certification requirements. An accurate simulation of the bird strike is still a challenge when applying numerical methods due to the complex physical phenomena which need to be correctly simulated in order to predict the response of the impacted structure. Non Linear explicit finite element analyses enable prediction of damage caused by the foreign object impact without the need for costly and time consuming experiments. This ability is particularly useful in the certification phase of the design process, in which the compliance with certification requirements has to be demonstrated. Numerical methods and techniques are therefore still being improved in order to enhance the accuracy of bird impact simulations and, consequently, reduce the requirements for gas-gun experiments.

The finite element (FEM) method is a powerful tool for development and optimisation of new structural components. However, modelling the high-speed bird-strike events of aeronautic parts poses several challenges, such as modelling of material failure and which FE formulation to use for the impacting bird. The recent study by Lagrand et al. [3] has emphasised the need for validated simulation tools for aid in design of critical components subject to bird strike. Today, this demand is boosted by the introduction of new and complex materials to the aircraft industry, such as structural composite materials. In their work, Lagrand et al. [3] carried out a sensitivity study on arbitrary Lagrangian Eulerian (ALE) FE techniques to accurately predict the behaviour of a bird striking a structural panel.

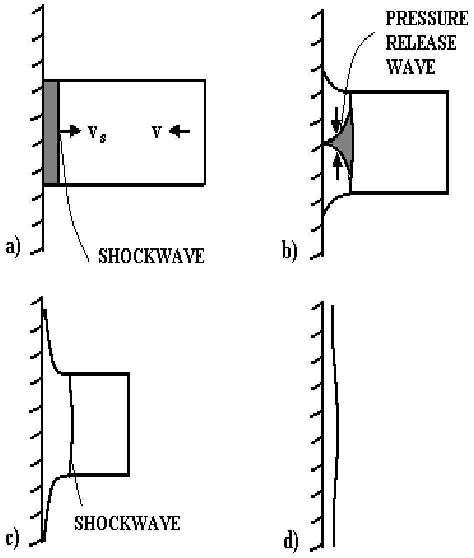


Fig.1 “Four phases of normal impact on to a rigid target. The shaded regions represent extremely high pressures”

The objective of this paper was to generate a model with the non-linear, FE code LS-DYNA to fully represent the bird-strike process of an aluminum alloy 2024-T4, 7075-T76. The FE model, material identification and comments the ALE formulation and the ALE–Lagrangian coupling algorithm that is used for the interaction between bird and structure.

II. CERTIFICATION REQUIREMENTS

The bird-strike airworthiness requirements relevant to the Boeing 787 Dreamliner are specified under FAR Part 25, Sub-part25.571 ‘‘Damage-tolerance and fatigue evaluation of structure”:

(e) Damage-tolerance (discrete source) evaluation. The airplane must be capable of successfully completing a flight during which likely structural damage occurs as a result of:

(1) Impact with a 4-pound bird when the velocity of the airplane relative to the bird along the airplane’s flight path is equal to Vc at sea level or 0.85 Vc at 8000 ft, whichever is more critical.

III. BIRD MATERIAL VALIDATION

The problem of finding a material that successfully simulates real birds during bird strike research arises in both numerical and experimental investigation methods. Gas-gun experiments with real birds, although providing the best method to realistically simulate an actual bird impact, lack the ability to provide repeatable test results as different birds have different anatomic structures and thus the effect on the impacted target differs in every single test. To overcome this shortcoming, the authors of [4] analyzed different homogeneous substitute materials which could be used in gas gun experiments in order to be able to validate experimental results. A further disadvantage of experimental test methods is the high cost involved in gas gun experiments on actual aeronautical components. The results published in [4] are an important reference for scientific research in the field of soft body impact, as it provides important test results as well as equations which theoretically explain the load distribution and pressure time dependency involved in a bird impact. As the bird strike usually occurs at higher velocities, very high stresses are generated in the bird material. These stresses greatly exceed the material’s strength, leading to a fluid-like deformation of the bird material. As the strength and viscosity in this approach are neglected, a simple pressure vs. density equation of state can be used to describe the constitutive behaviour of the bird material in numerical analyses. The conclusion of Willbeck’s experimental results in [4] is that the most suitable bird substitute material was gelatine with 10% porosity and a density of 950 kg/m^3. Another important conclusion was that the most appropriate shape of the impacting body is a cylinder with hemispherical ends and a length to diameter ratio equal to 2.

