The influence of bird-shape in bird-strike analysis

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ABSTRACT

This paper describes the results of simulations to assess the influence of bird shape during bird-strike. In the first part of this paper, simulations are presented which compare the results of a traditional bird shape model (hemispherical ended cylinder) impacting a square flat panel using the ALE and SPH techniques. In each case the bird is modelled with a mass of 8 lb and has physical dimensions (torso) representative of a Canadian goose. The simulation results show close agreement with one another for stagnation pressure and displacement of the panel.

Biometric data obtained from the IBRG (International Bird-Strike Research Group) is then used to construct a more detailed bird model of a Canadian goose that includes multi-material parts. The model is simulated using SPH and compared to the results of the hemispherical ended cylinder. The simulation results obtained using this new bird model indicates that a target may become pre-stressed from the initial impact of the head and neck, prior to the impact of the torso. This may have an important consequence for damage initiation and failure of the target.

INTRODUCTION

Bird-strikes present a significant financial and safety threat to aircraft worldwide. According to Allan and Orosz [1], bird-strikes were estimated to cost commercial aviation over $1 billion worldwide during 1999-2000. These costs are associated with damage to the aircraft and loss of revenue to the operator due to delays.

All new commercial aircraft are required to pass a certification test (standard) that demonstrates the aircraft can operate safely in the event of a bird-strike event. These certification standards were established by the U.S. Federal Aviation administration (FAA) and European Joint Aviation Authority (JAA) in a series of airworthiness standards for airframes and windshield of transport aircraft [2], e.g. in the case of aircraft (> 19 passenger seats) the empennage must demonstrate bird-strike tolerance against the impact of an 8lb (3.62kg) mass at cruise velocity V_c. The standards ensure that aircraft designers conduct extensive bird-strike testing and analysis of forward facing components: radomes, windshields and windows, aircraft engines and leading edge structures, before the aircraft is certified for flight.

The bird-strike certification test is conducted by firing euthanised birds from a gas cannon onto a target structure. Barber investigated the use of substitute materials (gelatine, gelatine and air, rubber) to replace real birds during bird-strike testing [3, 4]. Although, these artificial birds cannot be used in certification tests they can be used for design development of aircraft structures. The artificial bird can improve consistency of tests and reduce the biological hazard of using real birds. Although artificial birds have been used for many years by a variety of organisations there is no standardised artificial bird material or shape. Gelatine is perhaps the most popular and validated of bird materials, however the shape often varies between three primitive geometries: cylinder, hemispherical ended cylinder and ellipsoid. These geometries are chosen to reflect the principal mass and shape of a real bird; in most bird species this represents the torso of a bird. The use of a primitive geometry is also beneficial since it is generally easier to manufacture.

The IBRG (International Bird Strike Research Group) is currently investigating the use of new materials to replace the existing artificial bird for certification tests. This may result in a multi-material (composite) bird based on a non-primitive geometry. Although, it may be possible to represent a small bird species using a primitive geometry this may not be appropriate for a large bird species such as the Canadian goose, where the wings and neck contribute to the total mass of the bird. The representation of a large bird species in physical tests (non-certification) and numerical simulations is of particular interest at present due partly to their increasing population [8] and to the higher number of aircraft and flights.

Bird-Strike Simulation

Force-impulse models and semi-empirical equations can be used to predict the average force during a bird-strike event. Although these equations are often based on momentum conservation they may not account for the complex structural interaction that occurs between the bird and target. In most cases these models cannot be used to determine the level of damage imposed on a target.

Simulating a bird-strike event that accounts for structural interaction and damage is possible using software such as LS-DYNA [5, 6]. The simulations may be performed using a variety of numerical techniques including Arbitrary Lagrange Eulerian (ALE) and Smooth Particle Hydrodynamics (SPH) [7]. In many cases the bird model used in a simulation is based on a geometry and material type that represents the artificial birds used during physical experiments. The shape of the bird is often represented as a simple primitive geometry (cylinder, hemispherical ended cylinder or ellipsoid) to reflect the principal mass and shape; in most bird species this represents the torso of a bird.

