Modelling of bird strike on the engine fan blades using FE-SPH

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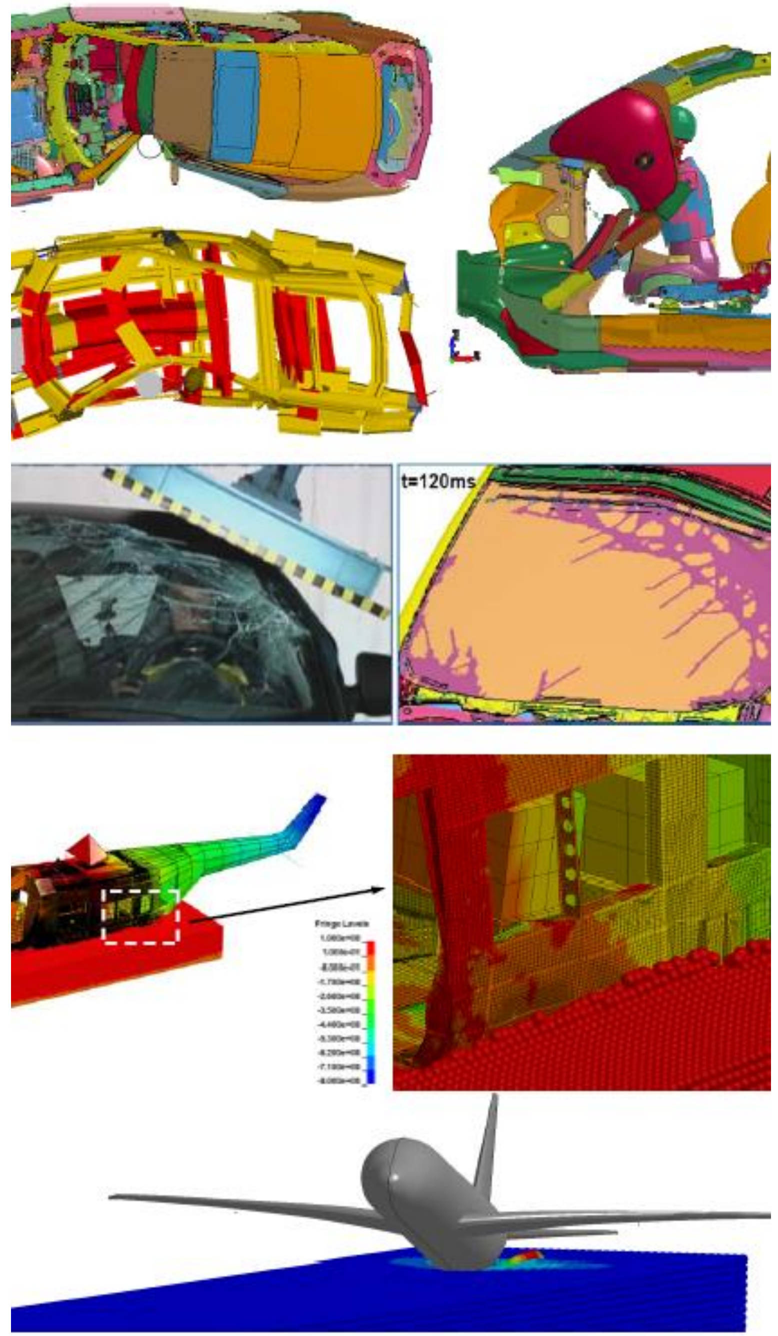


Outline

- Introduction
- SPH and modelling approach
- Simulation models
- Simulation results
    - Bird model validation
    - Parametric study of bird strike on an engine blade
- Summary

Acknowledgement: Part of this work is related to the Horizon2020 Project **EXTREME** Dynamic Loading - Pushing the Boundaries of Aerospace Composite Material Structures

Introduction

Birds surround a British Airways Boeing 757 in Budapest. Photo by Adam Samu

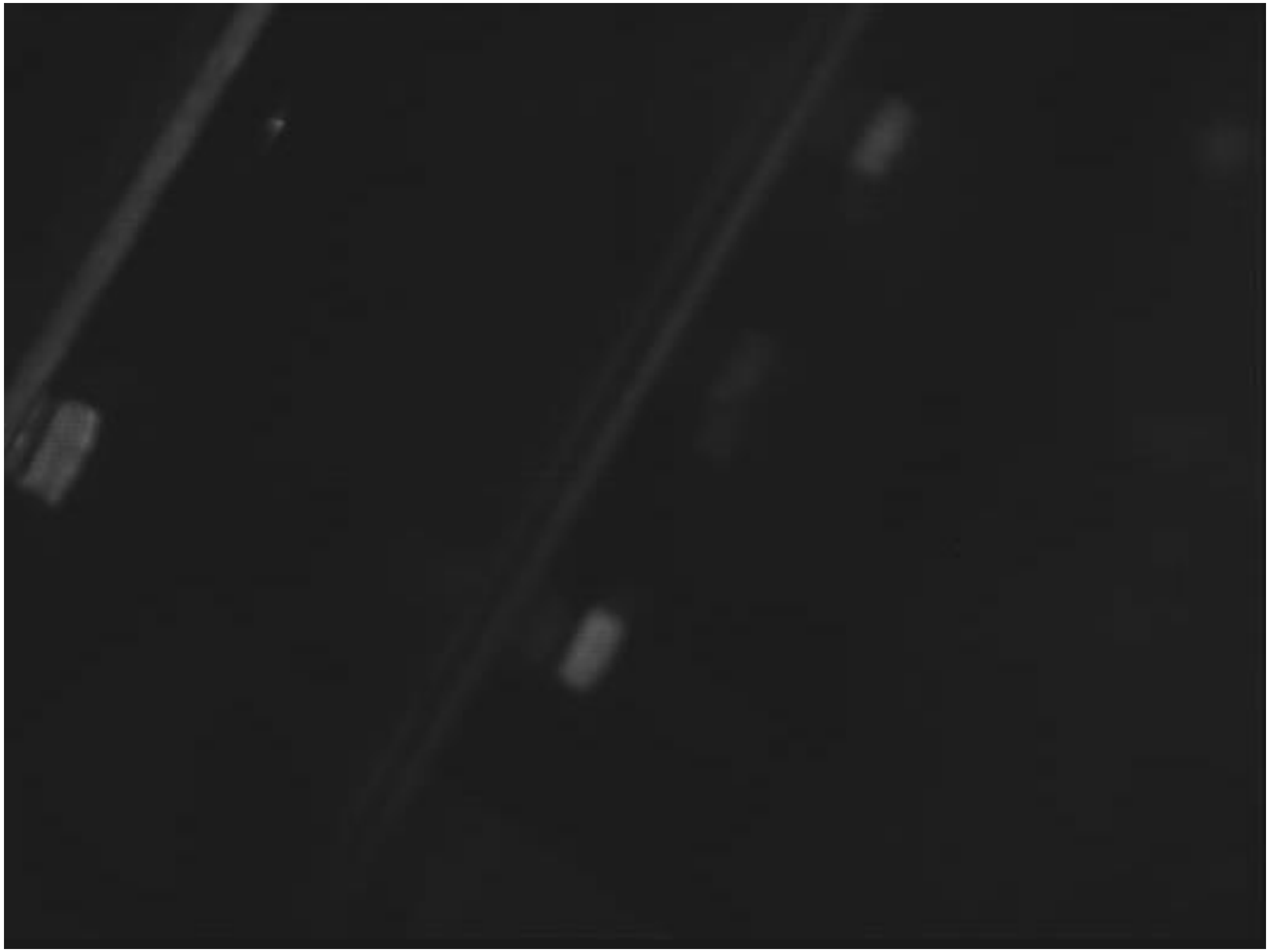
A320 ditching in the Hudson River and engine recovered afterwards