IV. BIRD MODELLING

In recent years, explicit FE codes have been used to develop high efficiency bird-proof structures. These codes adopted various finite element approaches to model the impact phenomena: the Lagrangian approach, Eulerian or Arbitrary Lagrangian Eulerian (ALE) approach, and recently solvers based on smoothed particle hydrodynamics (SPH).

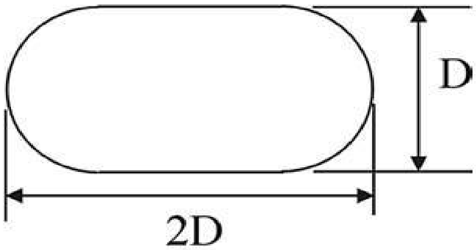


Fig.2 “Bird shape with hemispherical ends”

1. ALE formulation and ALE–Lagrange coupling

The bird was expected to undergo too large deformations for a pure Lagrangian description of motion to be a feasible option. For that reason a multi-material ALE formulation was chosen for the treatment of the bird. Multi-material implies that each element in the mesh is allowed to contain a mixture of two or more materials, in this case bird material and air. The ALE formulation means that the mesh is allowed to move independently to the material flow. In this case the mesh was assigned to translate and expand to enclose most of the bird material throughout the simulation process.

To solve the governing equations posed in an ALE reference system, LS-DYNA relies on a so-called operator split technique where each time step is split into a Lagrangian phase and an advection phase. In the Lagrangian phase, the FE model is treated as if it was purely Lagrangian. That is, the mesh is forced to follow the motion of the material flow. In the advection phase the nodes of the mesh are repositioned to new, preferred, locations and the solution is mapped from the old configuration onto the new one. A spatially second order accurate advection algorithm, referred to as the van Leer method, was used in this work. Both the operator split technique and the van Leer advection algorithm are described in [5].

The bird and the surrounding air have been represented in the model. The air is initially pressurised at 1 bar. An external pressure of the same magnitude is applied to act on all external element faces of the ALE mesh.

A penalty-based ALE–Lagrangian coupling algorithm was invoked to communicate contact forces between the bird material in the ALE mesh and the Lagrangian target. The function of the ALE–Lagrangian coupling algorithm is very similar to the one of a classical penalty-based contact algorithm. The contact pressure is simply proportional to the distance the bird material penetrates the target. Aside from numerical errors, the penalty-based coupling algorithm conserves both total energy and momentum, an important feature in impact analyses. The implemented algorithm is briefly described in [13].

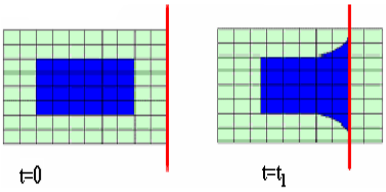


Fig.3 “Simplified ALE mesh movement”; void (green colour), material mesh (blue colour) [7]

In an explicit finite element analysis, the time step Δt is determined by the smallest element $l_{min.}$.The severe mesh distortion causes the time step to decrease to an unacceptably low value for the calculations to continue.

$$\Delta t = l_{min}/c \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where c is the wave sonic speed in the element. These excessive distortions condition, the time step until to lower values so to render the analysis with an inacceptable time.

2. Material identification of bird/air

The equation-of-state was defined by card *EOS_LINEAR_POLYNOMIAL of LS-DYNA, where the pressure P is expressed as

$$P=C_0+C_1\mu+C_2\mu^2+C_3\mu^3+(C_4+C_5\mu+C_6\mu^2)U \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (2)$$

where U is the internal energy per volume. The compression of the material is defined by the parameter $\mu=\rho/\rho_0$; where $\rho$and ρ_0 are the current and initial density of the material, respectively.

The bird material was identified for this model using the material properties specified by Lagrange et al. [6]; C0 = 0; C_1 = 2250MPa; C2…C6 = 0 and γ_d= 0.001 Ns/m^2. The total mass of the bird used in the experiments was 1.8 kg, the bird an initial density of ρ_0=950 kg/m^3 (based on the geometry).

