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Bird-Strike Modeling Based on the Lagrangian Formulation Using LS-DYNA

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ABSTRACT

In this first paper of a three-paper sequence, we developed a standard work using the Lagrangian approach in LS-DYNA. The results were compared against experimental results. First, a simple one-dimensional beam centered impact problem was solved analytically to validate the results produced by LS-DYNA. For this case, the results were within 2.5% error when compared with the analytical solution. Bird-strike events were divided into three separate problems: frontal impact on rigid flat plate, 0 and 30 deg impact on deformable tapered plate. The bird model was modeled as a cylindrical fluid. The peak pressures and forces were compared to those results available in the literature. The case for 0 deg tapered plate impact shows little bird-plate interaction because the bird is sliced in two parts and the results were within 10% difference from the test data available in the literature. The developed Lagrangian approach is suitable for bird-strike events within 10% error.

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1. Introduction

1.1 Motivation

We call collisions between a bird and aircraft "bird-strike events," and they are quite common and dangerous. According to the Federal Aviation Administration (FAA), wildlife strikes cost the U.S. civil aviation industry over $300 million and more than 500,000 downtime hours each year [1]. Also, people's lives have been lost or being in risk due to aircraft malfunctions after bird-strikes which make it imperative to design aircraft components capable of withstanding these impacts.

To obtain certification from the FAA, an aircraft must be able to land after an impact with a bird weighing 17.79 N (4 lb) at any point in the aircraft. For new jet engines designs, the FAA certification requires tests for medium and large bird ingestion. For the medium or flocking bird requirement, an engine must be capable of operating for five minutes with less than 25% thrust loss after impacting several birds weighing 6.67 N (1.5 lb) or 11.12 N (2.5 lb). For the large bird ingestion test, the engine must be able to ingest a bird weighing 26.69 N (6 lb) or 35.58 N (8 lb) and achieve safe shutdown. These tests take hours of planning to execute and cost millions of dollars to the jet engine manufacturing companies. Due to this, it is very important to be able to predict damage caused by a bird-strike impact on new engine designs to save money and time.

In order to predict the damage of the components of a fan blade during a bird-strike event, we created a standard work in LS-DYNA to model the blade and the bird. LS-DYNA allows us to model these events for its explicit solver and its ability to analyze complex geometries, material and load non-linearity, and study the interaction between the bird and the target. The Lagrangian method is one of the methods is studied and will be the focus of this first paper.

1.2 Background on Impact Problems

The impact event is not a new topic and it has been studied by various authors. Parkes [2] was the first to analyze the transversal impact of a mass against a cantilever beam. Stronge *et al*. [3] also discuss the theory involving irreversible or plastic deformation of structural elements composed of relatively thin ductile materials. The description of these deformations in a context of impact damage was also discussed.

The impact phenomenon was also analyzed theoretically by Goldsmith [4]. Goldsmith [4] included the theory of colliding solids and also analyzed a transverse impact of a mass on a beam assuming a equivalent system in which the beam is modeled by a massless spring. Goldsimth [4] used energy method and the Lagrangian equations of motion to obtain a relation between the static and dynamic deflections of the beam. A more complex impact problem is that involving a soft body impact against a rigid plate. Cassenti [5] developed the governing equations for this kind of impact. Cassenti [5] related the conservation equations with the constitutive equation of the impacting material to obtain analytically the Hugoniot pressure or the pressure generated in the beginning of the impact.

A bird-strike can be considered as a soft body impact problem. The characterization of birds impacting a rigid plate was studied by Barber *et al*. [6]. Barber *et al*. [6] found that peak pressures were generated in the impact of the bird against a rigid circular plate. This peak pressures were independent of the bird size and proportional to the square of the impact velocity. Four steps concerning the impact pressures were found: initial shock (Hugonniot Pressure), impact shock decay, a steady state phase and the final decay of the pressure. This pressure plots were used as a reference to compare the obtained pressures in the LS-DYNA simulation of the bird-strike event.

Bird-strike events have been studied using Lagrangian method in different finite element codes. Neiring [7] used a Lagrange model of the bird as the basis. His work shows different methods of computer simulation for the bird-strike event but states that an improvement is necessary due to large distortions experienced by the bird in the Lagrange model.

Barber et al. [6] found that bird impacts in rigid targets generated peak pressures independent of bird size and proportional to the square of the impact velocity, resulting in a fluid-like response. Barber *et al*. presented the time-dependent pressure plots for the impact of birds against a rigid cylindrical wall. This work was taken as reference to create simulations similar to those presented by Barber et al. [6]. The work performed by Moffat et al. [8] was used to reproduce models of impact of birds on tapered plates. Moffat *et al*. [8] worked in the use of an ALE description of bird-strike event to predict the impact pressures and damage in the target plate. This work used

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the MSC/DYTRAN code for the simulations instead of LS-DYNA which is the code used in this project. The article presents some previous work involving rigid plate impacts from Barber et al. [6] and a flexible tapered plate impacts from Bertke *et al*. [9]. These two kinds of impacts were reproduced in the work by Moffat et al. [8] using the finite element description in MSC/DYTRAN. The geometrical model that was used for the bird was a cylinder with spherical ends with an overall length of 15.24 cm and a diameter of 7.62 cm. The bird density is 950 kg/m^3. Moffat *et al*. [8] found that the pressures were insensitive to the strength of the bird and a yield stress of 3.45 MPa was taken for the rigid plate impact analysis. For the viscosity it was necessary to take higher values for impacts at 25°. The article shows plots of the shock pressures for different velocities and for different bird sizes. For the tapered plate impact simulation a 7.62 × 22.86 cm plate was used. The plate was tapered by 4° and the edge thickness was 0.051 cm which blended to 0.160 cm for the majority of the plate. The work did not specify the kind of element that was used for the tapered plate. For the LS-DYNA simulation performed in this research the tapered plate will be simulated using shell elements.

In this work, we attempt to create a standard work based on the Lagrangian formulation by identifying the most important influencing parameters in the bird-strike simulation and validate the simulation with the existing test data. One of the advantages of the Lagrangian model is that the numerical mesh moves and distorts with the physical material, allowing accurate and efficient tracking of material interfaces and the incorporation of complex material models.

2. Impact Analysis

The bird-strike events are considered as soft body impact in structural analysis because the yield point of the bird is far smaller when compared with that of the target. Thus, the bird at the impact can be considered as a fluid material. The soft body impact results in damage over a larger area if compared with ballistic impacts. Now, to better understand, bird-strike events let us first understand the impact problem and then apply it to the bird-strike event being studied in this work.

2.1 A Continuum Approach

Three major equations are solved by LS-DYNA to obtain the velocity, density, and pressure of the fluid for a specific position and time. These equations are conservation of mass, conservation of momentum, and constitutive relationship of the material and are essential to solve the soft body impact problem. The most important information in an impact analysis is the pressure generated by the body on the target. Thus, we proceed to explain the basic equations used to find the pressure generated at the beginning of the impact as developed in Cassenti [5].