In the first part of this paper, bird-strike simulations are presented which investigate the difference between the ALE and SPH techniques. The simulations will predict the impact of a traditional bird model (hemispherical ended cylinder using a single material type) into a square flat panel. In additional simulations, the physical shape of the hemispherical ended cylinder is developed using biometric data to create a multi-material bird based on the Canadian goose; these simulations will be used to investigate:

- The practicality of constructing a model and performing a simulation with different bird parts and material models.
    - If the IBRG develops a new artificial bird that consists of different materials, e.g. composites / cored birds and/or a significantly different shape, analysts may need to replace the existing bird models used in simulation.
- The influence of different bird parts during a bird-strike event; the neck of the Canadian goose may be of particular concern for external structures and engines.
    - Conducting physical experiments, which replicate a Canadian goose (neck extended) flying into a representative aircraft structure would be complicated to perform. Such a significant physical change may not be practical to manufacture, however, simulation can be used to analyse this change.

The model is simulated using SPH and compared to the results of the hemispherical ended cylinder using the same technique. It should be noted that the material models used to represent the constituent parts of the model are based on an EOS for gelatin; consequently the model is more representative of an artificial bird manufactured of similar shape.

Methodology

The bird-strike simulations presented in this section were performed using the ALE and SPH techniques within LS-DYNA 970 [5]. Simulation results are presented which compare a traditional bird shape model (hemispherical ended cylinder) impacting a square flat panel using the ALE and SPH techniques. The ALE simulations use 2nd order advection with a translating, contracting and expanding mesh which concentrates elements adjacent to the target during impact.

In additional simulations, the physical shape of the hemispherical ended cylinder is developed using biometric data obtained from the IBRG to create a multi-material bird based on a Canadian goose. The bird model is simulated using SPH and compared to the results of the hemispherical ended cylinder using the same technique.

In each simulation the bird is modelled with a total mass of 3.6kg (8 lb) and an initial velocity of 180 m/s. The target structure is modelled with properties of Aluminium L167 and is fixed in translation and rotation around the outside edge. The simulations results are presented in terms of maximum panel displacement, stagnation pressure and the effective stress at the point of impact. Consideration is also given to the change in global kinetic and global internal energy during the impact event.

Model Construction

The bird models were defined by a hemispherical-ended cylinder and were based on a standard volume of 3.958E+06 mm^3 and length 334 mm, resulting in an aspect ratio of 1.6. The bird model used in the ALE simulation was generated using the volume fraction option, which defines the bird's computational domain, position and physical dimensions (defined as material/fluid fraction). The bird was initially defined in 3144 cells in the ALE simulation.

The SPH bird models (hemispherical ended cylinder and multi-material model) were generated using in-house SPH pre-processor software. The hemispherical ended cylinder was generated using 13871 particles and the multi-material model was generated using 29903 particles.

The pre-processing software HyperMesh [9] was used to create the Finite Element (FE) mesh of a square flat panel with a surface area of 0.25m^2. The FE mesh of the flat panel was constructed using 10,000 quadrilateral shell elements (100x100) using an even mesh distribution.

Material Models

Single Material Bird

The bird models used in the ALE and SPH simulations were defined using a null material model (type 9) combined with the Grunëisen equation of state. The following null material parameters were used in the ALE and SPH simulations for the hemispherical-ended cylinder: ρ = 9.2E+02 kg/m^3, μ = 4E-04 Ns. The bird model used in the ALE simulation is defined in a rectangular computational domain consisting of solid hexahedral elements. In order to increase the speed of the solution process the elements unoccupied by the bird material model is defined using null material type 9 combined with the keyword ***INITIAL_VOID**. In this case the elements are approximated as fluid elements with very low densities.

Multi - Material Bird

The density values used in the multi-material model are as follows: head - ρ = 9.0E+02 kg/m^3, neck - ρ = 1.5E+03 kg/m^3, torso – ρ = 1.15E+03 kg/m^3 and wings - ρ = 8.45E+02 kg/m^3. These values were calculated to obtain a specific mass for each part based on the model volume; the mass and volume were determined from biometric data [10], e.g. torso mass for an adult Greylag goose was calculated by IBRG to be approximately 70% of total bird mass. The density values specified above for ALE and SPH simulations results in a total bird mass of 3.62kg (8lbs). The Grunëisen equation of state used in both the ALE and SPH simulations was defined using the following parameters: C = 1.4829E+03 m/s, S_1=2.0367.

