An investigation of soft impacts on selected aerospace grade alloys based on Johnson-Cook Material Model

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Abstract. In aerospace industry, metallic alloys are regularly used to manufacture various components ranging from stabilizers to engine shafts. These components must withstand foreign objective damage (FOD), which includes bird strikes, hail, ice, or any metal or concrete debris from the runway. In this current research, some selected aerospace grade alloys, namely, Al-2024-T3, Al-7075-T6, Ti-6Al-4V, and Inconel-718, which are regularly used to build potential aircraft components exposed to bird strike (otherwise known as soft impact) phenomena, is numerically tested to investigate their ability to resist the collision under two different impact velocities (117 m/s and 147 m/s). Finite element explicit code Ansys is adopted to run the test cases. Johnson-Cook flow stress and damage parameters are selected to model the alloy materials while Mooney-Rivlin parameters are utilized to represent the Lagrange bird model. From the investigation, it is found that the Inconel-718 plate is the best candidate to resist the bird impact and further analysis reveals that it can withstand an impact velocity of 327 m/s without being penetrated. Apart from Inconel-718 alloy, both Al-2024-T3 and Ti-6Al-4V plates are found to be damaged at the impact velocity of 147 m/s, while Al-7075-T6 is completely penetrated even at a lower impact velocity, 117 m/s. Finally, some recommendations and future research directions are suggested based on numerical outcomes.

1. Introduction
Every year, the aircraft industry suffers a great economic loss due to the collision between birds and different aerostructures, mostly fuselage nose, wing leading edge, and engine blade [1]. These structures are mainly made of metal alloys and composite materials, which vary significantly depending on the purpose of the aircraft. While impacting the aerostructures, bird strikes are considered as soft body impacts since the generated stress during the collision is much higher than the material strength of the bird [2]. A significant amount of research is carried out to understand the bird strike phenomena, which is improved with modern computation, and various aspects concerning bird materials, computational methods, structural design, impact resistance candidate materials, etc. are studied broadly. However, in the following section, the focus is concentrated on the research work, which mainly describes the material effects and their ability to withstand bird impacts.

McCarthy et al. [3] studied the bird strike on the wing leading edge structure made of laminae of glass composite and aluminum alloy, which is generally known as fiber metal laminate (FML). They
conducted both experimental and numerical investigations and found a good correlation suggesting that the skin will not penetrate in case of a bird impact of 129 m/s. A further study on the potentiality of FML as a bird strike resistance candidate material is examined by Guida et al. [4]. Their study concluded that the higher number of aluminum plies in FML provides better resistance and lower deformation values against bird impact. Another study on the wing leading edge made of aluminum skin and flexcore suggested that a change of outboard skin thickness from 1 mm to 1.4 mm helps to achieve an undamaged structure [5].

Hanssen et al. [6] studied the performance of an aluminum foam-based sandwich panel due to the high impact velocity of birds, to be accurate 190 m/s, and found that a minimum core thickness of 150 mm is required to avoid any penetration during a collision. A similar study to achieve the dynamic response of aluminum foam-based sandwich panels suggested that the impact energy absorption can be improved significantly in case of increasing the thickness of a foam core of a single sandwich panel or first foam core of a double sandwich panel [7].

To investigate the flap mechanism made of epoxy resin composite material, Orlando et al. [8] conducted bird strike simulation both experimentally and numerically, and signified that the numerical tool is an efficient mean to reduce the cost and time of manufacturing aerostructures. More recently, Liu et al. [9] carried out extensive experimental and numerical research on bird strike case studies of different materials including composites, aluminum alloys, honeycomb, and foam materials. Their investigation determined that the finite element codes are reliable to investigate bird strike case studies on aerostructures. Zammit et al. [10] studied the collision between bird and composite engine fan blades numerically and proposed that the Chang-Chang model can be utilized to capture the failure of composite materials during high impact cases. A further numerical study on the blade-like composite plates revealed that the boundary condition has a significant effect on the bird strike events when failure can be avoided, altering the boundary conditions from simply supported to clamped-clamped [11]. Wang and Yue [12] conducted numerical simulations of bird impacts on windshield structure at different velocities. Their study revealed that when the impact velocity changes from 100 m/s to 150 m/s, a crack on the windshield is developed and a hole is found on the tip of the crack. Another study carried out by Reza et al. [13] on five different windshield structures concluded that glass with Polyvinyl butyral (PVB) interlayer is best to prevent bird strike damage and the oblique impact can cause more damage to the structure than direct impact. A similar conclusion is also observed by Qiu et al. [14] where they reported that displacement at the centre of the plate (impact point) increases with the growing impact angle.