Let us begin with the general form of the conservation of momentum, which can be stated as follows:

$$\nabla\sigma + \rho\,\mathbf{b} = \frac{D}{Dt}(\rho\,\mathbf{V})$$

where $\boldsymbol{\sigma}$ is the stress tensor, **b** the body force vector per unit mass, $\boldsymbol{\rho}$ the density, and **V** the velocity vector. For the impact problem, no body forces are considered: thus, **b** = 0. Further, it is assumed that for equilibrium the normal compressive stress acting in the contact interface balance the normal pressure exerted for the body over the target within the contact area. Also, it is assumed that the shear stresses are neglected. Thus, the conservation of momentum becomes

$$-\nabla\mathbf{P} = \frac{D}{Dt}(\rho\,\mathbf{V}) \tag{1}$$

where **P** is a diagonal matrix containing only normal pressure components. The second equation used in the analysis is the conservation of mass and it is written as per unit volume as follows:

$$\frac{D\rho}{Dt} + \rho\,\nabla\cdot\mathbf{V} = 0 \tag{2}$$

Equations (1) and (2) consist of four independent equations involving seven unknowns. The unknowns are three components of the pressure, three velocities, and the density. A third equation which will relate the pressure and density is the constitutive relationship. This reduces the seven unknowns to five and the system of equations can be solved. For this work different materials are used to model the impact analysis. We can express constitutive relation in its general form as follows:

$$\mathbf{P} = \mathbf{P}(\rho) \tag{3}$$

2.2 Lagrangian Approach

The various formulations existent for the finite element analysis differ in the reference

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coordinates used to describe the motion and the governing equations. The Lagrangian method uses material coordinates (also known as Lagrangian coordinates) as the reference; these coordinates are generally denoted as X. The nodes of the Lagrangian mesh are associated to particles in the material under examination; therefore, each node of the mesh follows an individual particle in motion, this can be observed in Figure 1. This formulation is used mostly to describe solid materials. The imposition of boundary conditions is simplified since the boundary nodes remain on the material boundary. Another advantage of the Lagrangian method is the ability to easily track history dependant materials. The main disadvantage of the Lagrangian method is the possibility of inaccurate results and the need of remeshing due to mesh deformations. Since in this method the material moves with the mesh, if the material suffers large deformations as observed in Figure 2, the mesh will also suffer equal deformation and this could leads to inaccurate results.

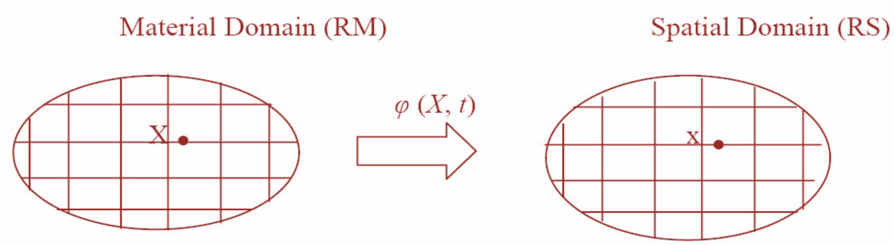

Figure 1: Description of motion formulation.

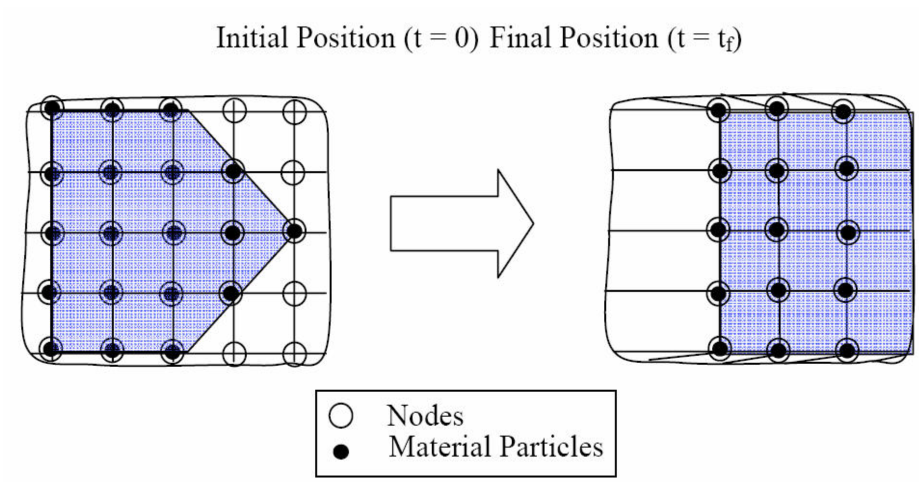

Figure 2: Lagrangian mesh.

The Lagrangian method uses material coordinates (also known as Lagrangian coordinates) as the reference. The major advantage of the Lagrangian formulation is that the imposition of boundary conditions is simplified since the boundary nodes are always coincident with the material boundary. Each individual node of the mesh follows the associated material particle during motion. This allows easy tracking of free surfaces, interfaces between materials and history-dependant relations. The major disadvantage of this method is that large deformations of the material lead to large distortions and possible entanglement of the mesh. Since in the Lagrangian formulation the material moves with the mesh, if the material suffers large deformations, the mesh will also suffer equal deformation and this leads to inaccurate results. These mesh deformations cause inaccuracy in the simulation results. To correct this problem, re-meshing must be performed which requires extra time.

2.3 Material Models

Two types of materials were used for the bird model: material null and the elastic fluid. The material null considers a fluid material composed of 90% of water and 10% of air. This material allows consider equation of state without computing deviatoric stresses. The equation of state used with this material was the equation of state tabulated. This equation of state defines the pressure **P** as follows

$$\mathbf{P} = \mathbf{C}\left(\varepsilon_V\right) + \gamma\,\mathbf{T}\left(\varepsilon_V\right)\,E$$

For the type of impact problems studied in this work, temperature does not play a big role. In this context, the term $\gamma\,\mathbf{T}\left(\varepsilon_V\right)\,E$ vanishes and thus the equation of state reduces to

$$\mathbf{P} = \mathbf{C}\left(\varepsilon_V\right)$$

The volumetric strain ε_V is given by the natural logarithm of the relative volume. The second type of material is the elastic fluid material. This material is an isotropic elastic material. The bulk modulus, *K*, is defined as a function of the young modulus and the Poisson's ratio as follows

$$K = \frac{E}{3\left(1 - 2\,\nu\right)}$$

The constitutive relationship used here is based on the final Hugoniot pressures and is expressed as follows

$$\dot{\mathbf{P}} = -K\,\dot{\varepsilon}$$

where $\dot{\mathbf{P}}$ is the pressure rate and $\dot{\varepsilon}$ the deviatoric strain rate. In contrast with the material null the elastic fluid material considers the computation of the deviatoric stresses which are the stresses that

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will cause deformation to the element.