Target Structure

The flat panel geometry was modelled using Lagrangian shell elements with element formulation 2 – Belytschko-Tsay, thickness = 10.0mm. The structure was represented using a Johnson and Cook [11] plasticity model (type 15) for Aluminium L167. The parameters for this material model were obtained from experiments conducted within the Advanced Technology Centre, BAE Systems, Filton: ρ = 2.7 g/cm^3, G = 0.27 Mbar, E = 0.72 Mbar, ε = 0.33, σ_y = 3.26E-03 Mbar, E_{TAN} = 7.1E-03 Mbar. Interaction between the bird and target is accounted for in ALE simulations using the ***CONSTRAINED_LAGRANGE_IN_SOLID** keyword. In the case opf the SPH simulation an automatic nodes to surface contact was used.

Initial and Boundary Conditions

In each simulation the bird is modelled with a total mass of 3.6kg (8 lb) and an initial velocity of 180 m/s. The target structure is modelled with properties of Aluminium L167 and is fixed in translation and rotation around the outside edge.

In the ALE simulation the computational domain of the bird model was constrained at a fixed point to allow the mesh surrounding the bird to expand and contract during impact. The implementation of this feature will allow the computational domain of the bird to follow the mass moving average of the bird, concentrating elements (reducing the element size) in regions where the velocity and pressure gradients are largest. The mesh contraction stage occurs when the bird is moving towards the target and during the initial impact or compression stage. The mesh expands outwards as the bird spreads out across the surface of the panel. The mesh expansion and contraction feature is initialised in LS-DYNA using the ***ALE_REFERENCE_SYSTEMS_GROUP** command.

Simulation Results

In the following section, simulation results are presented which compare a traditional bird shape model (hemispherical ended cylinder) impacting a square flat panel using the ALE and SPH techniques. The simulation results of the multi-material model is then compared to the results of the hemispherical ended cylinder using the SPH technique.

Traditional Bird Model

A schematic showing the initial set-up for the ALE and SPH simulations is presented in Figure 1. The change in global energy (total, internal and kinetic) during the bird-strike simulation is presented in Figure 2 for each technique. The results indicate a linear decrease in kinetic energy during impact, with a linear increase in internal energy. The exchange of internal and kinetic energy is largely associated with the deceleration and pressure increase for the bird model during impact. When the simulation reaches t = 1.75ms the internal and kinetic energy curves cross one another; for t > 1.75ms the values remain constant. Although the internal and kinetic energy values are the same for each technique at the beginning of the simulation, the values are shown to vary relative to one another during the coarse of the simulations. The difference in total energy at t = 2ms is approximately 8% between each technique; it is interesting to note that the total energy increases with the SPH technique by 2%, in the ALE simulations the total energy decreases by approximately 6% from the starting value. The decreasing in total energy in the ALE simulation is associated with a loss of energy in the contact interface.

The stagnation pressure on the surface of the flat panel is presented in Figure 3 for each technique. Simulation results using ALE initially show a rapid increase in pressure to a magnitude of 300MPa that decays over 0.7ms. The simulation results obtained using the SPH technique show a similar trend; however the pressure values fluctuate with a higher amplitude, which may have contributed to the overshoot in peak pressure. This fluctuation does not appear to have a significant effect on the effective stress at the impact position, Figure 4 or on the resultant displacement of the panel, Figure 5 over a period of 2ms.

In general, the simulation results for the ALE and SPH techniques are shown to be in close agreement with one another. In the ALE simulation the computational domain of the bird model was based on a non-cartesian mesh with volume fraction data to define the position of the bird. The mesh was constrained at a fixed point to allow the mesh surrounding the bird to expand and contract during impact. Although this approach was shown in earlier trials to improve accuracy it did increase the pre-processing time; the extent of mesh contraction and expansion was determined through simulations to ensure the bird material did not flow outside the computational domain. In contrast, it took less time to generate the bird model used in the SPH simulation; this approach only requires the definition of SPH particles (position and mass) and does not use the mesh contraction and expansion feature.

The ALE and SPH simulations were both performed on a single PC workstation (2.0GHz CPU, 1GB RAM). It took approximately 3hrs 45min for each simulation to complete a 2ms event.