The air was modelled as an ideal gas by setting $C_0 = C_1 = C_2 = C_3 = C_6 = 0$ and $C_4 = C_5 = \gamma-1$; where γ is the ratio of specific heats, i.e. specific heat at constant pressure divided by specific heat at constant volume. In this case the pressure P is given by

$$P= (\gamma-1)\rho/\rho_0 U, \quad U=\rho_0 RT/\gamma-1 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (3)$$

where the internal energy U is defined by the absolute temperature T (in Kelvin) and the specific gas constant R = 287 J/kgK: The initial internal energy U0 of the gas was defined for a temperature of T = 293K: Equivalently, LS-DYNA card *EOS_IDEAL_GAS can be used to model the air.

3. Mechanical Properties of AA2024-T4, AA7075-T6

Table.1 AA7075-T6

DENSITY	2.83E-006 KG MM^-3

AA7075-T6 ISOTROPIC ELASTICITY

TEMPERATURE C	YOUNG'S MODULUS MPA	POISSON'S RATIO	BULK MODULUS MPA	SHEAR MODULUS MPA
	71700	0.33	70294	26955

Table.2 AA 2024-T4

DENSITY	2.78E-006 KG MM^-3

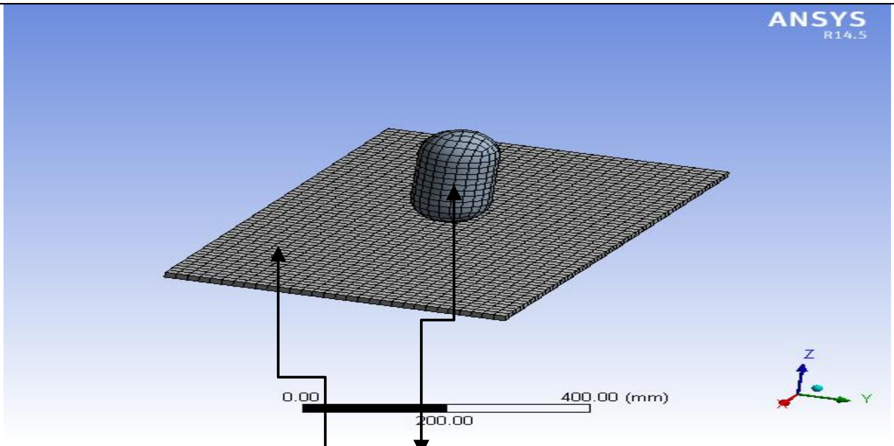
AA 2024-T4 ISOTROPIC ELASTICITY

TEMPERATURE C	YOUNG'S MODULUS MPA	POISSON'S RATIO	BULK MODULUS MPA	SHEAR MODULUS MPA
	73100	0.33	71667	27481

V.NUMERICAL RESULTS

The ability to predict bird strike induced damage without costly and time consuming experiments is the most valuable in the preliminary phase of design of aircraft structural components. According to FAR 25.571 – “Damage-tolerance and fatigue evaluation of structure”, the design of the fuselage structure must ensure that catastrophic failure does not occur at an impact with a 4 lb (1.81 kg) bird at the expected operating velocities. Fuselage structures are exposed to bird strikes at relatively low velocities. Taking this into account, this work presents results of a bird strike simulation which included a bird mass used in certification (after FAR 25.571) at 90 m/s. The bird material used in this simulation is an EOS with properties which replicate a water and air mixture with 10% porosity, as described in Section III. The material dimensions are analyzed in 1m length×0.5m width×0.012m thickness as per aircraft data sheet dimensions are followed.

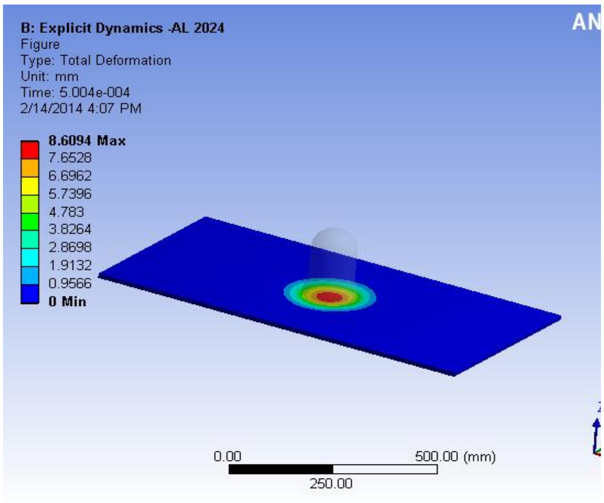
The deformation of the 1.81 kg impactor at an initial velocity of 90 m/s is shown in Fig 4. The analyzed impact is simulated for -0.5 ms to 2.5ms of real time, after which bird material has lost its kinetic energy and no further increase of damage at the impacted structure is expected. As shown by the contours of equivalent stresses, the fuselage structure is exposed to very high stresses which are spread to a wide area of the composite skin. The Fig 5& 6 is showing that material behaviour of different time intervals.