According to the criterion set by Federal Aviation Regulation 29.631, Hu et al. [15] tested a helicopter composite cockpit (HCC) experimentally and numerically and summarized that the designed HCC can meet the airworthiness requirements successfully. A more recent numerical study of soft impact conducted by Zhou et al. [16] on different angle ply composite square laminates suggested that the damage maps are sensitive to ply orientation; however, the local maximum damage of the laminate is less affected by varying ply angle. In a different study, the same group of researchers concluded that different composite material exhibits different damage profiles during impact [17].

In summary, it is evident that the material plays a crucial role to resist bird-induced damage in aerostructures. In addition, due to the emerging success of metal additive manufacturing, metal alloys will play a critical part in upcoming aerospace engineering innovations. Therefore, in this current research, a comparative study is carried out on some leading aerospace grade alloys, namely, Al-2024-T3, Al-7075-T6, Ti-6Al-4V, and Inconel-718 in terms of bird strike resistance capability. Moreover, the best-performed alloy is further studied to investigate the maximum impact resistance velocity it can withstand before any penetration occurs. All investigations are conducted adopting commercial explicit code Ansys.

2. Research method
2.1. Bird geometry

Three different bird geometries are well recognized to conduct numerical simulations; namely, (a) straight-ended cylinder, (b) hemispherical-ended cylinder, and (c) ellipsoid [18]. For this current study, a straight-ended cylindrical geometry is considered since in practice, this shape can be easily achieved. The diameter is formulated from, 

\[ D = \sqrt[3]{\frac{8m}{4\rho (4 + 2)}} = 112.4\text{mm} \]  

where \( m = 1.8\text{kg} \) and \( \rho = 968\text{kg/m}^3 \) (density of the bird material) and the length of the cylinder is defined as, \( L = 2D = 224.8\text{mm} \) [19].

2.2. Computational bird model and material definition

In computational solid mechanics, fluid can be modeled using four different methods; namely, Lagrange, Euler, Arbitrary Lagrange Euler (ALE), and Smoothed-particle hydrodynamics (SPH). Each method has its’ advantages and disadvantages [20] and one of these methods must be validated before a series of numerical simulations is conducted using commercial software codes (Abaqus, Ansys, Pam-Crash, LS-Dyna, etc.). Since the bird behaves as fluid during the impact with aerostructures, any above validated computational method is utilized to solve the bird strike problem. In this present study, the Lagrange method with a node erosion algorithm is chosen as the computational bird model, which is found to be computationally efficient and accurate [21].

As described earlier, the bird behaves as fluid during the collision; many researchers have used either Mie-Grüneisen or Polynomial equation of state (EOS) to define the fluid properties of the bird. In addition, Murnaghan EOS is equally popular [22]. However, more often in the gas gun tests, either ballistic gelatine or rubber is used as a substitute bird material, which can be tested in the lab to obtain the EOS parameters. For this current investigation, a Mooney-Rivlin material model of ballistic gelatine is utilized, Table 1. Please note that both the computational bird model and the material selected for this study were validated in a recent research work of the authors [21].

| Material | Density, \( \rho, \text{kg/m}^3 \) | Material Constant, \( C_{10}, \text{MPa} \) | Material Constant, \( C_{01}, \text{MPa} \) |
|----------|-----------------------------------|---------------------------------------------|---------------------------------------------|
| Gelatine | 968                               | 0.218                                       | 0.0805                                      |

2.3. Target plate geometry and material selection

Aerospace grade alloys selected for this present study are chosen based on the materials used regularly and in a large extent to construct civil airframe structures, such as Al-2024-T3 and Al-7075-T6 [23].
fighter airframe structures, such as Ti-6Al-4V [24] and turbine blade such as nickel-chromium based super alloy Inconel-718 [25].