Multi-material Bird Model

A schematic showing the initial set-up for the multi-material bird is presented in Figure 6. Simulations performed with the multi-material model show a similar change in global energy when compared with the hemispherical ended cylinder; the total energy remains constant while the internal energy increases and kinetic energy decrease, Figure 2. The principal difference between the simulation results is the time at which the internal and kinetic energy shows a significant change. In the case of the multi-material model the internal and kinetic energy does not show a significant change until t > 1.75ms; when the torso impacts the panel. At times t < 1.75ms the head and neck impact the panel; due to their lower mass they have a lower internal and kinetic energy relative to the torso.

The stagnation pressure at the centre of impact is presented in Figure 7 for the multi-material model and the hemispherical ended cylinder. The simulation results obtained using the multi-material model show an increase in stagnation pressure during impact of the head, reaching a magnitude of 150MPa. This pressure then remains constant during impact of the neck. When the torso of the bird model begins to impact the deformed panel (t = 1.75ms) the simulation shows an increase in stagnation pressure to a value of 250MPa. After this time the pressure decays, indicating the end of the bird impact event. The simulation results using the multi-material model show a lower stagnation pressure applied over a longer time when compared with the simulation using a hemispherical ended cylinder.

The effective stress of the panel at the centre of impact is presented in Figure 8 for the multi-material model and the hemispherical ended cylinder. The influence of the head and neck of the multi-material model are shown to result in a lower effective stress, which increases during impact of the torso to a magnitude of 1GPa. After this peak value is reached the effective stress decays. The displacement of the flat panel shows a similar behaviour to the stagnation pressure and effective stress, Figure 9. Initially, the resultant displacement at the impact position is lower in the multi-material than the hemispherical ended cylinder, however the displacement of the panel increases significantly upon impact of the torso. The displacement of the panel reaches a maximum value of approximately 45mm at t = 3.0ms, somewhat later than results with the hemispherical ended cylinder (t = 2.0ms)

It is interesting to note that prior to the impact of the bird torso, the resultant displacement reached a value of approximately 10mm. This result indicates the target panel is under pre-stress prior to the torso impact; this may have significance on the final level of damage predicted for the structure.

Summary and Conclusions

This paper describes the results of simulations to assess the influence of bird shape during bird-strike. In the first part of this paper, simulations are presented which compare the results of a traditional bird shape model (hemispherical ended cylinder) impacting a square flat panel using the ALE and SPH techniques. The ALE technique was implemented with a moving mesh approach to capture the deformation of the bird model during impact. The simulation results show close agreement with one another for stagnation pressure, von-Mises stress and displacement of the panel. However, the simulation results obtained using SPH showed high frequency variations in pressure and stress, which may be attributed to the stochastic nature of the technique. In additional simulations, the physical shape of the hemispherical ended cylinder is developed using biometric data to create a simple multi-material bird based on a Canadian goose. The simulation results obtained using this new bird model indicates that a target may become pre-stressed from the initial impact of the head and neck, prior to the impact of the bird's torso. This may have an important consequence for damage initiation and failure of the target. The mass and length of the neck may also be significant during bird-strike for aero-engines since the duration of impact effectively increases. It is also possible that damage, initiated on fan-blades during the initial stage of impact (head and neck) would increase due to a secondary impact from the torso; the significance of these effects will be investigated in future work.

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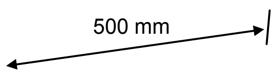

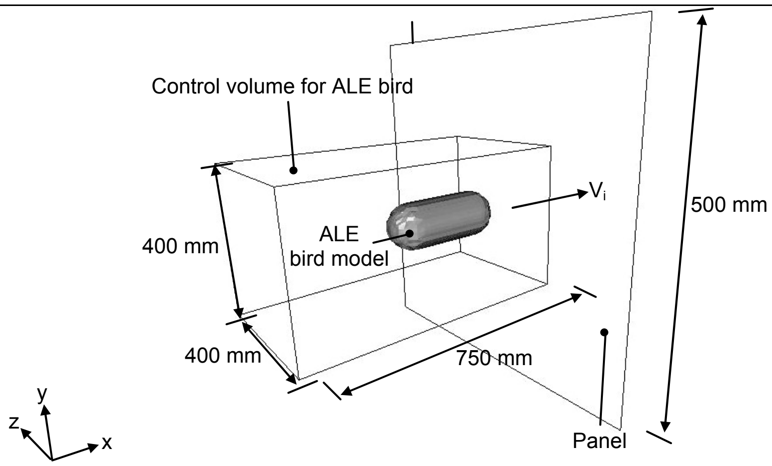

Figure 1 Schematic showing the bird-strike model for a square flat panel impact.