Birds strike test facility, Rolls Royce (2007)*

Introduction

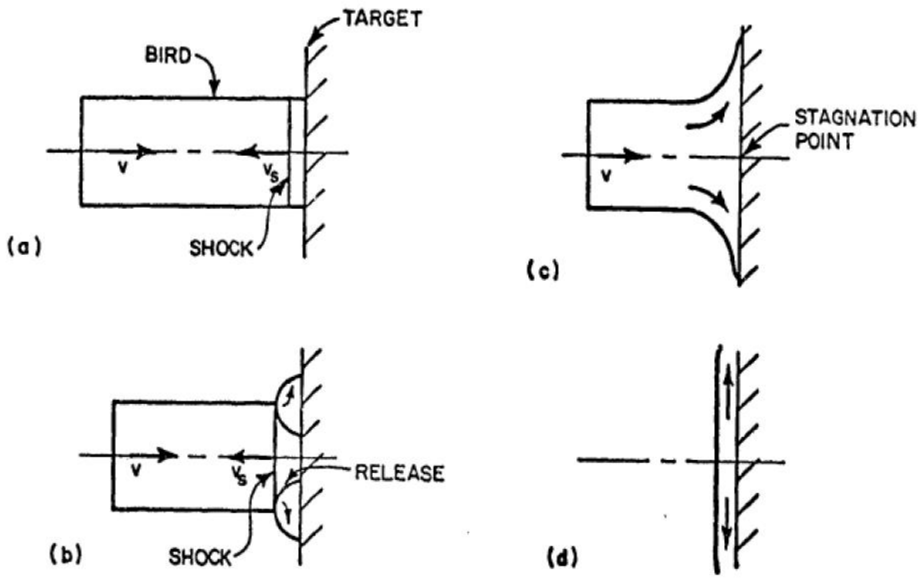
- To manage the risks, Aviation Authorities developed safety regulations for foreign object ingestions by turbine engine;
- Requirement is blade to stay intact after impact;
- Problems associated with pronounced deformation and failure are:
  - Release of the debris and further damage of the engine;
  - Plastic deformation can cause imbalance of the engine and oscillations of the rotating parts;
- The first bird strike tests were performed with real birds;
- Alternative for experimental testing is artificial gelatine birds, which allowed for better control of the test conditions and repeatability;
- Gelatine material is modelled as a fluid;