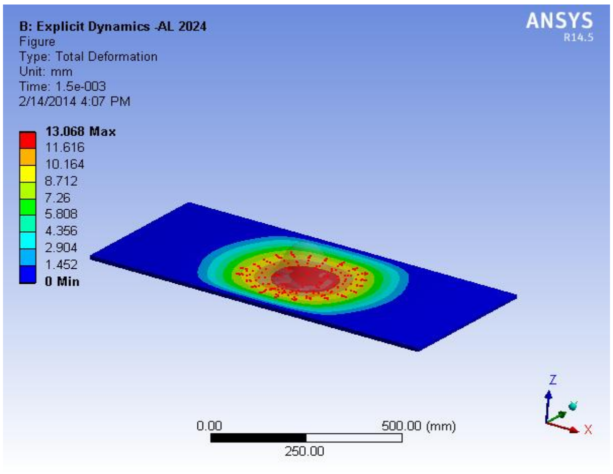
Bird dimension

Material dimension

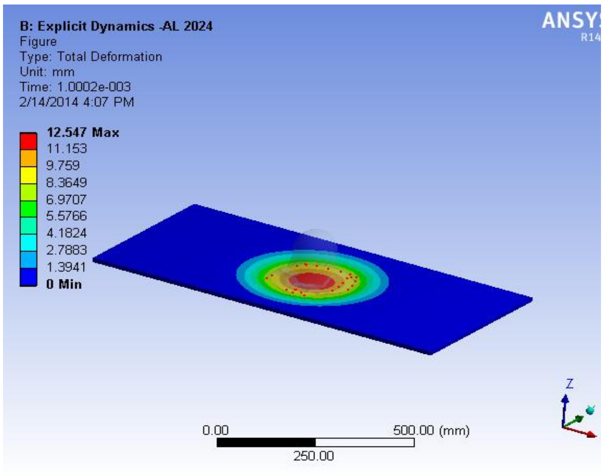
Fig .4 “Impact angle locations at AA2024-T4, 7075-T6”



0.5ms



1.5ms



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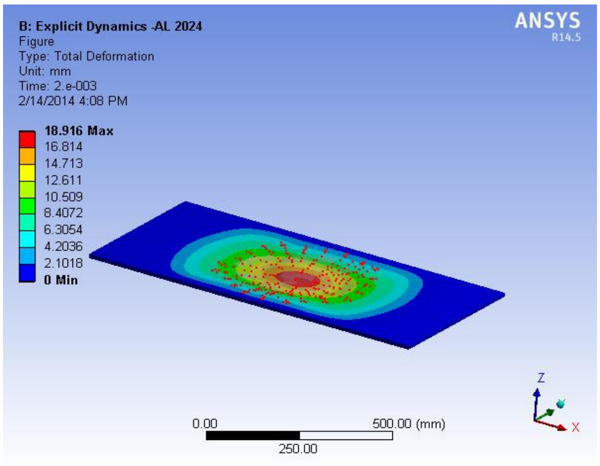

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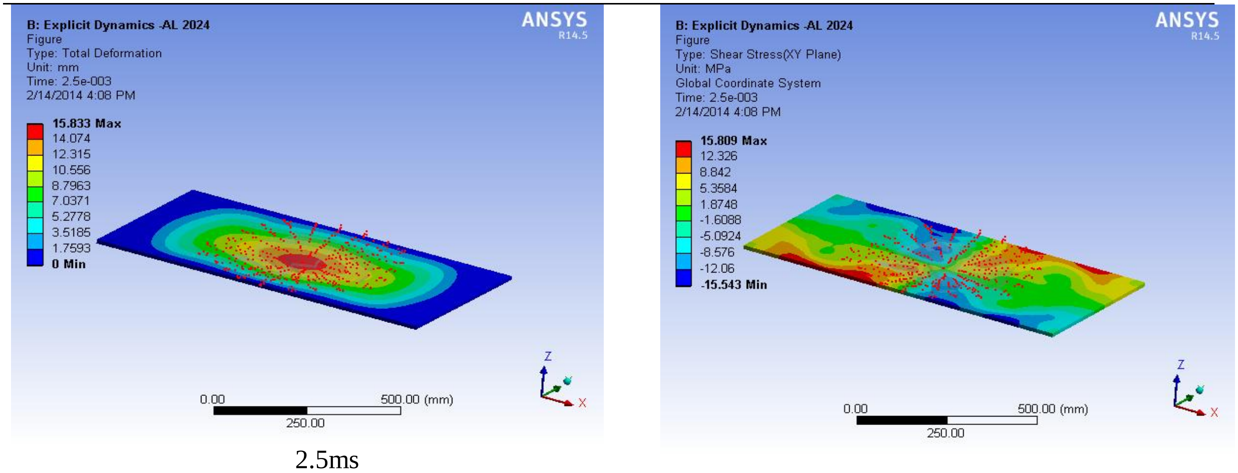


