Numerical Methodology for Aerostructures Hail Impact Damage Prediction

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Abstract. The two numerical approaches for modelling of soft-body impact in ABAQUS/Explicit have been applied in this work for prediction of high-velocity hail impact damage in aeronautical structures. The applied methods are the CEL (Coupled Eulerian Lagrangian) and SPH (Smoothed Particle Hydrodynamics), while the impacted structure is a metallic slat structure. Comparison of the CEL and SPH methods has been performed by impact simulations at a rigid plate, aimed to validate the applied material model, and by simulation of the slat structure impact. Two material models have been applied to study the effect of high strain-rates at the damage process in the metallic structure. The first is the standard isotropic plasticity model that defines material failure based on the value of equivalent plastic strain. The second constitutive model in the analyses is the Johnson-Cook model that includes the effects of strain rate and temperature on the material failure process. The simulations have been stable, illustrating the robustness of ABAQUS/Explicit in these highly nonlinear impact cases. Compared to the CEL, the SPH method is computationally more efficient.

1. Introduction
This work deals with the numerical simulation of hail impact, a common type of foreign object impact in aeronautical structures. As in the bird strike, hail impact is numerically considered as a soft body impact as the stresses generated in the impactor significantly exceed the material strength resulting in a fluid-like deformation. Therefore, special numerical techniques need to be used in the simulation of these phenomena to counter the problems that arise in the application of traditional Lagrangian finite element models for the impactors. As explained in Section 2, the SPH (Smoothed Particle Hydrodynamics) and CEL (Coupled Eulerian Lagrangian) numerical techniques, available in ABAQUS/Explicit, are evaluated for this task.

According to [1], the risk of hail strike incidents is reduced by i) damage-tolerant aircraft design, ii) efficient weather radars and iii) combination of efficient weather radars and ground equipment. The severity of in-flight hail strikes can be perceived by considering the extreme hail sizes, that can be involved in these incidents, and the impacting velocities. According to [2], the structural integrity in the design certification should be assured for the impact of a 110 mm diameter hailstone at cruise velocities of the aircraft.

As the hail strike scenario is in certain situations unavoidable, numerical approaches can be applied to design impact-resistant aerostructures. That is especially the case for exposed structural parts: radome, windshield and wing and stabilizer leading edges. Due to the strict bird strike damage...
tolerance certification requirements, the exposed forward-facing structural elements are designed to withstand most of the hail impact cases. However, impact with the extreme hail-stone sizes at high velocities presents a significant threat to air transport safety. Therefore, numerical simulation of the hail impact at a large airliner metallic slat structure is investigated in this work using the CEL and SPH techniques in Abaqus/Explicit.

2. Numerical methodology
Details of the employed numerical approaches are presented in this Section.

2.1. CEL and SPH models
The methodology presented in this work is a continuation of the bird strike damage prediction methodology developed in the previous work of the authors, e.g. [3]. This methodology was based on the application of the CEL technique that was available at that time in Abaqus/Explicit. The obtained results demonstrated that the bird strike damage can be predicted reliably and accurately using CEL. However, a significant drawback of the methodology is the very high computational cost of CEL analyses. To tackle this deficiency, the SPH technique, available in the newer versions of Abaqus/Explicit, was applied by the authors in the simulation of the soft body impact in aeronautical structural items in this work.

The CEL technique allows application of the Eulerian description of the highly deformable impactor whereas the impacted structure is modelled using the traditional Lagrangian formulation. The three-dimensional EC3D8R finite elements, that are static throughout the analysis, enable the flow of Eulerian material through the model. These multi-material finite elements are occupied by the Eulerian material to an extent defined as the Eulerian Volume Fraction (EVF). This output parameter takes values ranging from 0 for completely void elements to 1 for fully occupied elements thereby enabling tracking of the material deformation process throughout the analysis [4].

Contact of the Eulerian material with the Lagrangian structure is modelled through an extension of the Abaqus General contact algorithm. To accurately model the load transfer in the impact, a relatively fine mesh of the Eulerian elements at the impact location has to be used. Additionally, the size of the static volume containing Eulerian elements must be large enough to contain the material throughout the analysis, as material leaving the volume causes numerical difficulties. Consequently, a very large numerical model containing many EC3D8R elements is usually applied in the impact analyses leading to a very high computational cost of the CEL technique.

Contrary to the CEL technique, the mesh-free SPH impactors consist of particles, whose physical properties are predicted based on the physical properties of neighbouring particles. The Kernel function is introduced to define this relationship. The distance at which the particles influence each other is known as the smoothing length. In the numerical implementation of SPH in Abaqus, the smoothing length is defined automatically, changing its value during the simulation based on the deformation process. According to [4], the average number of particles within the smoothing length sphere is between 50 and 60 to ensure accurate simulations.