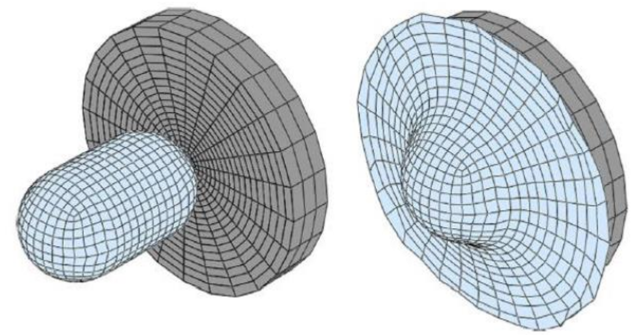
Introduction



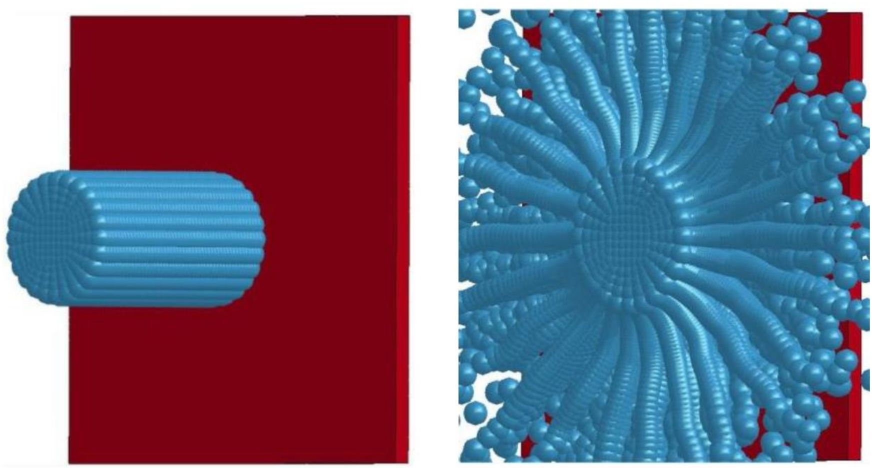
Bird strike onto a flat panel

Introduction

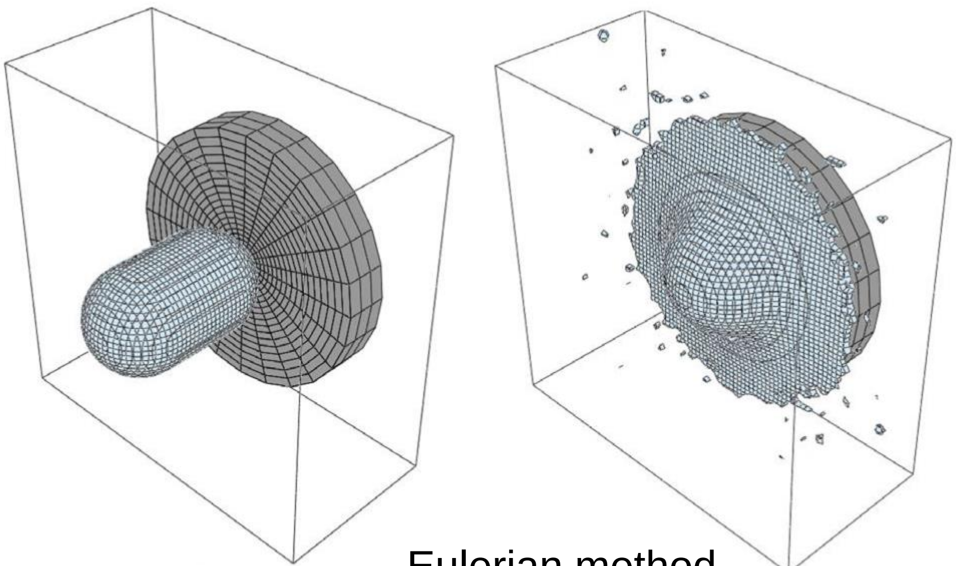




Lagrangian method



SPH method



Eulerian method

Introduction

- The main aim of the work presented here was simulation of bird strikes on lightweight engine blades;
- The simulations were performed with an in-house developed Smoothed Particle Hydrodynamics (SPH) code coupled with a transient nonlinear Finite Element (FE) code;
- The key aspects of the analysis were:
  - modelling of contact between the bird and the blade;
  - validation of the bird model;
  - parametric studies of the bird shape, radial impact location and bird slice size;
- Simulation results were compared and validated in terms of final deformed blade shape recovered from the bird strike test;

Smooth Particle Hydrodynamics

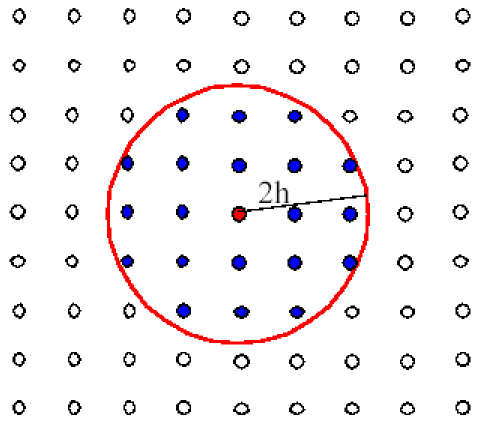
- SPH is a meshless Lagrangian particle method, where the motion of a continuum is described by the movement of a finite number of discrete particles, which are used in the spatial discretisation of the state variables;
- The SPH method is very good for modelling problems associated with impact characterised with large displacements, strong discontinuities and complex interface geometries

$$f(\boldsymbol{x}) = \int_{\Omega} f(\boldsymbol{x}') W(|\boldsymbol{x} - \boldsymbol{x}'|, h) d\boldsymbol{x}'$$

$$\nabla f(\boldsymbol{x}_I) = \sum_J \frac{m_J}{\rho_J} f(\boldsymbol{x}_J) \left[\nabla W(|\boldsymbol{x}_I - \boldsymbol{x}_J|, h) \right]$$

$$h = \lambda \Delta p$$

$$\langle \mathbf{F}_i \rangle = -\sum_{j=1}^{np} \frac{m_j}{\rho_j^0} (\mathbf{v}_i - \mathbf{v}_j) \otimes \nabla_{x_i^0} W(|\mathbf{x}_i^0 - \mathbf{x}_j^0|, h^0)$$

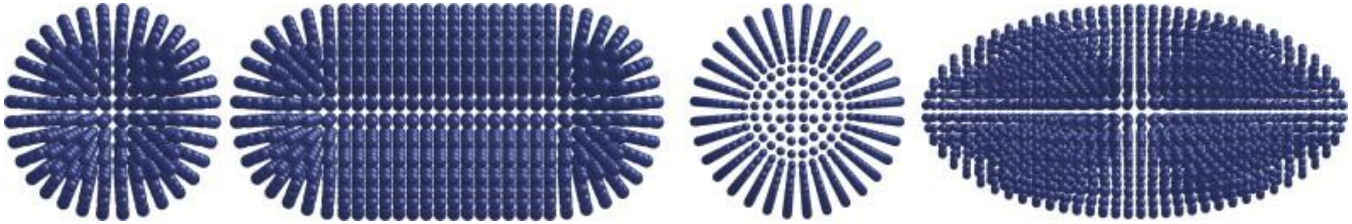


Simulation Models
Bird model - SPH

- Two different bird shapes were considered:
  - Hemispherical, most commonly used shape; (HSEB)
  - Ellipsoidal bird recommended by International Bird Strike Group (ELSB)
- Bird mass in all calculations was 0.68kg and length to diameter ratio was equal to two;

$$\rho = -0.063 \times \log_{10} m + 1.148 \qquad \log_{10} D = 0.335 \times \log_{10} m + 0.900$$

	Number of particles	Volume [10^{-3} m^3]	Diameter [m]	Length [m]
hemispherical-ended model	5120	7.01	0.081	0.162
ellipsoidal model	6256	7.01	0.097	0.194



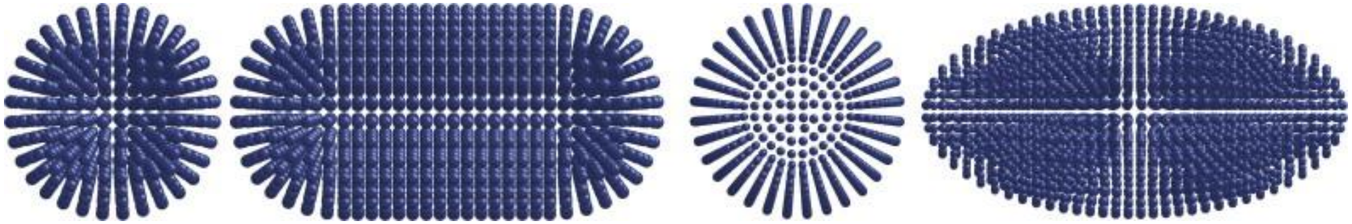
Simulation Models
Bird model - SPH

- Elastic plastic hydrodynamic material model was used in the formulation, together with Murnaghan Equation of State:

$$P = P_0 + B\left(\left(\frac{\rho}{\rho_0}\right)^{\gamma} - 1\right)$$

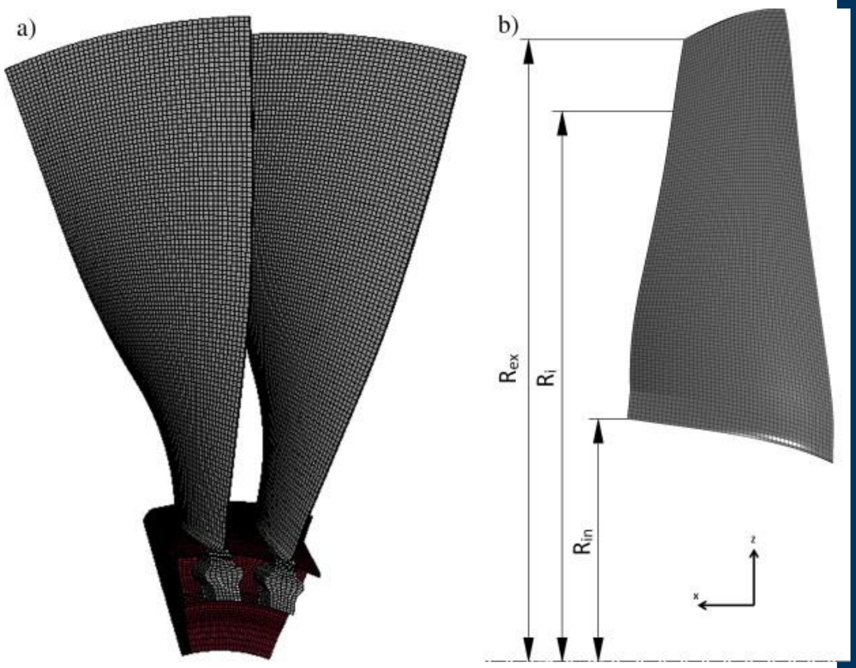
Material properties	Unit	Value
Density	[10^2 kg/m^3]	9.7
Shear modulus	[GPa]	2.07
Yield Stress	[MPa]	0.02
Plastic modulus	[MPa]	0.001

EOS data	Unit	Value
Reference pressure	[MPa]	0
Material parameter B	[MPa]	128
Material constant γ	[-]	7.98



Numerical Model
Titanium Blade Model - FEM

- Blade disk assembly consists of 22 equally spaced titanium blades attached to the disk;
- A simplified two blade model was used in the simulations;
- The bird impacts the leading blade;
- Mesh sensitivity analysis was conducted and the final model for the parametric study consisted of 105,048 solid elements;
- Engine shaft deformation was neglected;



$$R_{ex} = 570\,mm$$

$$R_i = 514\,mm$$

$$R_{in} = 175\,mm$$

Simulation Model
Titanium Blade Model - FEM

- Blade material Ti-6Al-4V
- Johnson Cook elastic viscoplastic material model used for the blade material with Gruneisen Equation of State;

$$\sigma_Y = \left[A + B\left(\bar{\varepsilon}^p\right)^n\right]\left[1 + C\ln\left(\dot{\varepsilon}^*\right)\right]\left[1 - \left(T^*\right)^m\right]$$

$$d\bar{\varepsilon}^p = \left(\frac{2}{3}d\bar{\varepsilon}_{ij}^p d\bar{\varepsilon}_{ij}^p\right)^{\frac{1}{2}} \qquad \bar{\varepsilon}^p = \int_0^t d\bar{\varepsilon}^p$$

$$\dot{\varepsilon}^* = \frac{\dot{\bar{\varepsilon}}^p}{\dot{\varepsilon}_0}$$

$$P = \frac{\rho_0 c^2 \mu\left[1 + \left(1 - \frac{\gamma_0}{2}\right)\mu - \frac{a}{2}\mu^2\right]}{\left[1 - \left(S_1 - 1\right) - S_2\frac{\mu^2}{\mu + 1} - S_3\frac{\mu^3}{\mu + 1}\right]} + \left(\gamma_0 + a\mu\right)E$$

Johnson Cook Material Parameters		
Density	[10^3 kg/m^3]	4.42
Yield stress	[MPa]	1098
Shear modulus	[GPa]	42
Strain hardening modulus, B	[MPa]	1092
Strain rate dependence coef. C	[-]	0.014
Temperature dependence exp. m	[-]	1.1
Strain hardening exponent n	[-]	0.93
Melting temperature T_m	[K]	1878
Heat Capacity	[J/kgK]	580

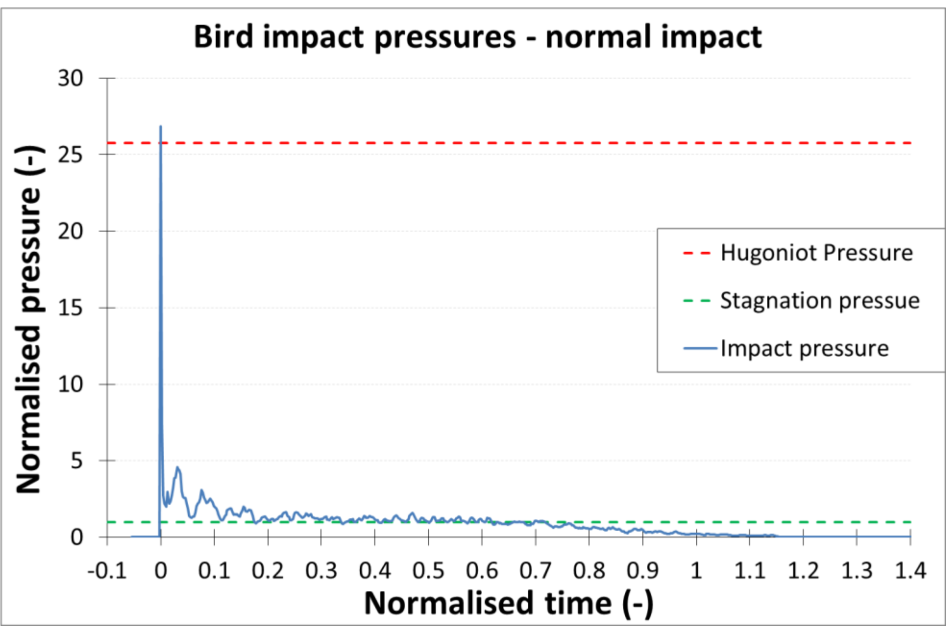
Gruneisen EOS data		
Velocity curve intercept	[10^3 m/s]	5.13
First slope coefficient	[-]	1.028
Grunaisen coefficient	[-]	1.23
First order volume correction	[-]	0.17

Simulation Results

- Simulations performed with the LLNL Dyna3D code coupled with in house developed SPH solver;
- Bird initial velocity and rotational speed of the engine are: $v = 77.2\, m/s$, $\omega = 806\, rad/s$
- Termination time was $t = 4ms$
- Simulation programme:
  - Bird model validation;
  - Contact algorithm analysis;
  - Initialisation analysis;
  - Parametric dynamic analysis:
    - the bird shape on the plastic deformation of the blade;
    - time instance of impact - bird slice size;
    - radial impact location;