To compare the impact-induced damage tolerance of the metal alloys, a target plate is modeled with a dimension of 770 mm (height) \( \times \) 770 mm (width) \( \times \) 1.7 mm (thickness) and standard fasteners are used to clamp the target plate, Figure 1. The projectile is modeled in such a way that it will impact at the middle node of the plate.

2.4. Johnson-Cook flow stress model

Johnson-Cook material and damage model is widely adopted to solve strain rate related problems in impact case studies. The flow stress behavior of a metallic material can be expressed as follows [26]:

\[
\sigma = (A + B\dot{\varepsilon}^\nu)(1 + C \ln \dot{\varepsilon})(1 - T^m)
\]

(1)

where \( \sigma \) denotes equivalent stress, and \( \dot{\varepsilon} \) is the equivalent plastic strain. Other material constants such as \( A \) describes the yield stress of the material under reference conditions, \( B, n, C \) denotes to strain hardening constant, strain hardening coefficient, and strengthening coefficient of strain rate, respectively. Finally, constant \( m \) describes the thermal softening coefficient of the model (in case of thermal effect consideration). The damage model can be written as follows:

\[
\varepsilon_f = [D_1 + D_2 \exp(D_3(\frac{\sigma_{eq}}{\sigma_{eq}^*}))][1 + D_4 \ln \dot{\varepsilon}_p^*][1 + D_5 T^*]
\]

(2)

where \( D_1 \) to \( D_5 \) are the damage model constants, \( \sigma_{eq} \) is the mean stress and \( \sigma_{eq}^* \) is the equivalent stress. The Johnson-Cook material parameters and damage constants of the selected alloys are given below in Table 2.

| Parameters                                | Al-2024-T3 [27] | Al-7075-T6 [28] | Ti-6Al-4V [29] | Inconel-718 [30] |
|-------------------------------------------|------------------|------------------|----------------|------------------|
| Density, \( \rho \), \( \text{kgm}^{-3} \) | 2700             | 2700             | 4430           | 8190             |
| Poisson's ratio, \( \nu \)                | 0.3              | 0.3              | 0.33           | 0.33             |
| Young's modulus, \( E \), \( \text{GPa} \) | 70               | 70               | 110            | 185              |
| Yield stress, \( A \), \( \text{MPa} \)   | 352              | 520              | 862            | 1200             |
| Strain hardening modulus, \( B \), \( \text{MPa} \) | 440             | 477              | 331            | 1284             |
| Strain hardening exponent, \( n \)        | 0.42             | 0.52             | 0.34           | 0.54             |
| Reference strain rate, \( \dot{\varepsilon}_0 \), \( \text{s}^{-1} \) | \(3.3 \times 10^{-4}\)  | \(5 \times 10^{-4}\)  | 1              | \(1 \times 10^{-3}\)  |
| Strain rate coefficient, \( C \)          | 0.0083           | 0.001            | 0.012          | 0.006            |
| Thermal softening exponent, \( m \)       | 1.7              | 1                | 0.8            | 1.2              |
| Reference temperature, \( T_0 \), \( \text{°K} \) | 293              | 293              | 293            | 293              |
| Melting temperature, \( T_{\text{mel}} \), \( \text{°K} \) | 775              | 893              | 1900           | 2073             |
| Specific heat, \( J/\text{kg-\text{°K}} \) | 900              | 910              | 670            | 435              |
| \( D_1 \)                                  | 0.13             | 0.096            | -0.09          | 0.11             |
| \( D_2 \)                                  | 0.13             | 0.049            | 0.25           | 0.75             |
| \( D_3 \)                                  | -1.5             | -3.465           | -0.5           | -1.45            |
| \( D_4 \)                                  | 0.011            | 0.016            | 0.014          | 0.04             |
| \( D_5 \)                                  | 0                | 1.099            | 3.87           | 0.89             |
2.5. Mesh generations and boundary conditions
To mesh the target plate and bird projectile, 3D solid element with hexagonal mapped mesh type is utilized. The target plate is meshed with 15 mm elements while the bird projectile with 10 mm. A more refined automatic meshing is set for the fasteners. Total number of generated elements is 241889, which is found to be optimum and further increased elements’ number would cause more computation time without varying the numerical outcomes. An illustration (Figure 2) of the meshed bodies are given below.