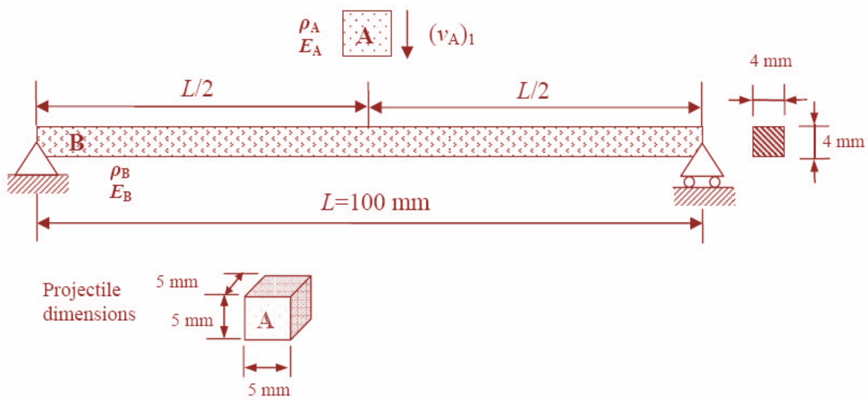

Figure 3: Beam impact problem.

3. Beam Centered Impact Problem

Before studying bird-strike events, we proceeded to solve a beam centered impact problem (Goyal and Huertas, [10]). The problem consisted in taking a simply supported beam of length, L, of 100 mm over which a rigid object of mass, m_A, of 2.233 × 10^{-3} kg impacts at a constant initial velocity of, $(v_A)1$, 100 m/s. The beam has a solid squared cross section of length 4 mm, modulus of elasticity, E_B, of 205 GPa, and a density, ρ_B, of 3.925 kg/m^3. Figure 3 shows a schematic of the problem. The goal of this problem is to obtain the pressure maximum peak pressure exerted at the moment of impact. The problem is solve analytically and then compared to the corresponding outputs from LS-DYNA for the Lagrange method.

3.1 Analytical Solution

Since the impact occurs at only one point, the problem can be solved by concentrating all the mass of the beam at the point of impact, i.e., at the center of the beam. Thus this will simplify the problem to a problem of central impact between two masses, as shown in Figure 4.

The theorem of impulse and momentum may be divided into two parts, as shown in Figure 5. The first stage is the impact between the two masses with its respective initial velocities. At this stage an impact force occurs in the beam that is exactly the same as that generated by the beam against the projectile. The second stage is when both masses stick together with a common velocity, experiencing a perfectly plastic impact. In other words the coefficient of restitution for this problem is zero. Thus the final velocity is calculated as follows:

$$(v_A)_2 = \frac{m_A}{m_A + m_B} (v_A)_1 \tag{4}$$

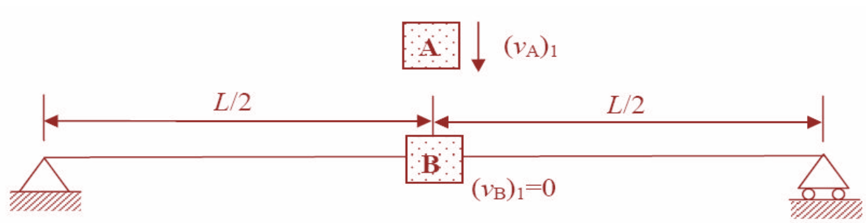

Figure 4: Beam impact problem simplification.

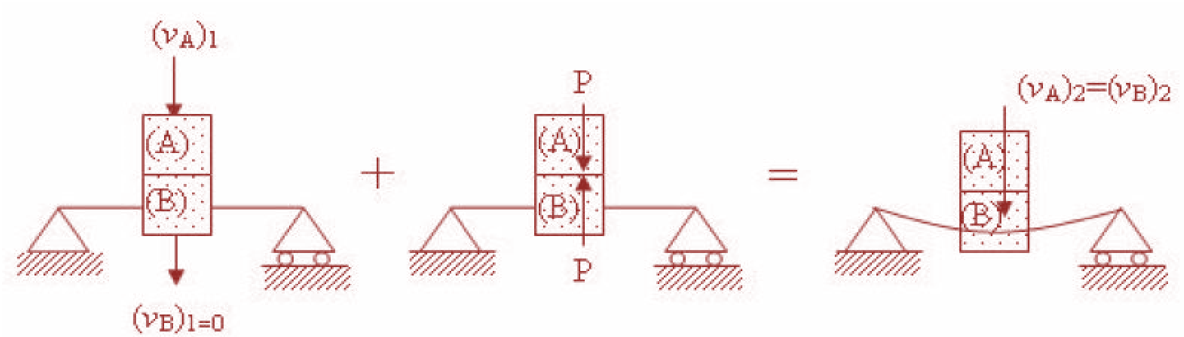

Figure 5: Visualization of the theorem of impulse and momentum.

Now, as a consequence of concentrating all the mass at the center of the beam, the model is similar to that of a one degree of freedom damped vibrating system with a force f(t). Since the impact time is infinitesimal, the function f(t) can be assumed as a impulsive time-average constant force F_{ave} acting during the time of the impact and it is found as follows

$$F_{\text{ave}} = \frac{m_A}{\Delta t} (v_A)_2 \tag{5}$$

where Δt is the time it takes to complete the impact. Equation (5) has two unknowns: the average force and the impact time. The impact time is taken to match the impact time given by LS-DYNA, and thus perform a fair comparison. Once the impact time in known, the force is obtained straight forward using Equation (5).

3.2 Lagrange Simulation

Now we solve the problem using the Lagrangian description in LS-DYNA. Figure 6 shows the Lagrangian simulation and Figure 7 shows the plot for the impact force. The measured impact time was Δt = 8.08 μs. Only the initial impact pulse was considered for effects of comparison because we are trying to compare a simple model discarding the possibility that the Lagrange

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simulation produced a not completely plastic impact. Substituting values in Equation 5, the analytical impact force is 27.65 kN and the pressure 1.106 GPa. In impact problems, we are mostly interested in the highest impact force. Thus, there is 2.4% difference when comparing the peak force with the Lagrangian simulation to the analytical solution.

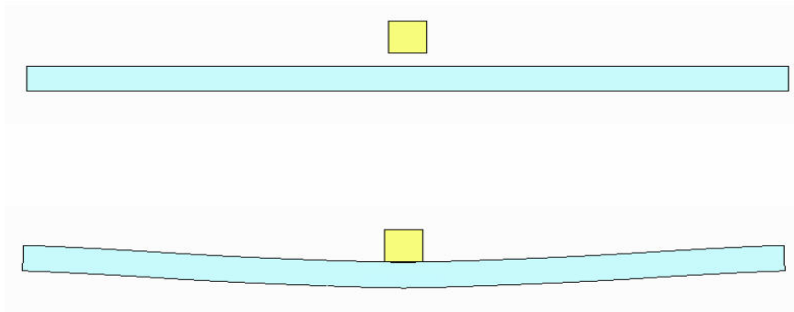

Figure 6: Lagrange simulation of transversal beam impact.