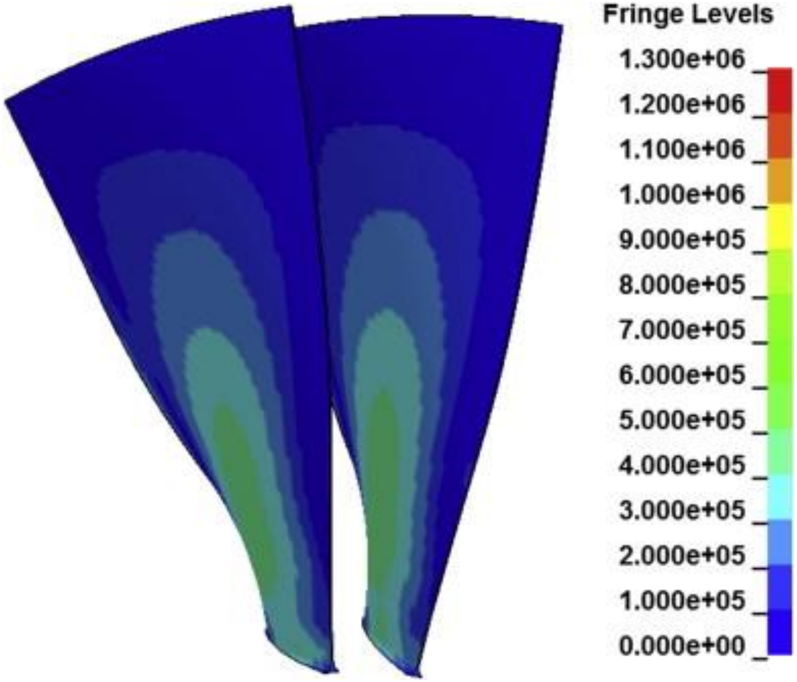
Simulation Results
Bird model Validation

- Hemispherical bird modelled with 21 000 particles, pitch = 1 mm
- Pressure read from rigid wall in the middle of impact
- Good correlation with Wilbeck (1978) test data



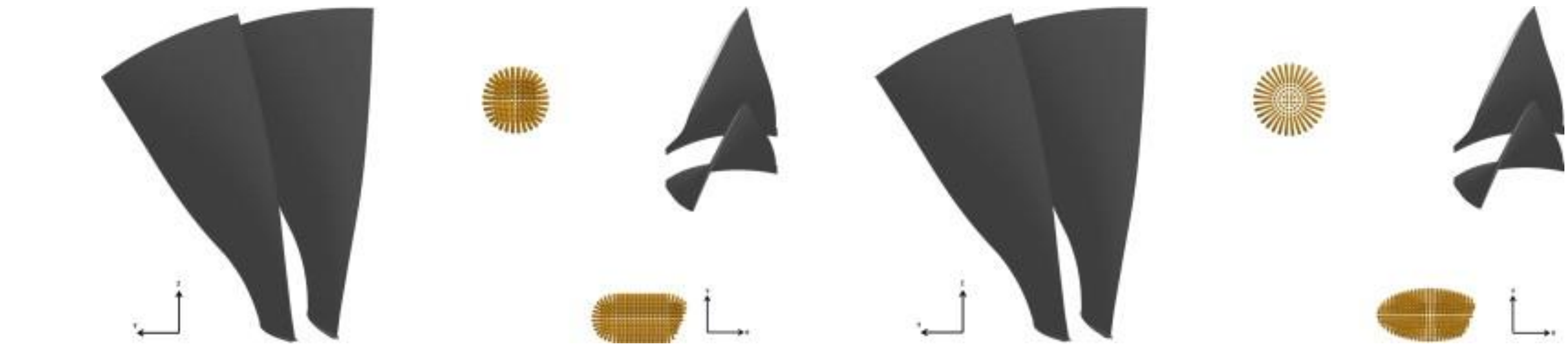
Simulation Results
Initialisation

- Initialisation to account for pre stress state induced by the centrifugal forces;
- Global bending effects are affected by the rotation;