For the boundary condition of the problem, all fasteners made of structural steel are kept as rigid while the plate is clamped with the fasteners. Two different velocities are given to the projectile, case I with 117 m/s and case II with 147 m/s. After the comparison, the best alloy will be investigated further to determine the maximum impact velocity it can withstand.

3. Results and discussions

3.1. Deformation plots
At first, the deformation results on the back face of the plate are plotted for both cases I and II, in Figure 3. It is found that, for an impact velocity of 117 m/s (case I), Al-7075-T6 will have the highest deformation before a complete penetration occurs, around 106.77 mm after reaching 2.2 milliseconds (ms), Figure 3 (a). Another aluminum alloy candidate, Al-2024-T3 exhibits the highest deformation among the plates without penetration, around 79 mm. Inconel-718 has shown the least deformation with the highest value of 39.7 mm.

For the second impact case, after reaching a maximum deformation value of 112.6 mm and 78.2 mm, a complete penetration is found for Al-2024-T3 and Ti-6Al-4V. However, Al-2024-T3 can resist the impact until 1.8 ms while Ti-6Al-4V fails before that, at 1.62 ms. Finally, it is found that Inconel-718 recovers from the impact after reaching the highest deformation of 50 mm. Please note that the deformation value of Al-7075-T6 is not presented for case II since a complete failure is already found in the previous case, which eliminates the necessity for further investigations.
3.2. Maximum absorbed energy plots
Next, the maximum absorbed energy by the alloys due to gelatine impacts are plotted in Figure 4. From the figure, it is evident that for both cases, the maximum peak energy during the impact event is absorbed by Al-2024-T3, which is the least stiff among alloys. As the stiffness and strength increases, a tendency to absorb less kinetic energy is identified. For the case I, Al-2024-T3 absorbs almost 17% more kinetic energy than Al-7075-T6 without being penetrated. However, for case II, along with Ti-6Al-4V, Al-2024-T3 fails to withstand impact after absorbing a maximum of 11kJ, which is 38% higher than Inconel-718.

3.3. Equivalent plastic strain and damage contours
Finally, the equivalent plastic strain and damage contours of the plates with selected alloys are plotted in figure 5 (case I) and 6 (case II). From the contour, figure 5 (a), it is identified that the equivalent plastic strain of Al-2024-T3 is 18.95%. This also indicates that severe plastic deformation is occurred on the impacted area (centre of the plate) due to the soft impact. Figure 5 (b) demonstrates that before a complete penetration of Al-7075-T6, the equivalent plastic strain value has been reached up to 28.2% and then eventually got damaged completely, Figure 5 (c). For Ti-6Al-4V, the equivalent strain is found to be 6.5%, which can be considered as moderate damage to the plate, Figure 5 (d). Finally,
Inconel-718 exhibits only 1.78% equivalent strain value, which is significantly lower than any other alloy candidate, Figure 5 (e).

![Figure 5. Equivalent plastic strain and damage contours for case I](image)

For case study II, it can be seen that both Al-2024-T3 and Ti-6Al-4V plates have attained an equivalent plastic strain value of 29.2% and 18.3% respectively, Figure 6 (a) and (c), before complete damage is observed, Figure 6 (b) and (d). For Inconel-718, the calculated equivalent strain value is 4.84% without exhibiting any further damage.

![Figure 6. Equivalent plastic strain and damage contours for case II](image)

3.4. Determination of maximum impact velocity for Inconel-718 plate

To determine the maximum impact of the Inconel-718 plate without any penetration (complete damage), a further investigation is carried out increasing the impact velocities. For each step, a 30 m/s velocity is added to the previous step and the impact simulation is carried out until a complete penetration is observed (figure 7). From the figure, the penetration velocity is determined as 357 m/s.
Moreover, it is revealed that the Inconel-718 plate can withstand around 76% higher impact velocity compared with Al-2024-T3 and Ti-6Al-4V while 94.5% higher than Al-7075-T3.

| Impact velocity | Penetration (Complete Damage) |
|-----------------|-------------------------------|
| 177 m/s         | No                            |
| 207 m/s         | No                            |
| 237 m/s         | No                            |
| 267 m/s         | No                            |
| 297 m/s         | No                            |
| 327 m/s         | No                            |
| 357 m/s         | Yes                           |