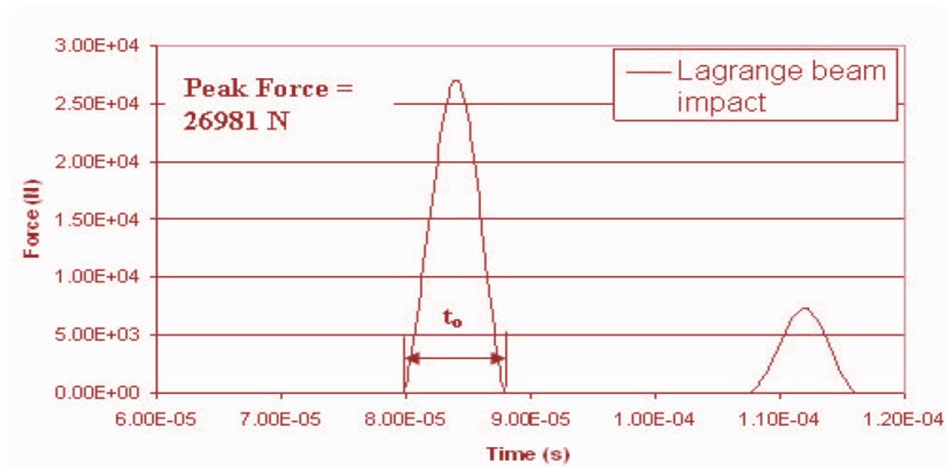

Figure 7: Impact force for the Lagrangian simulation.

4. Bird-Strike Impact Problem

The beam centered impact problem was based on rigid body impact in which the analytical load computation is relatively easily taking. The results obtained from this example provided us confidence in the methods being used and thus we proceeded to analyze the bird-strike impact problem. The bird-strike impact problem is a soft body impact which is different from the rigid body impact. It is a soft body impact problem because the bird is deformable and is composed of fluid and air, and the yield stress is far smaller when compared to that of the target.

Figure 8: Damage caused by bird-strikes.

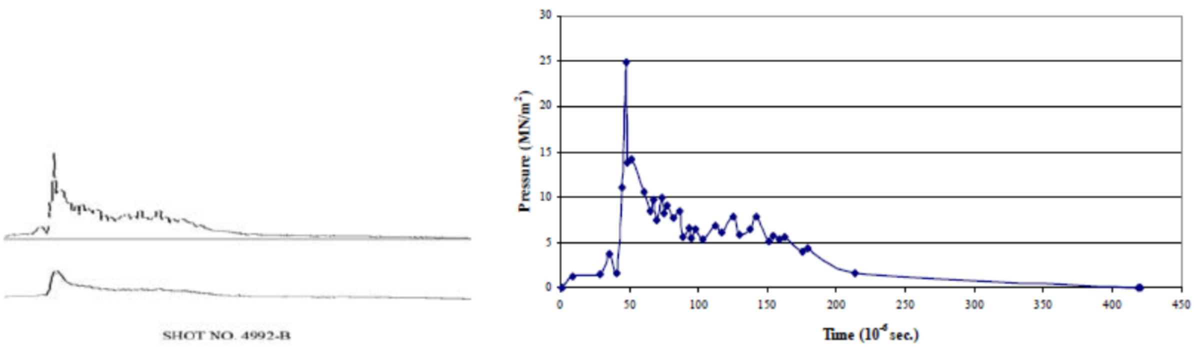

Figure 9: Graphical representation of Pressure Time oscillograph for shot 4992-B [7].

Although the characterization for soft body impact is a complex problem, researchers have studied this problem using test data. Barber et al. [6] performed an experimental characterization of bird-strike events. A bird-strike event may occur in different parts of an aircraft; however, the scope of this work is to study bird-strike against fan-blades. Figure 8 shows the damage caused by bird impact on the turbine fan blades. This only shows us that this problem is crucial and that by predicting the impact pressure will help us design better fan blades. Furthermore, a fan blade is composed of both flat and tapered sections. Thus, we focus our attention on analyzing bird-strikes against flat and tapered plate using the Lagrange formulation in LS-DYNA. We use the work by Barber *et al*. [6] as a mean of comparison. The results within 10% would be acceptable since the actual testing model is not available.

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4.1 Preprocessing

4.1.1 Bird-Model

How to model a bird is quite challenging and a model that best meets the testing bird properties must be used. The model considered in this work is that of a cylinder, as suggested by Bowman and Frank [11]. It has been shown that this model of bird produce close results to real birds. In addition, the bird model is assumed isotropic, symmetric and homogeneous. An approximate aspect ratio (L/D) of 2.03 was used for our bird model. The dimensions vary depending on the mass of the bird, and are selected from the test data by Barber et al. [6]. The material properties of the bird were similar to a gelatin material with 90% water and 10% air mixture. It is important to highlight that the mass of the testing birds plays an important role in the computer simulation because the pressure distribution greatly depends on the density of the impacting object. Table 1 summarizes the main properties used for modeling the bird.

Table 1: Properties for the model of bird.

Density	912.61 kg/m^3
Pressure Cutoff	0.09974 MPa
*Diameter	40 mm
*Length	90 mm
Impact Velocity	198 m/s (442.9 mph) Rigid flat plate 477.4 m/s (1067 mph) Tapered plate

4.1.2 Rigid Flat Plate Target

In this research we use a rigid flat plate target and a deformable tapered plate target. The purpose of using a rigid flat plate target is to compare the simulations with the experimental data obtained from Barber et al. [6]. Barber et al. [6] used a rigid flat plate for their experiments which can be modeled as a circular rigid plate with dimensions of 1 mm thickness and 15.25cm of diameter. The material of the target disk was 4340 steel, with a yield strength of 1035 MPa, Rockwell surface hardness of C45, modulus of elasticity modulus of 205 GPa, and a Poisson's ratio of 0.29. These properties of the material will be used in LS-DYNA to model the flat rigid plate.

4.1.3 Deformable Tapered Plate Target

The deformable tapered plate target properties were taken from the work by Moffat et al. [8], who simulated the impacting bird (as a sphere) on a tapered plate using MSC/DYTRAN software. The properties for the tapered plate are given in.

Table 2: Tapered plate properties (fixed at the two shortest sides).

Material	Titanium 6-4 plate
Yield Strength	828.0 MPa (1.20091×10^5 psi)
Density	4410 kg/m^3 (0.1593 lb/in^3)
Poisson ratio	0.31
Effective Length	22.86 cm (9.0 in)
Width	7.62 cm (3.0 in)
Tapered angle	4.0°
Leading edge thickness	0.051 cm (0.0200787 in) Blended uniformly up to 0.160 cm (0.06299 in)

4.1.4 Test Data for Bird-Strike Event

Barber et al. [6] simulated the bird-strike event as a solid cylinder with dimensions that vary depending on the mass of the bird. The birds used in the tests weigh about 100 grams and are fired at velocities ranging from 60 to 350 m/s. To achieve a better simulation of the bird-strike event the densities of the computer simulated bird must be calculated based on the masses of the tests and the recommended bird cylinder-like computer model. The target disk must be modeled as a circular rigid plate. The material for the target disk was steel 4340 and Rockwell surface hardness of C45.