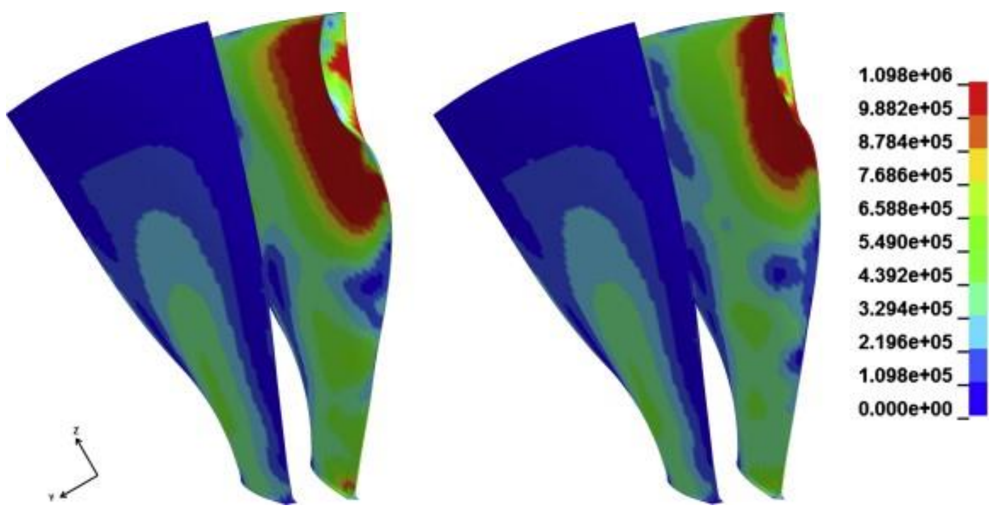


Distribution of the Von Mises stress

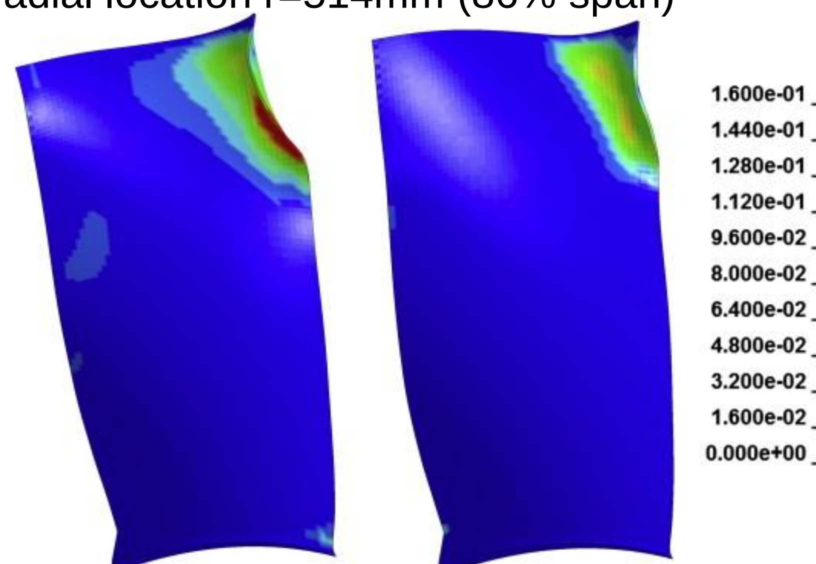
Simulation Results
Dynamic analysis – bird shape



Impact by two bird shapes at the same radial location r=514mm (86% span)

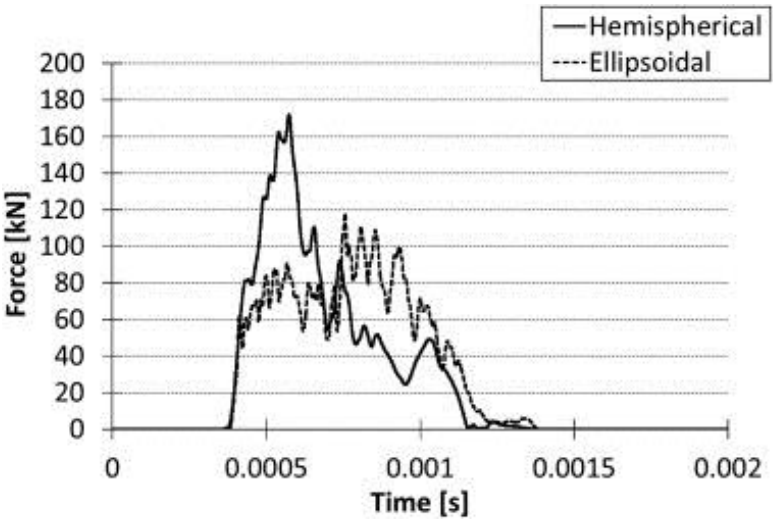


Distribution of the Von Mises stress after impact by HSEB (left) and ELSB (right)



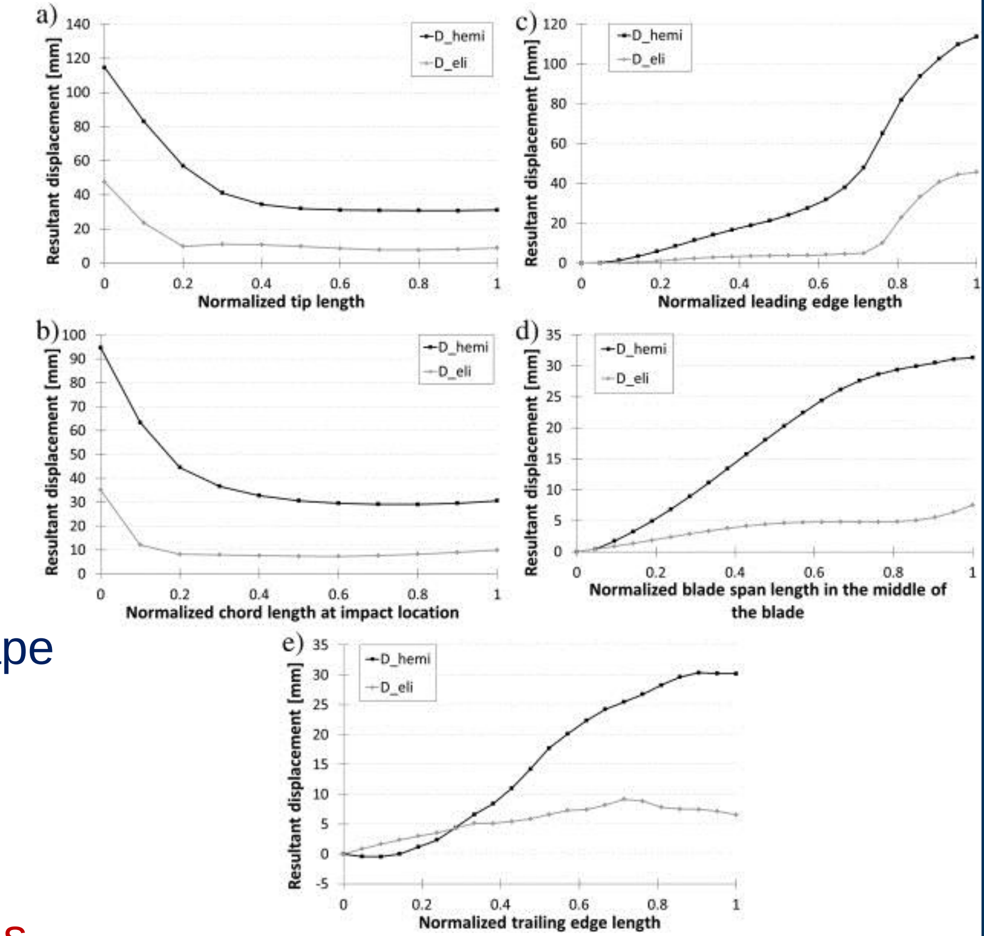
Distribution of the effective plastic strain after impact by HSEB (left) and ELSB (right)

Simulation Results
Dynamic analysis – bird shape



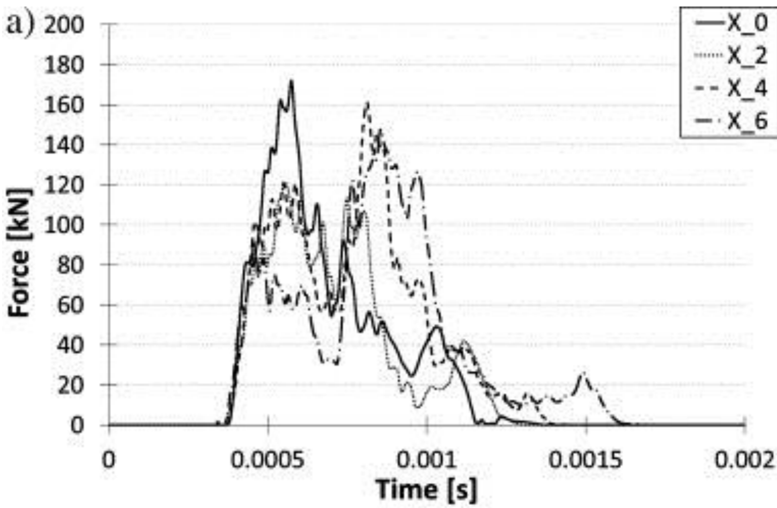
Comparison of the final deformed shape after elastic unloading shows that the HSEB impact induced more severe deformation