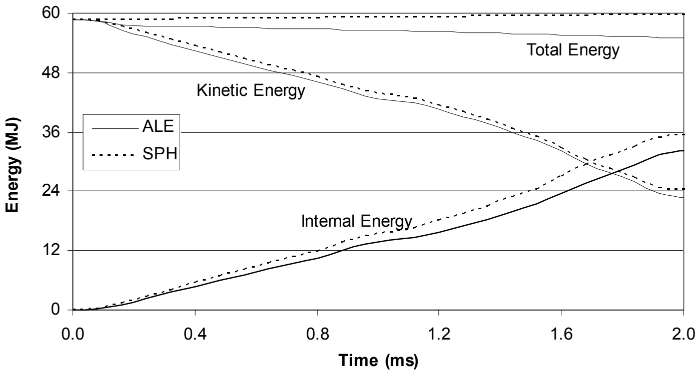

Figure 2 Variation in global energy resulting from the impact of a hemi-spherical ended cylinder into a square flat panel.

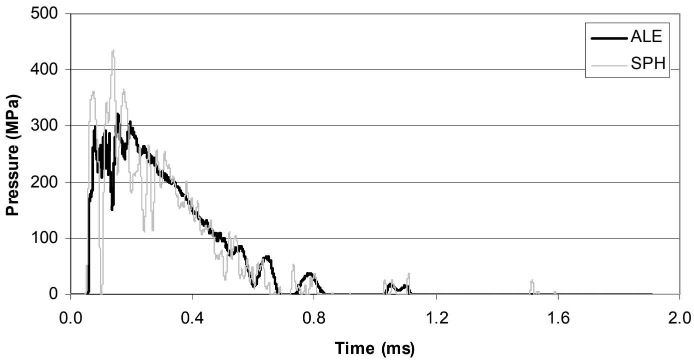

Figure 3 Stagnation pressure (centre of target) predicted for the impact of a hemi-spherical ended cylinder into a square flat panel.

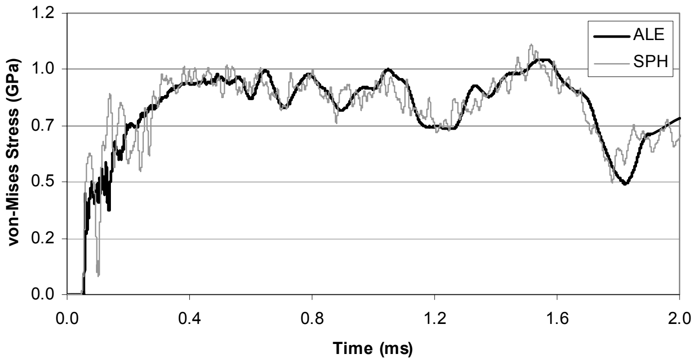

Figure 4 von-Mises stress (centre of target) predicted for the impact of a hemi-spherical ended cylinder into a square flat panel.

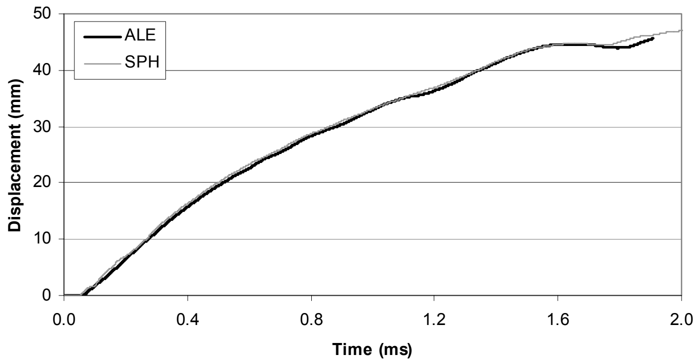

Figure 5 Resultant displacement (centre of target) predicted for the impact of a hemi-spherical ended cylinder into a square flat panel.