In this research, we compared the tendencies on the pressure-load curves of the computer simulations with experimental data, and determined velocities and densities based on the mass and velocity quantities of the test data. To have a fair comparison of the results obtained by the bird-strike simulation using LS-DYNA and the Barber et al. [6] research it is necessary to reproduce as accurate as possible the results displayed from the pressure transducers recording the impact event. Because of not having the digital experimental data of the test results to be reproduced, the graphs presented on Barber's report are imported into MatLab to obtain approximate readings, which are later compared with those obtained by LS-DYNA.

The pressure plots shown in Figure 9 depict the data by Barber *et al*. [6] in which the loads generated in the impact are characterized. This is done in an effort to study the loading caused by

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this kind of impact in a real aircraft. All the LS-DYNA simulations performed in this research are observed and compared with the test data. It is important to identify the stages in the loading which are observed by Barber et al. [6]. The pressure measured in the test data shows about three different stages as seen in Figure 9. The first and most important is the peak pressure generated at the beginning of the impact. This pressure applied to the plate will tell us the magnitude of the average maximum load that the target material has to resist. A secondary stage of the pressure that the bird exerts over the plate is a steady state phase which occurs for a short period of time, on the order of 150 to 400 μs. In this stage there are some high frequency variations of the pressure which influence on the target will depend on the geometric characteristic of the same. A final stage of the recorded pressure time plot is the fall of the pressure to a null value. For the purposes of this research, velocities and densities were determined based on the mass and velocity quantities of the test data.

The computer simulations are based on the data given by the Barber et al. [6] research and the bird model used. The purpose of these simulations is to compare results obtained by using the Lagrangian method with the experimental results. LSDYNA data output parameters such as *DATABASE RCFORC were used to obtain the impact force diagrams.

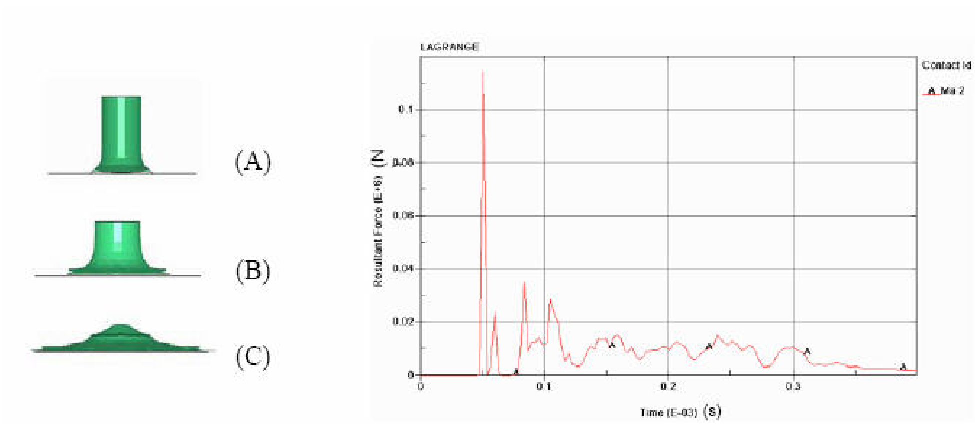

Figure 10: Lagrangian bird deformation and force plot when using *MAT NULL.

We used a uniform cylindrical representation for the Lagrangian bird model because it attempts to represent the artificial bird used in a real bird-strike test with those performed by Bowman and Frank [11]. It is further assumed that this bird model is isotropic, symmetric and homogeneous. Solid elements were used for the construction of the Lagrangian bird model. The elements used for the target are of shell type with constant thickness of 1 mm (0.0393 in). All the nodes of the shell target were constrained in translation and rotation trying to represent the rigid plated used by Barber et al. [6]. A constraint in displacement and rotation in all directions was applied to all the nodes in the shell target and to the thickness of the shell element using the *BOUNDARY SPC card.

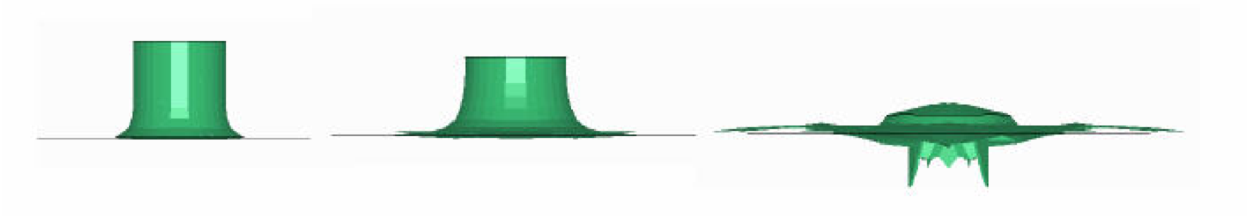

Figure 11: Deformation of the bird model for the Lagrangian simulation using the FORMING NODES TO SURFACE contact.

4.2 Frontal Bird-Strike Event in Rigid Plates

4.2.1 Using *MAT NULL

First we studied the different types of contacts, starting with the *CONTACT ERODING NODES TO SURFACE and the material type null. This contact type is a one-way contact which allows for compression loads to be transferred between the slave nodes to the master surface and it is recommended when the surface orientation is known throughout the analysis. The erosion contact type allows the removal of the elements due to failure criteria to make the calculation more stable. This contact type contains logic that allows the contact surface to be updated as the external elements are deleted. The deformation for this simulation and the force plot generated by LS-DYNA are shown in Figure 10. The maximum value of force obtained from the simulation was 0.114 MN (25628 lbf). Additionally, the pressure was calculated using an approximate area at the impact time, which is measured as 1300 mm^2. Thus the peak pressure obtained is 87.6 MPa, which is 117% higher than the peak pressure found by Barber et al. [6]. When the values of the relative volume in tension and compression were changed to 1.1 and 0.8 the resultant force obtained was 0.523 MN. Therefore, this parameter is extremely sensitive for the Lagrange simulation.

Now we consider the *CONTACT FORMING NODES TO SURFACE to define the contact between the bird model and the target. The deformation was not as smooth as it was when using

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the *CONTACT ERODING NODES TO SURFACE. It can be seen in Figure 10 that at the final deformation, a considerable amount of the bird model actually penetrates the target. The main reason is that this contact type is suitable for metal stamping and not for rigid structures. The maximum force value obtained for this simulation was 0.0404 MN. This value was 64.63% lower than the maximum value obtained in the previous Lagrangian simulation. The fact that the deformation shows errors and that the behavior of the force was very different when compared to force plots of previous simulations leads to the conclusion that this simulation does not provide accurate results.

Lastly, we change the contact type to *CONTACT NODES TO SURFACE. This is a constraint based contact in which the forces are computed to keep the slave nodes in the master surface. The deformation of this simulation presented instability error. This error was similar to that observed in the simulation performed using *CONTACT FORMING NODES TO SURFACE, as shown in Figure 11. The force plot from this simulation was 0.0404 MN, resulting in a maximum force value same as in the previous simulation.