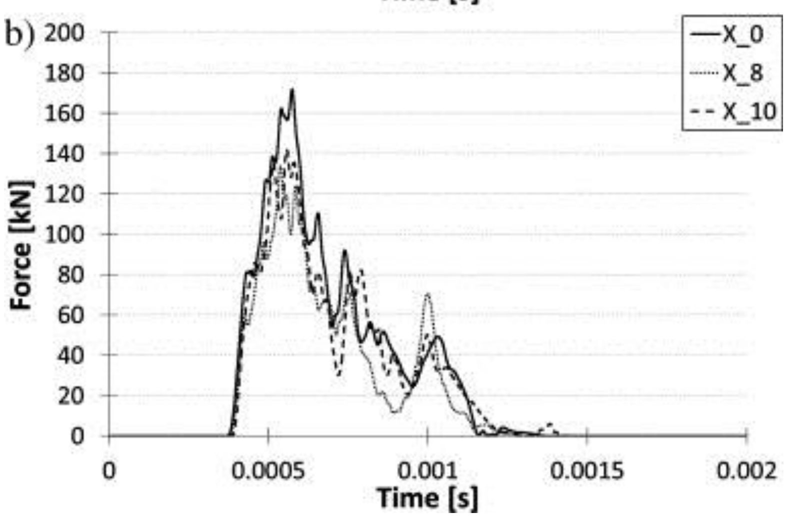
HSEB used in the subsequent analysis

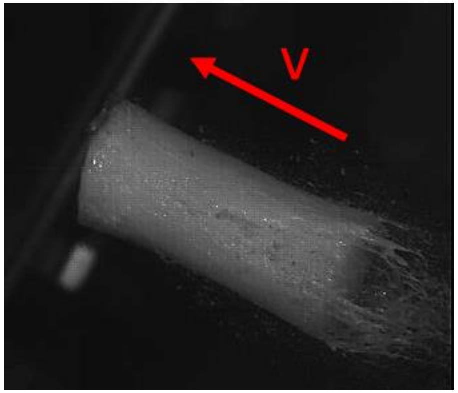


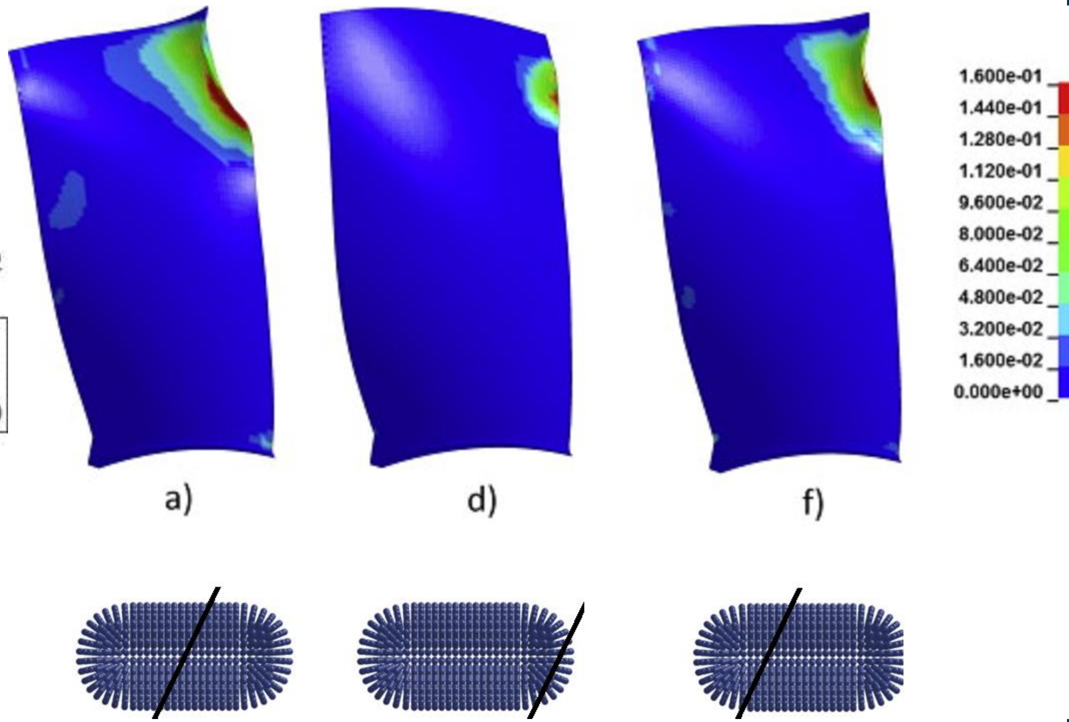
Displacement comparison for HSEB and ELSB impact: (a) tip, (b) impacted radius, (c) leading edge, (d) middle line across the blade span, (e) trailing edge