2.5ms

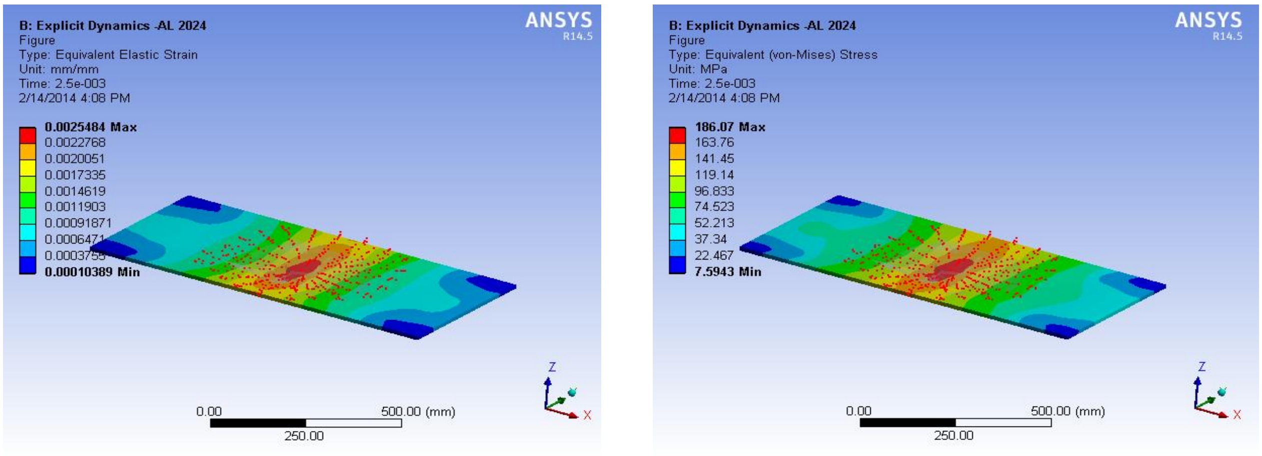
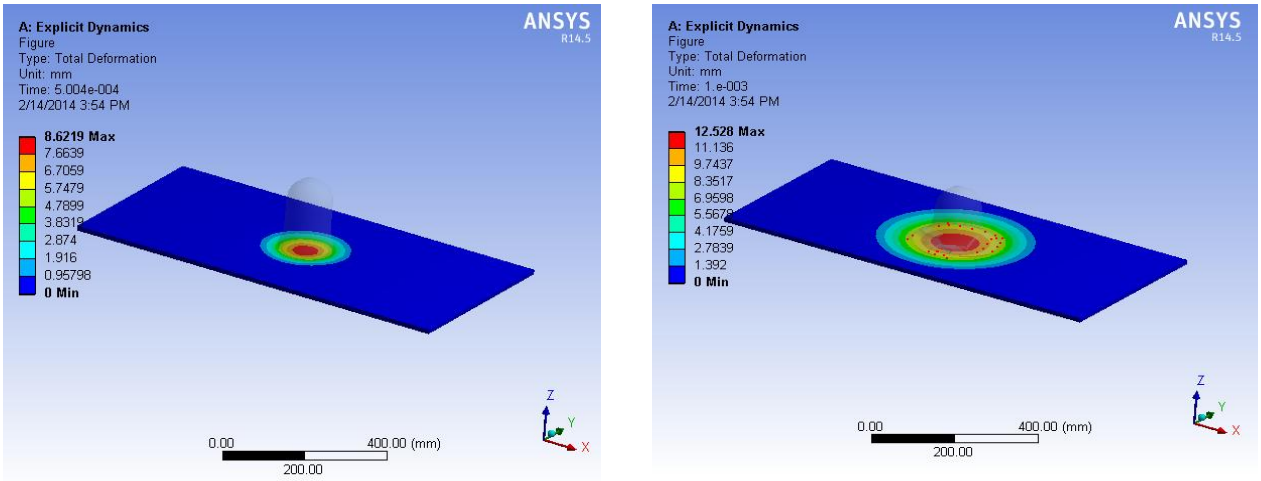
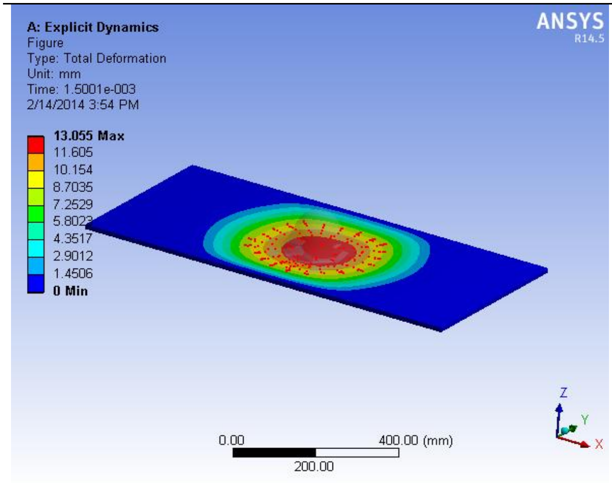