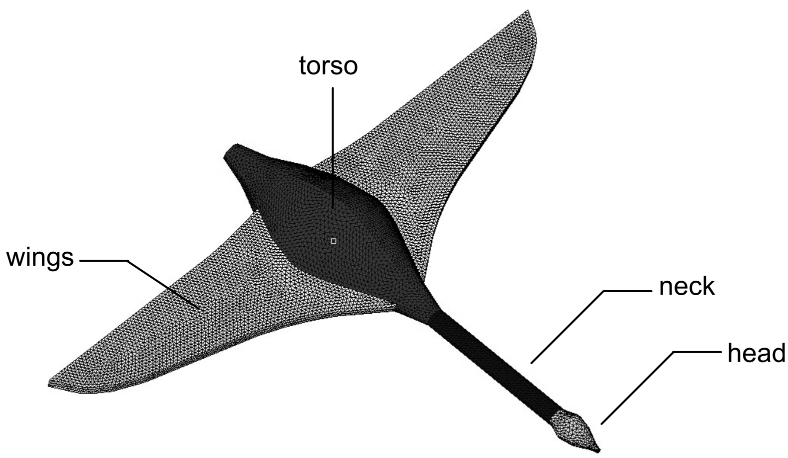

Figure 6 Schematic of the multi-material bird model used in the SPH simulation.

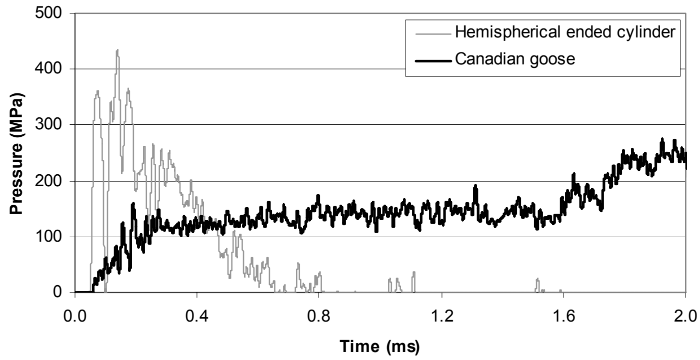

Figure 7 Stagnation pressure (centre of panel target) predicted for the impact of a multi-material bird model, compared to a hemi-spherical ended cylinder.

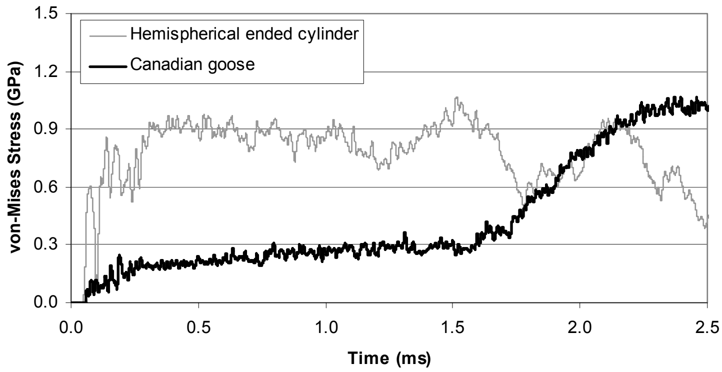

Figure 8 von-Mises stress (centre of panel target) predicted for the impact of a multi-material model, compared to the hemi-spherical ended cylinder.

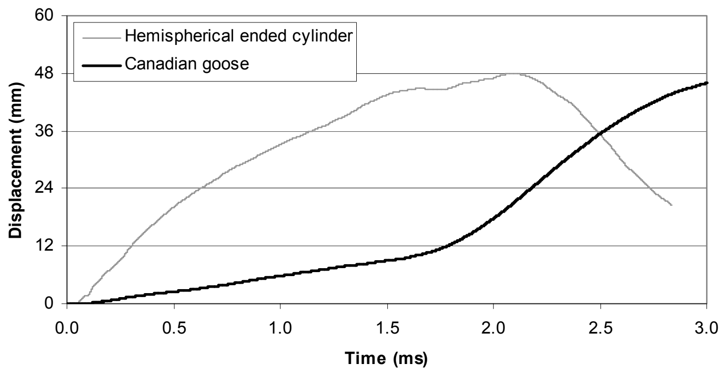

Figure 9 Resultant displacement (centre of panel target) predicted for the impact of a multi-material model, compared to the hemi-spherical ended cylinder.