4.2.2 Using *MAT ELASTIC FLUID

For this simulation we changed the bird material from *MAT NULL to *MAT ELASTIC FLUID. Since the results produced using *MAT NULL are not acceptable due to the large margins of error, we decided to study to change the material model for the bird. The same three types of contacts are studied for this material as well. First, *CONTACT ERODING NODE TO SURFACE was used. A different outcome is expected because the equation of state for this material model is different.

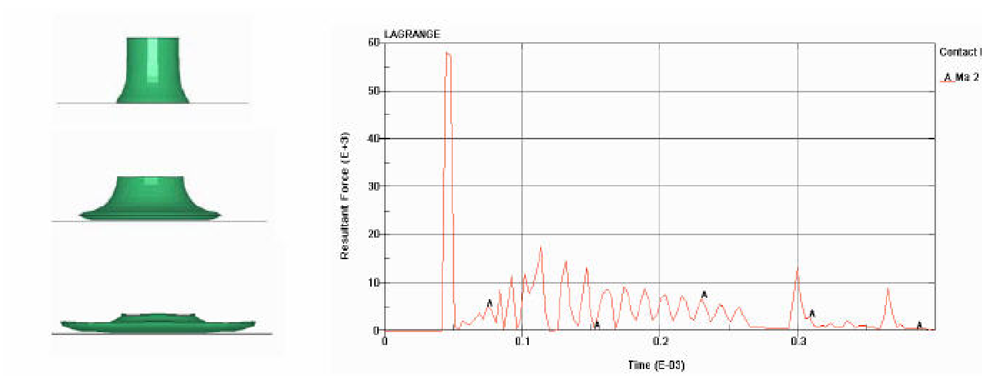

Figure 12: Lagrangian bird deformation and force plot when using *MAT ELASTIC FLUID.

Figure 12 shows how the bird deforms after the impact and the force plot. The maximum impact force obtained from this simulation was 0.0581 MN and it was obtained at 44.9 μs. Since the pressure is needed in order to compare these results with the test data provided by Barber et al. [6], we calculated the impact area by measuring the diameter of impact at the same time in which the peak force occurred. This area was only an approximation to compute the maximum peak pressure. It was calculated measuring the diameter of the impact area as shown in Figure 13. The diameter was 41.18 mm therefore the approximated area was 1331.8 mm^2. Thus the peak pressure is 43.66 MPa, which is has 9.15% difference when compared to that obtained by Barber et al. [6]. Results for all other cases were not acceptable and thus *CONTACT ERODING NODES TO SURFACE is the contact type recommended for bird-strike problems.

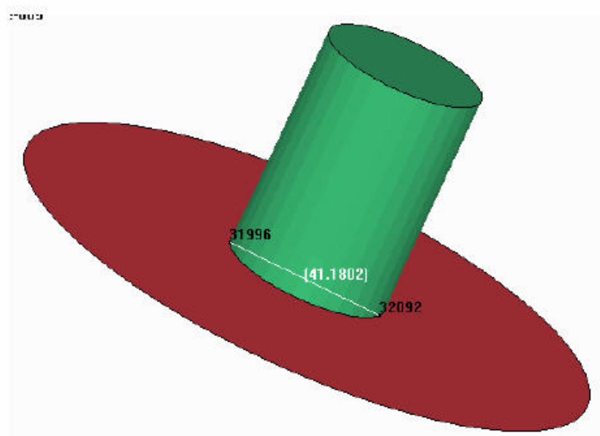

Figure 13: Diameter in the peak force impact time.

Table 3: Peak impact pressure comparison for various contact types and material models.

Simulation	Peak impact pressure (MPa)	Error %
Barber et al. (1975)	40.00	—
Lagrange MAT_ELASTIC_FLUID eroding	43.66	9.15
Lagrangian MAT_NULL and eroding node to surface contact	87.00	117
Lagrangian MAT_NULL Nodes to surface	26.43	33.9
Lagrangian MAT_NULL Forming	26.43	33.9
Lagrangian MAT_ELASTIC_FLUID and forming contact	26.60	33.50
Lagrangian MAT_ELASTIC_FLUID and node to surface contact	26.60	33.50

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4.2.3 Comparison

The three Lagrangian simulations were performed varying contact cards and bird material types. There is no difference between the results of the simulations using the *CONTACT FORMING NODES TO SURFACE and *CONTACT NODES TO SURFACE cards. Simulations with these contacts do not provide a smooth deformation of the bird because a significant amount of the bird actually penetrates through the target causes errors in the force and thus pressure values. Results are summarized in Table 3.

On the other hand, the Lagrangian simulation performed using the *CONTACT ERODING NODES TO SURFACE contact card provided the best deformation and the force plots when using *MAT ELASTIC FLUID. The peak pressure obtained using the eroding contact with MATERIAL NULL was 117% when compared with the test data. When using *MAT ELASTIC FLUID the approximate pressure was 9.15% higher to that value obtained by Barber *et al*. [6].

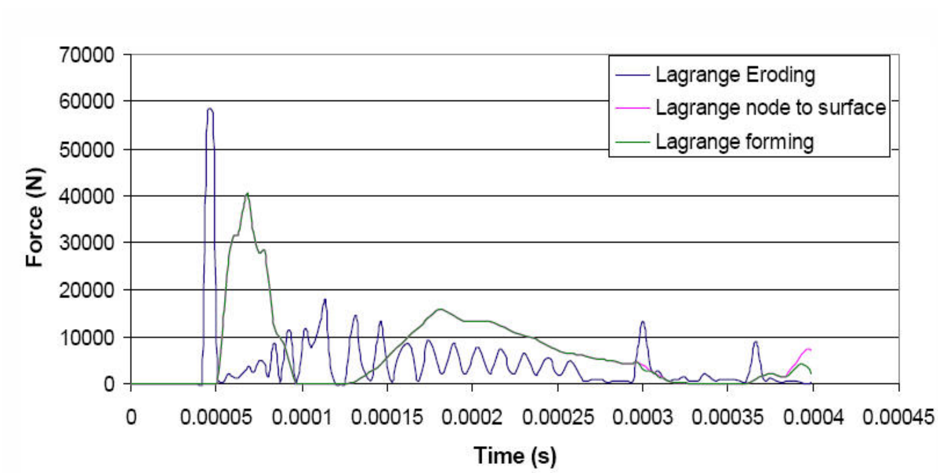

Figure 14: Comparison of the Lagrangian simulations for *MAT ELASTIC FLUID.

In addition, if we compare the force plots of the Lagrangian simulations using material elastic fluid, as shown in Figure 14, we observe that the highest value corresponds to the eroding contact type. The contact forming and nodes to surface have an error of 33.5% when compared with the experimental value of 40 from Barber *et al*. [6]. Thus, for the Lagrangian model we recommend a bird-model with material elastic fluid and an eroding node to surface contact type.