Fig.5"Bird deformation at increasing time intervals during the simulations of AA2024-T4"

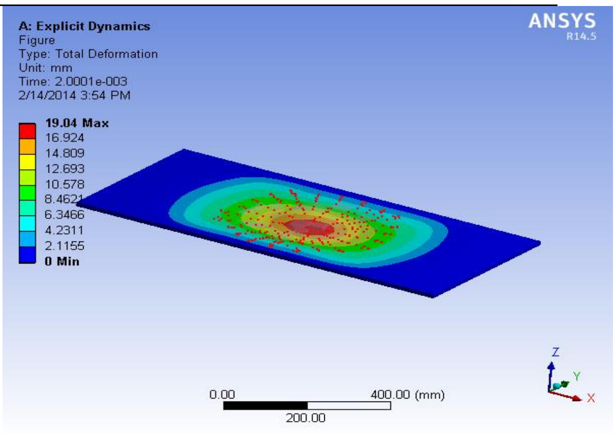


1ms

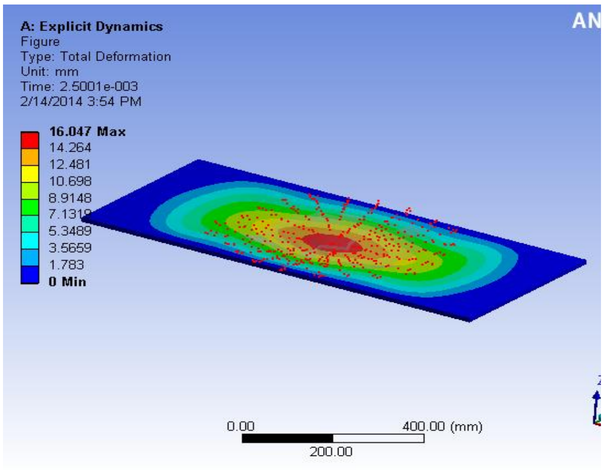
0.5ms

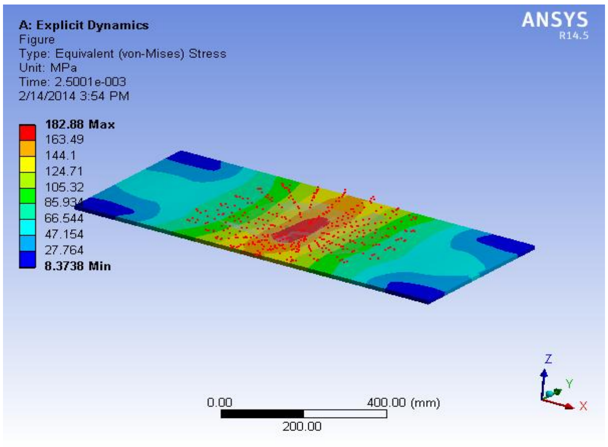


1.5ms



2ms





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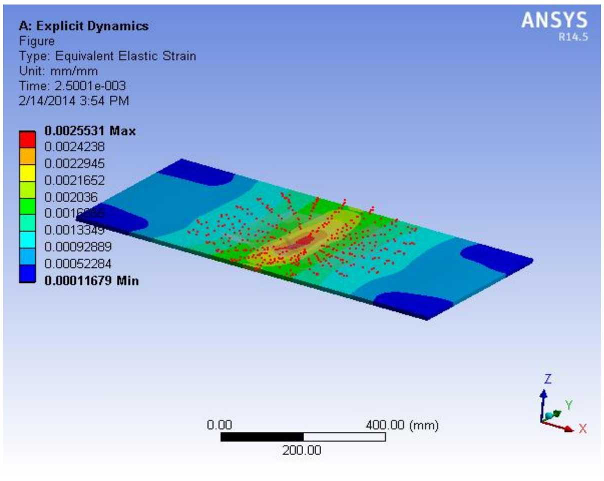