Figure 7. Determination of maximum impact velocity

Figure 8. Equivalent plastic strain (Inconel-718) before failure

From figure 8, it is observed that before the complete damage occurs and penetration occurs, the Inconel-718 plate exhibits a 61.55% equivalent plastic strain value. This indicates that despite being stiffer, Inconel-718 can be severely deformed before complete failure. Finally, the damage contour is shown in figure 9. Unlike Al-2024-T3 and Ti-6Al-4V plates, the penetrated area is found to be significantly smaller. Moreover, some elements were removed by the solver, which were connected with the fasteners due to reaching the geometric strain value of 1.5. The primary reason for this phenomenon is that due to the large deformation, the connected areas of the plate tore out from the fasteners. However, this phenomenon has not been experienced before for any other investigations.

Figure 9. Complete damage contour at 357 m/s

4. Conclusions

In this present investigation, a series of numerical simulations are conducted to compare the capability of aerospace-grade alloys to withstand soft impact damage at 117 m/s and 147 m/s. It is found that Inconel-718, which is a nickel-chromium based alloy, can resist the bird strike for both impact velocities without significant plastic deformation. However, Al-2024-T3 and Ti-6Al-4V can endure the collision for 117 m/s with severe and moderate plastic deformation, respectively, and complete damage with penetration is observed for 147 m/s. The fourth selected alloy, Al-7075-T6, which is stiffer and stronger than Al-2024-T3 alloy, is found to be damaged in the first case study (117 m/s) with complete penetration. Finally, a further investigation on the Inconel-718 plate revealed that it can withstand a soft impact with any penetration up to 327 m/s, which is 76% higher than Al-2024-T3 and Ti-6Al-4V.

Based on the results found in this investigation, some recommendations can be made. In the case of supersonic flights where aerodynamic heating is inevitable [31], Inconel-718 can be an excellent choice for airframe skin since, at higher working temperatures, Al-2024-T3 exhibits different
mechanical behavior. For civil aircraft components, where it can be confirmed that the impact velocity would be lower than 100 m/s, Al-2024-T3 can be selected as a lightweight material. However, the safety of an aircraft cannot be compromised. Therefore, despite being heavier, the engine blades can be made of Inconel-718, which suffer most due to bird strikes. Finally, it is important to note that experimental case studies are critical to confirm the impact behavior of the material in practice. Moreover, engine blades and leading-edge structure made of the alloy should be investigated for future potentiality.

References

[1] Metz I Ellerbroek J Mühlhausen T Kügler D and Hoekstra J 2020 The Bird Strike Challenge *Aerospace* 7 1-20

[2] Martin N 1990 Nonlinear finite-element analysis to predict fan-blade damage due to soft-body impact *Journal of Propulsion and Power* 6 445-450

[3] McCarthy M Xiaoj J McCarthy C Kamoulakos A Ramos J Gallard J and Melito V 2004 Modelling of Bird Strike on an Aircraft Wing Leading Edge Made from Fibre Metal Laminates – Part 2: Modelling of Impact with SPH Bird Model *Applied Composite Materials* 11 317-340

[4] Guida M Marulo F Polito T Meo M and Riccio M 2009 Design and Testing of a Fiber-Metal-Laminate Bird-Strike-Resistant Leading Edge *Journal of Aircraft* 46 2121-2129

[5] Guida M Marulo F Meo M and Riccio M 2008 Analysis of Bird Impact on a Composite Tailplane Leading Edge *Applied Composite Materials* 15 241-257

[6] Hanssen A Girard Y Olovsson L Berstad T and Langseth M 2006 A numerical model for bird strike of aluminium foam-based sandwich panels *International Journal of Impact Engineering* 32 1127-1144

[7] Liu J Li Y Gao X Liu P and Kong L 2015 Dynamic response of bird strike on aluminium foam-based sandwich panels *International Journal of Crashworthiness* 20 325-336

[8] Orlando S Marulo F Guida M and Timbrato F 2017 Bird strike assessment for a composite wing flap *International Journal of Crashworthiness* 23 219-235

[9] Liu J Li Y Yu X Gao X and Liu Z 2018 Design of aircraft structures against threat of bird strikes *Chinese Journal of Aeronautics* 31 1535-1558