4.3 Impact for a Tapered Plate (Impact at 30 deg)

Now we explain the simulation of a cylindrical bird impacting a tapered plate along the thinnest side. The deflection of the leading edge and the loads generated in the impact were computed for LS-DYNA. The results are compared to those provided by Moffat et al. [8] by modeling the bird as sphere. Here, however, our bird model is a cylindrical-type projectile. The cylindrical form was chosen to be consistent to the worked performed here. In the Lagrangian approach, the sphere model creates problems because of the node superimposition due to the mesh type. These variations in density and overall solid dimensions of the bird should not produce huge differences to the results obtained by Moffat et al. [8]. The cylinder dimensions and properties are same as those used in the flat plate impact with the difference that the impact velocity is 477.4 m/s (1067 mph).

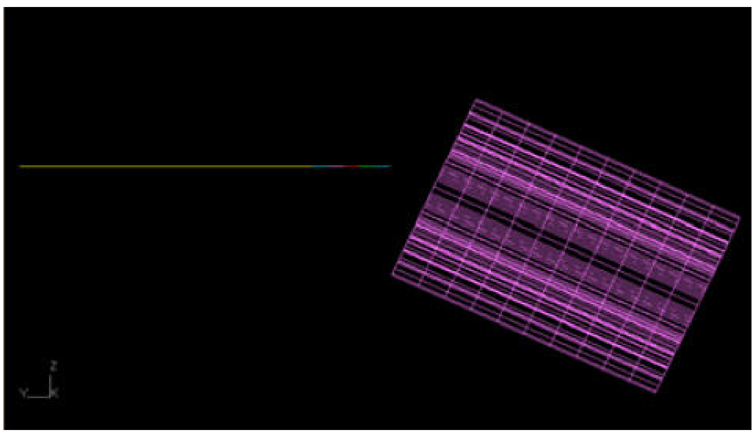

Figure 15: Lagrangian bird impacting the tapered plate at 30°.

The boundary nodes of the plate corresponding to both sides were fixed with *SPC BOUNDARY card. The tapered section of the plate was simulated by increasing the mesh and assigning different parts with different *SECTION SHELL cards. The cards differ from each other in the thickness of the elemental nodes. Five different parts were created for the tapered section of the plate.

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Figure 16: Snapshots of the a bird impacting the tapered plate at 30°.

Moffat et al. [8] found that the maximum deflection in the leading edge was 1.05 in when a bird impacts the simulated tapered plate at 30°. The impact angle of the bird was 30° and was measured between the axis of the cylinder and the plane of the tapered plate as showed in Figure 15. Figure 16 shows the deformation of the tapered plate during the impact when the bird is modeled using *MAT ELASTIC FLUID. As observed some elements are eliminated during calculations due to negative volumetric strains failure. Figure 18 shows the top view of the tapered plate leading edge deflection.

The maximum deflection was found to be 1.19 in as seen in Figure 18. This deflection was measured using the tool of the LS-PREPOST to measure the change in coordinates using as point of reference the position of the corner of the plate which is constrained in translation and rotation in the x, y and z directions. Also, Figure 18 shows the resultant force in the contact interface and the maximum value was 0.056 MN.

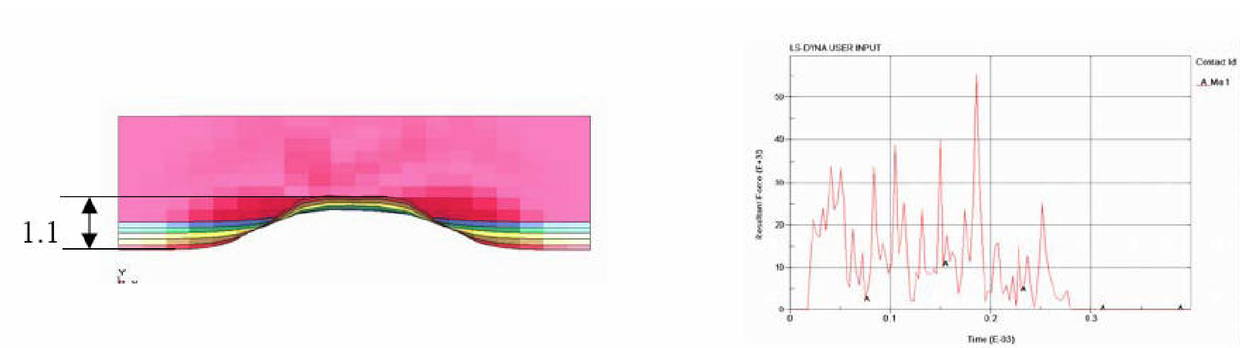

Figure 17: Top view of the deformed tapered plate leading edge after the impact and the resultant force for the Lagrange simulation of the impact of a bird against a tapered plate with an angle of 30 degrees.

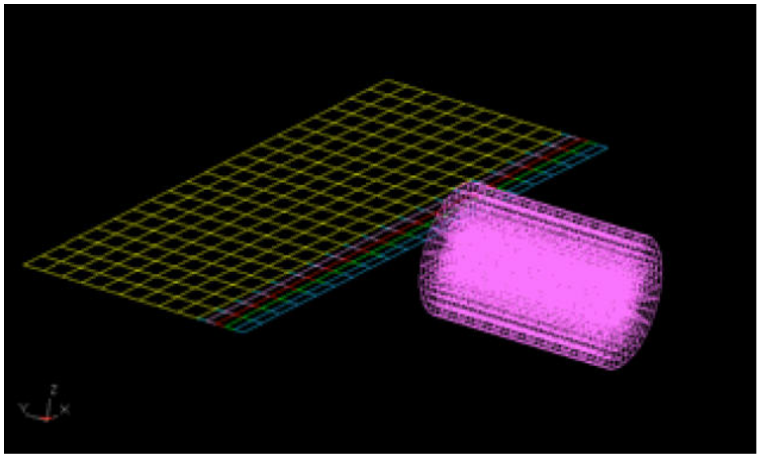

Figure 18: Lagrangian bird impacting the tapered plate at 0°

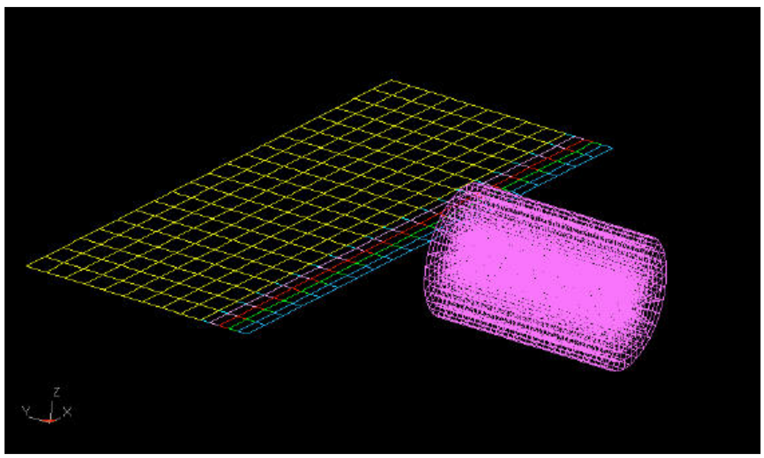

Figure 19: Lagrangian bird impacting the tapered plate at 0°

Table 4: Maximum normal deflection for a bird impacting a tapered plate at 30°.