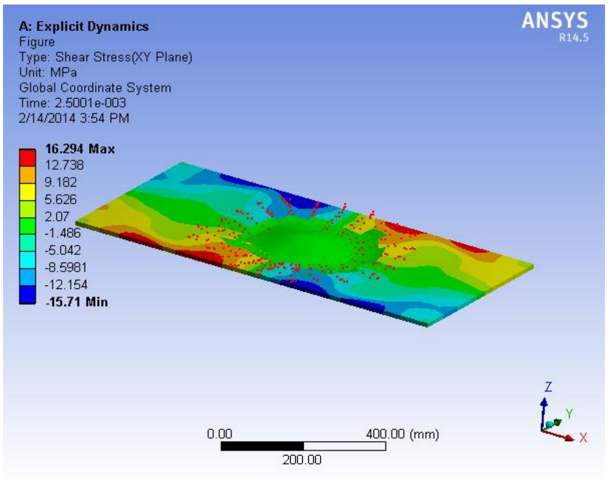

Fig. 6 “Bird deformation at increasing time intervals during the simulations of AA7075-T6”

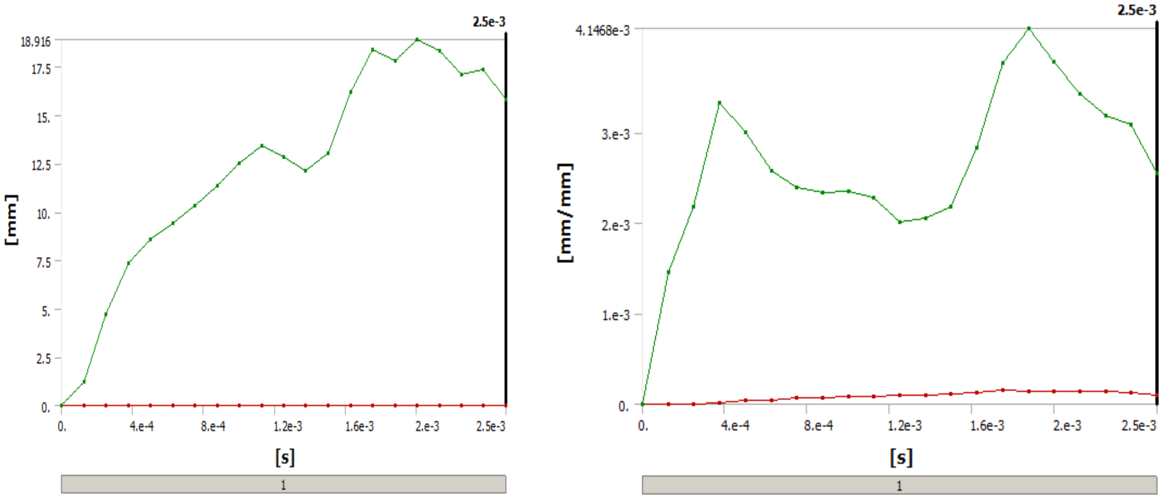

Fig.7 “Time - Total deformation and Equivalent Elastic strain History Plot for AA2024-T4”