According to [4], the accuracy of SPH is generally lower compared to the CEL technique. However, the significantly better computational efficiency allows the application of more refined impactor models, thereby enabling accurate modelling of the load transfer during the impact. Therefore, the goal of the research in this work is to compare the CEL and SPH models in the hail impact simulations.

2.2. Constitutive models
An essential component of the hail impact damage prediction methodology is the hail material constitutive model. The mechanical properties of hailstones are influenced by the atmospheric conditions at which they are generated, resulting in a heterogeneous microstructure and large discrepancies in the mechanical properties of individual hailstones. Consequently, artificially produced hailstones (Simulated Hail Impactors – SHI) are used in the experimental testing to reduce large
scatter in the measured results. Furthermore, numerical constitutive models simulate the behaviour of the SHI impactors for the same reason.

To ensure accurate load transfer to the impacted structure in the numerical approach, the contact forces generated at the impact have to be accurately simulated. Therefore, the constitutive model used in this work was defined based on the model introduced in [5,6], where an isotropic elastic-ideally plastic material model with strain rate dependent compressive strength was used to model the numerical hail impactor. The scaling parameters, shown in Table 1, used in this work are selected to interpolate the average values of available experimentally measured data (designated as C1 in [5,6]). The mechanical properties of the hail material are defined as 9.38 GPa elastic modulus and 0.33 Poisson’s ratio, as defined in [6]. Additionally, the static compressive strength, defined as 5.2 MPa, is scaled by the strain rate dependent scaling factors in Table 1. Material failure is simulated using the tensile failure criterion that is initiated at 0.517 MPa hydrostatic stress. In this case, the deviatoric stress is set to be equal to zero while the hydrostatic stress is kept at the critical value [4]. This type of material behaviour is also applied in the Equation of State (EOS) models that are usually employed in the modelling of numerical impactors for bird strike simulations. The density of the hail material is selected to be 900 kg/m$^3$, after [26].

Table 1. Applied scaling factors of the hail compressive strength [5].

| Scale factor [-] | Strain rate [s$^{-1}$] |
|------------------|------------------------|
| 1                | 0                      |
| 1.01             | 0.1                    |
| 1.495577759      | 0.5                    |
| 1.709011483      | 1                      |
| 2.204589242      | 5                      |
| 2.418022966      | 10                     |
| 2.913600725      | 50                     |
| 3.127034449      | 100                    |
| 3.622612208      | 500                    |
| 3.836045932      | 1000                   |
| 4.331623691      | 5000                   |
| 4.545057415      | 10000                  |
| 5.040635174      | 50000                  |
| 5.254068897      | 100000                 |
| 5.749646657      | 500000                 |
| 5.96308038       | 1000000                |

The CEL and SPH numerical impactor models were validated using the available experimentally measured contact forces [6,7] at the high-velocity impact. These simulations were performed at a wide range of hailstone diameters and initial velocities. As an example of the results, the numerically predicted contact forces at a 38.1 mm diameter hailstone impact at 142 m/s are shown in Figure 1. The experimental setup was simulated as a rigid plate impact that was analysed using a total of 1026675 EC3D8R elements in a volume of 0.3 m x 0.3 m x 0.2 m in the CEL model whereas 131838 particles were used to model the 38.1 mm diameter hailstone sphere in the SPH simulation.

As shown, the numerical impactors can sufficiently accurately simulate the generated impact forces. In this case, the maximal contact force is accurately predicted by the CEL model and underestimated by the SPH model, while the force release stage of the impact was accurately predicted by both models. However, these conclusions are not general as they depend on the simulated hailstone diameters and initial velocities. Figure 1 also shows the results obtained by the Lagrangian impactor from [6].
Figure 1. Validation of the numerical impactors, contact forces at a 38.1 mm hailstone impact at 142 m/s, experimental values and Lagrangian results are taken from [6].

Two material models were used in this work to model the mechanical behaviour of the impacted slat structure made from Aluminium alloys. The first is the standard isotropic elastic model with piecewise linear isotropic plasticity, while the second is the Johnson-Cook strain rate dependent plasticity and damage model. The elastic properties of both models for the applied materials in the slat model are presented in Table 2.

Table 2. Al-alloys elasticity properties [7].

| Material         | $E$ [GPa] | $\nu$ [-] | $\rho$ [kg/m$^3$] |
|------------------|-----------|-----------|-------------------|
| Al2024-T42       | 72.400    | 0.33      | 2780              |
| Al7010-T73651    | 71.016    | 0.33      | 2796              |
| Al-honeycomb     | 1.6655    | 0.30      | 98                |

The material properties defining the isotropic plasticity behaviour were selected based on the data provided in [7]. Material failure was simulated using the Shear failure criterion in Abaqus/Explicit, by deleting material points which reach a state of 18% equivalent plastic strain.