Tapered impact simulation at 30°	Maximum normal deflection (in / cm)	Error %
Moffat et al. (2001)	1.05 / 2.6667	—
Lagrange using *MAT_NULL	1.36 / 3.4544	29.8
Lagrange using *MAT_ELASTIC_FLUID	1.19 / 3.0226	13.3

Results in LS-DYNA were obtained in US units. Hence, the results were converted to SI units.

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Table 4 summarizes the results. The simulation using material elastic fluid and eroding node to surface give acceptable results when comparing to the work done by Moffat. Only a 13.3% of error, taking in consideration that the shape of the bird used in our case was different from that used by Moffat. One reason why the better approximation is the Lagrange simulation using the material elastic fluid could be because the material elastic fluid computes the stresses that cause the deformation in the bird or the deviatoric stresses. Also, the material null does not take account for this stresses the energy in the impact will be absorbed by the target resulting in a higher force produced.

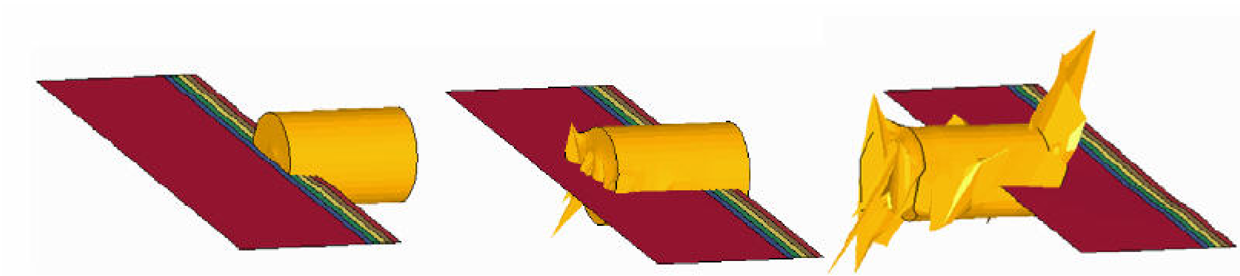

Figure 20: Snapshots of the a bird impacting the tapered plate at 0° when using *MAT NULL.

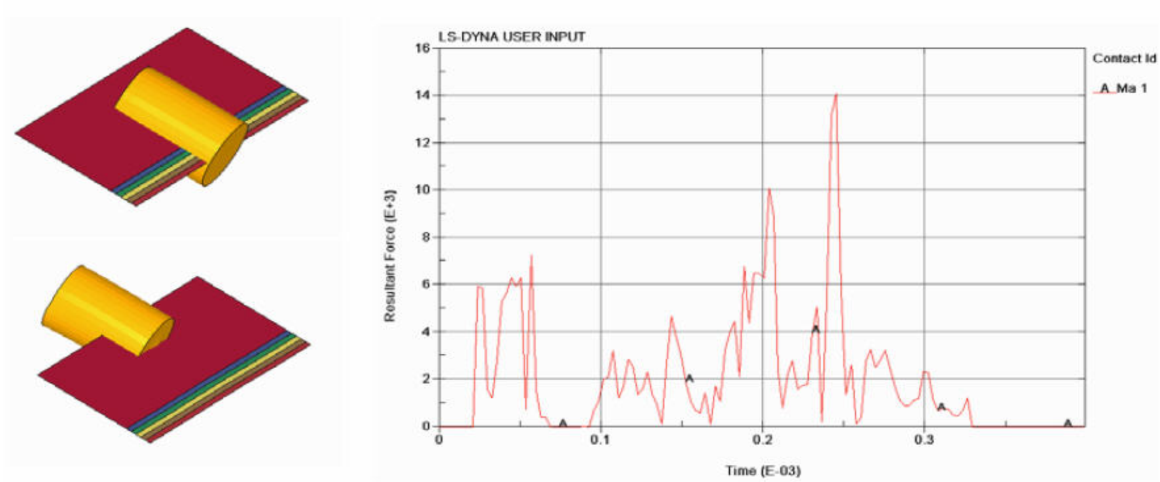

Figure 21: Snapshots and force history of a bird impacting the tapered plate at 0 when using *MAT ELASTIC FLUID.

4.4 Impact for a Tapered Plate (Impact at 0 deg)

In this simulation the angle of impact is changed to 0°. The bird and plate properties were the same as the used in the 30° impact. Figure 19 shows the geometrical model for this case. Once again, results with *MAT NULL do not model the actual bird deformation as shown in Figure 20.

During simulations, some elements of the bird were deleted which were produced due to failing in the negative tensile or compressive volumetric strains.

As observed in Figure 21 the bird and target slightly interact and no deformation of the tapered plate was obtained. This is expected since the bird impact occurs from the thinnest edge of the tampered plate and the bird is basically sliced in two parts. This occurs as we change the material type from *MAT NULL to *MAT ELASTIC FLUID.

The maximum force obtained was using materials null and elastic fluid was 0.0142 and 0.01411 MN, respectively. There is 0.637% difference for the force between the two material models (material null and material elastic fluid). The material null which considers a fluid material with 90% water and 10% air and the material elastic fluid which model an isotropic fluid material can be used for 0° impact analysis to calculate the force. The reason is that the deviatoric stresses are not computed. The similitude in the results for the 0° impact can be explained because in the case in which the material elastic fluid is used there was very little deformation of the bird and therefore there was no computation of the deviatoric stresses.

5. Concluding Remarks

The Lagrangian method used in LS-DYNA has shown to be robust for the one-dimensional beam centered impact problem. The peak pressure from has an error smaller than 2.5% when compared to the analytical results. Thus, the Lagrangian methods can be used to study soft-body impact problems, such as bird-strike events.

For the frontal bird-strike impact against a flat rigid plate, one must use eroding type contact and material elastic fluid. *MAT ELASTIC FLUID is a material specialized to model a fluid-like behavior taking in consideration the deviatoric stresses which are not considered in the *MAT NULL. The Lagrangian simulations show that the results are in within 10% when compared to the experimental data.

For the 0 deg bird impact against a tapered plate, there was a small fluid-structure interaction

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because the bird is basically sliced in two parts. For the 30 deg bird impact against a tapered plate, the Lagrangian produce a maximum normal deflection within 13.3% when compared to the maximum normal deflection found by Moffat.

The main difference is error is due to the negative volume error, which occurs as a result of mesh tangling do to its sensitivity to distortion, resulting in small time steps and sometimes loss of accuracy.

6. Acknowledgments

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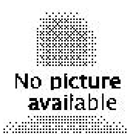

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