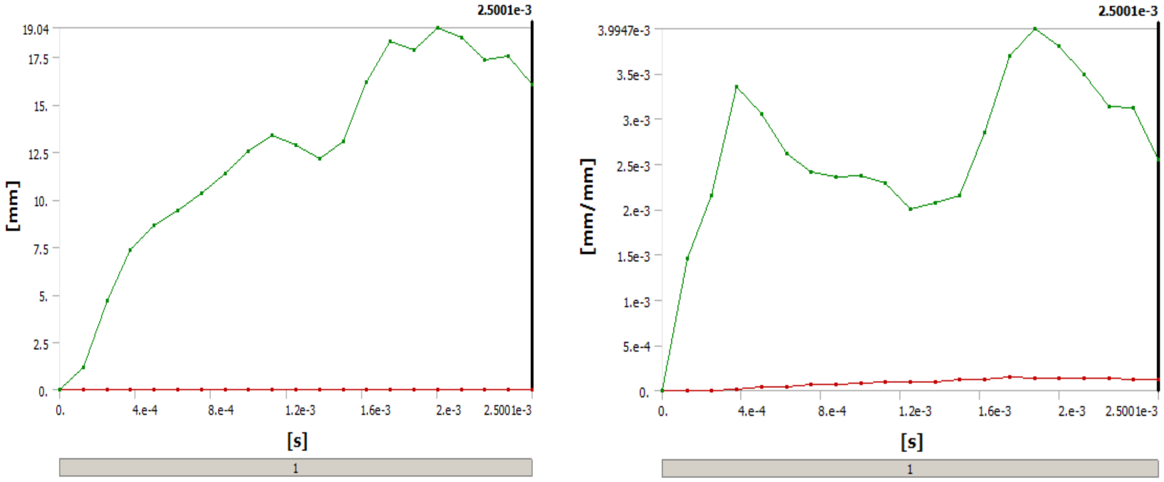

Fig.8 “Time - Total deformation and Equivalent Elastic strain History Plot for AA7075-T6”

TIME [S]	MINIMUM [MM]	MAXIMUM [MM]
1.1755e-038	0.	0.
1.2529e-004		1.2009
2.5019e-004		4.6993
3.7524e-004		7.371
5.004e-004		8.6219
6.2523e-004		9.4348
7.5016e-004		10.328
8.7503e-004		11.378
1.e-003		12.528
1.1251e-003		13.412
1.2501e-003		12.89
1.3752e-003		12.145
1.5001e-003		13.055
1.625e-003		16.186
1.7502e-003		18.357
1.8751e-003		17.886

2.0001e-003		19.04
2.125e-003		18.496
2.25e-003		17.322
2.3751e-003		17.569
2.5001e-003		16.047

Table .3 “Total deformation occurring on different time intervals in material of 7075-T6”

TIME [S]	MINIMUM [MM]	MAXIMUM [MM]
1.1755e-038	0.	0.
1.2529e-004		1.2109
2.5019e-004		4.7261
3.7524e-004		7.3835
5.004e-004		8.6094
6.2523e-004		9.4206
7.5015e-004		10.324
8.7503e-004		11.387
1.0002e-003		12.547
1.1251e-003		13.428
1.25e-003		12.876
1.375e-003		12.123
1.5e-003		13.068
1.6252e-003		16.173
1.75e-003		18.381
1.8751e-003		17.821
2.e-003		18.916
2.1251e-003		18.311
2.2501e-003		17.137
2.375e-003		17.356
2.5e-003		15.833

Table .4 “Total deformation occurring on different time intervals in material of 2024-T4”

VI. CONCLUSIONS

This paper presented the work performed to design a fuselage by employing the finite element method coupled to a meshless method in order to reduce the experimental costs. In particular, a classical FE approach was adopted to model the fuselage (rectangular shape) while Arbitrary Lagrangian- Eulerian (ALE) was used for modelling the bird. Excellent qualitative correlation between the lagrangian bird numerical model test were obtained in terms of global deformations mode while for the quantitative comparison difference were found when measuring the highest deformation.

The equation of state defines the polynomial state of the fluid. Developing an accurate equation of state for the fluid model was a key step in this fluid–structure interaction study. An accurate equation of state was necessary to obtain reliable results form the simulation. It will affect the kinematics of the lagrangian particles at impact and as a result influence the loads applied to the structure by the fluids.

The ALE approach is still very good to simulate a real impact event, like the one on the fuselage, the results conducted in different metallic materials for AA2024-T4, AA7075-T6.

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