[10] Zammit A Kim M and Bayandor J 2010 BIRD-STRIKE DAMAGE TOLERANCE ANALYSIS OF COMPOSITE TURBOFAN ENGINES 27th *International Congress of the Aeronautical Sciences* (Nice: International Congress of the Aeronautical Sciences)

[11] Zhou Y Sun Y and Huang T 2019 Impact responses of slender composite plates for bird-strike testing of fan blades *Latin American Journal of Solids and Structures* 16 1-12

[12] Wang F and Yue Z 2010 Numerical simulation of damage and failure in aircraft windshield structure against bird strike *Materials & Design* 31 687-695

[13] Hedayati R Ziaei-Rad S Eyyazian A and Hamouda A 2014 Bird strike analysis on a typical helicopter windshield with different lay-ups *Journal of Mechanical Science and Technology* 28 1381-1392

[14] Qiu J Wang D Liu C Chen L Huang H and Sun Q 2020 Dynamic response of bird strike on honeycomb-based sandwich panels of composite leading edge *International Journal of Crashworthiness* 1-14

[15] Hu D Song B Wang D and Chen Z 2016 Experiment and numerical simulation of a full-scale helicopter composite cockpit structure subject to a bird strike *Composite Structures* 149 385-397

[16] Zhou Y Sun Y and Huang T 2019 SPH-FEM Design of Laminated Plies under Bird-Strike Impact *Aerospace* 6 1-14

[17] Zhou Y Sun Y and Huang T 2019 Bird-Strike Resistance of Composite Laminates with Different Materials *Materials* 131-22
[18] Meguid S Mao R and Ng T 2008 FE analysis of geometry effects of an artificial bird striking an aeroengine fan blade International Journal of Impact Engineering 35 487-498
[19] Hedayati R and Jahanbakhshi M 2015 Finite element analysis of an aluminum airplane stabilizer against birdstrike Journal of the Brazilian Society of Mechanical Sciences and Engineering 38 317-326
[20] Hedayati R and Sadighi M 2015 Bird strike: An Experimental, Theoretical and Numerical Investigation (Woodhead Publishing)
[21] Aslam M Rayhan S ke Z and Yu W 2020 Ballistic gelatin Lagrange Mooney-Rivlin material model as a substitute of bird in finite element bird strike case studies Latin American Journal of Solids and Structures 17 pp 1-16
[22] Zhou J 2017 Experimental and numerical investigation of soft impact loading on aircraft materials Ph.D. Dissertation (Imperial College, London)
[23] Rambabu P Eswara Prasad N Kutumbarao V and Wanhill R 2016 Aluminium Alloys for Aerospace Applications Aerospace Materials and Material Technologies 29-52
[24] Singh P Pungotra H and Kalsi N 2017 On the characteristics of titanium alloys for the aircraft applications Materials Today: Proceedings 4 8971-8982
[25] Farahani H Ktabchi M and Zangeneh S 2017 Determination of Johnson–Cook Plasticity Model Parameters for Inconel718 Journal of Materials Engineering and Performance 26 5284-5293
[26] Murugesan M and Jung D 2019 Johnson Cook Material and Failure Model Parameters Estimation of AISI-1045 Medium Carbon Steel for Metal Forming Applications Materials 12 1-8
[27] Rodriguez-Millan M Garcia-Gonzalez D Rusinek A and Arias A 2018 Influence of Stress State on the Mechanical Impact and Deformation Behaviors of Aluminum Alloys Metals 8 1-20
[28] Flores-Johnson E Shen L Guiamatsia I and Nguyen G 2014 Numerical investigation of the impact behaviour of bioinspired nacre-like aluminium composite plates Composites Science and Technology 96 13-22
[29] Zhang Y Outeiro J and Mabrouki T 2015 On the Selection of Johnson-cook Constitutive Model Parameters for Ti-6Al-4V Using Three Types of Numerical Models of Orthogonal Cutting Procedia CIRP 31 112-117
[30] Echavarri B 2012 Flow and fracture behavior of high performance alloys Ph.D. Dissertation (Universidad Politécnica de Madrid)
[31] Rayhan S and Islam M 2019 Numerical aero-thermal-structural analyses of a fighter jet wing during supersonic flights 8TH BSME INTERNATIONAL CONFERENCE ON THERMAL ENGINEERING