Simulation Results
Dynamic analysis – bird slice size





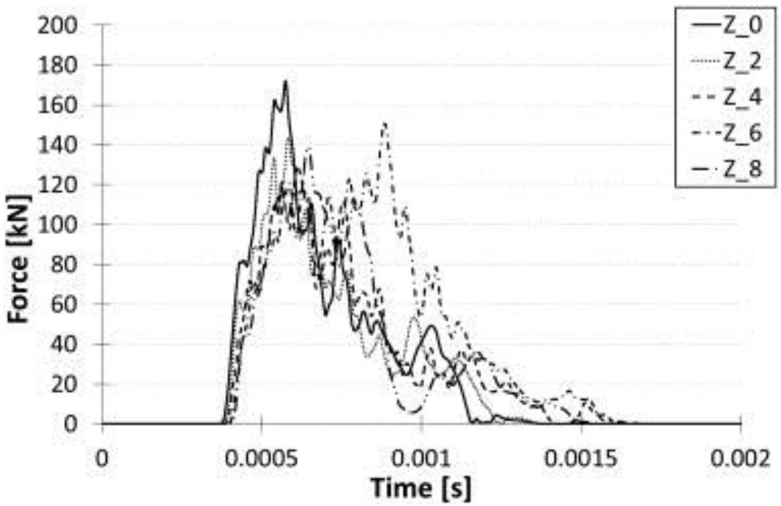




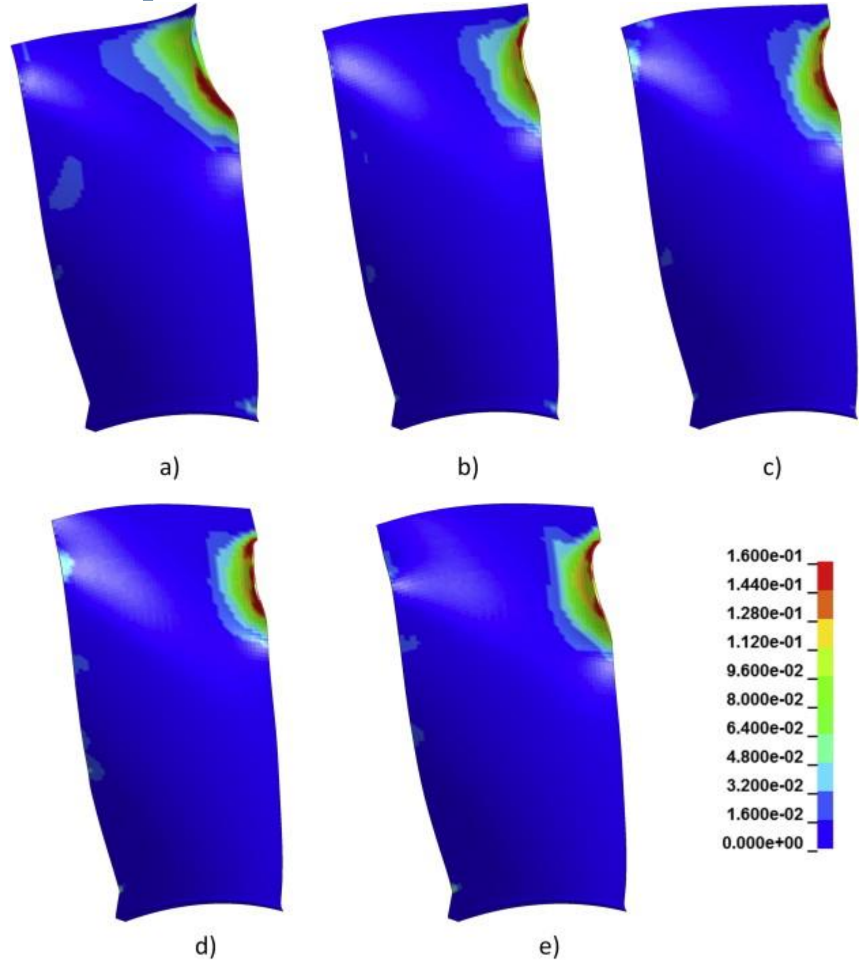
Effective plastic strain: (a) x_0=14mm, (d) x_6=2mm, (f) x_10=22mm

the deformation of the blade after impact is strongly related to the bird slice size cut off by the leading blade

Simulation Results
Dynamic analysis – radial impact location



Contact force magnitude is related to the pitch angle which increases with the distance from the rotation axis;



Effective plastic strain: (a) z_0=514mm, (b) z_2=504mm, (c) z_4=494mm, (d) z_6=484mm, (e) z_8=474mm

The response of the blades was dependent on the bird impact locations

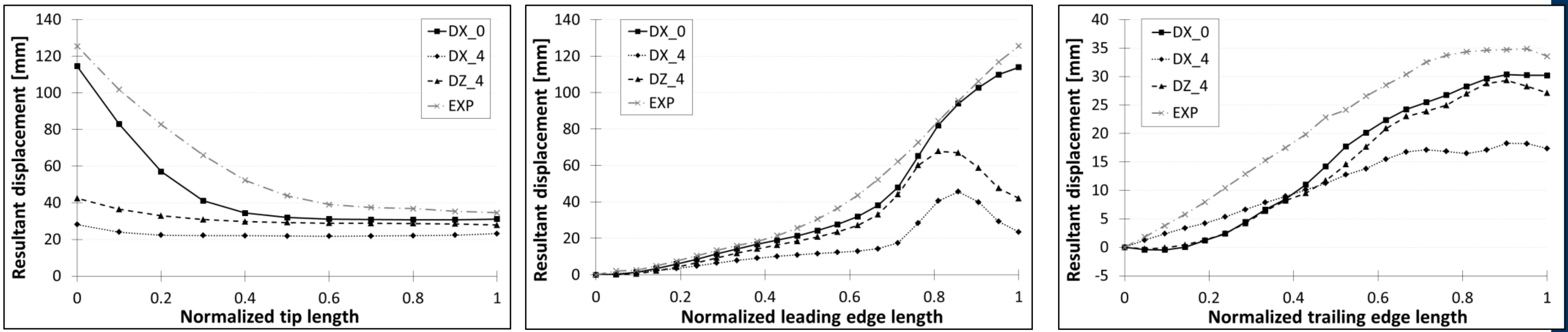
Simulation Results
Dynamic analysis – validation

Comparison of the simulation (red) and the experimental (yellow) final deformed shapes - front and top views

- Bird shape has significant influence on the deformation of the impacted blade;
- The bird body diameter and mass of the bird slice cut off are two main parameters which controls plastic deformation of the blade;
- The bird slice size has significant influence on the extent of blade deformation

final shape in the X_0 case is the closest to the experimental results. Bending and twisting of the blade match test results

Simulation Results
Dynamic analysis – validation



Displacement comparison for the bird slice size

- Impact location has considerable effect on the blade’s permanent deformation;
- Contact force peak and average contact force control the deformation mode and extent of plastic deformation;
- Comparison to the experimental results showed a good level of reliability of the numerical results;

final shape in the X_0 case is the closest to the experimental results. Bending and twisting of the blade match test results

Summary

- Bird strike on the engine fan blades was modelled using coupled FE-SPH code, the bird was discretised with the SPH particles and the blade was discretised with finite elements;
- Parametric studies considered shape of the gelatine bird, bird slice size generated at impact and radial impact location;
- All three variables in the parametric studies significantly affect the extent of plastic deformation generated at this impact event;
- Contact between the front blade and trailing blade was observed only in one impact scenario;
- The numerical results were validated against the experimental data suggesting a good level of reliability of the numerical results.
- FE-SPH has been also applied to other bird strike scenarios: bird strike on composite fan blade and bird strike at a leading edge;

Thank you for your attention

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