The strain rate dependent Johnson-Cook plasticity model defines the yield stress $\sigma_y$ as

$$\sigma_y = \left[A + B \cdot \left(\dot{\varepsilon}_{pl}\right)^n\right] \cdot \left[1 + C \cdot \ln \left(\frac{\dot{\varepsilon}_{pl}}{\dot{\varepsilon}_0}\right)\right] \cdot \left[1 - \left(\frac{T - T_0}{T_{melt} - T_0}\right)^m\right],$$

where $A$ is the static yield strength, $B$ and $n$ are strain hardening parameters, $C$ defines the effect of plastic strain rate, $\dot{\varepsilon}_0$ is the referent strain rate defined as $1$ s$^{-1}$, $\dot{\varepsilon}_{pl}$ is the equivalent plastic strain and $\dot{\varepsilon}_{pl}$ is the equivalent plastic strain rate. The temperature ($T$) effects are defined by the parameters $m$, $T_0$, $T_{melt}$ is the melting temperature. The state of material failure is defined once the accumulated plastic strain reaches the failure strain defined as

$$\varepsilon_{pl}^f = \left[D_1 + D_2 \exp \left(D_3 \frac{p}{q}\right)\right] \left[1 + D_4 \ln \left(\frac{\dot{\varepsilon}_{pl}}{\dot{\varepsilon}_0}\right)\right] \left[1 + D_5 \frac{T - T_0}{T_{melt} - T_0}\right].$$

The failure strain in Equation 2 is defined by the parameters $D_1$-$D_5$, while $p$ is the hydrostatic stress and $q$ is the equivalent von Mises stress.

As explained in Section 3.1, the Johnson-Cook model was applied in this work only for the Al2024-T42 alloy as the impact at the leading edge skin of the slat structure was simulated. The applied parameters for the Johnson-Cook model are provided in Table 3, after [8].
Table 3 Parameters of the Johnson-Cook model for Al2024 [8].

| Parameter | Symbol | Value   |
|-----------|--------|---------|
| A         | A      | 368.98  |
| B         | B      | 683.97  |
| C         | C      | 0.0083  |
| n         | n      | 0.73    |
| m         | m      | 1.7     |
| $T_{melt}$| $T_{melt}$ | 783     |
| $T_0$     | $T_0$ | 294     |
| $D_1$     | $D_1$ | 0.112   |
| $D_2$     | $D_2$ | 0.123   |
| $D_3$     | $D_3$ | 1.5     |
| $D_4$     | $D_4$ | 0.007   |
| $D_5$     | $D_5$ | 0.0     |

3. Numerical model

3.1. Slat structure

The slat structure finite element model was employed previously by the authors in the bird strike simulations, e.g. in [9], and is therefore only briefly explained here. The model, shown in Figure 2, consists of a total of 31350 finite elements, including 17175 shell (S3, S43) elements of the thin-walled structure, 5670 SC8R three-dimensional shell elements for the facelayers and 8505 C3D8 solid elements for the core of the trailing edge sandwich structure. The shell-to-solid coupling constraint was used to connect the dissimilar finite element types in the model. Most of the structure is made from Al2024 alloy, only the main ribs to which the slat mechanism actuators are connected are made from the Al7010 alloy. The leading edge skin is reinforced by a Z-shaped spar throughout the complete slat span.

![Impact location](image)

Figure 2. Slat structure FE model with applied skin shell thicknesses.

3.2. Boundary and initial conditions

The impact location, shown in Figure 2, is selected to be located at the skin between the reinforcing ribs, as the impact results in the most pronounced damage state in the structure in this case. The slat structure is fixed by the nodes on the trailing edge of the main ribs that are fully restrained to simulate the effect of the slat mechanism. The initial velocity is defined as prescribed velocity of the hail impactor, also includes the 28° leading edge sweep angle.

The EASA recommendation [2], according to which the simulations in this work were performed, define two distinct hail impact scenarios that should be considered in the certification stage: the single large diameter (110 mm) and the multiple small diameter (50 mm) impact case. From a structural integrity viewpoint, the single large diameter hail impact presents a greater threat to flight safety, as the kinetic energy is more focused, resulting in the more pronounced damage state in the structure. Consequently, simulation of the 110 mm diameter hailstone at the assumed cruise speed of the airliner of 200 m/s was simulated in this work. The CEL model is simulated in this case using a volume of 1 m
x 1 m x 0.6 m, discretized by 656667 Eulerian elements, whereas 5622 particles are used to model the 110 mm sphere in the SPH model.

4. Results
The deformation processes of the CEL and SPH impactors are illustrated in Figure 3. The presented results were shown for the application of the Johnson-Cook model, while the impactor deformation process is very similar if the isotropic plasticity model is used for the impacted structure. Both numerical impactors accurately capture the fluid-like deformation of the hailstone. The more compact deformed shapes of the CEL model are a result of the visualisation of the Eulerian material in CEL analysis that was done in this Figure using the EVF value equal to 0.5.

![Figure 3. Comparison of the deformation processes of CEL and SPH impactors.](image)

The resulting damage state in this impact case is shown in Figure 4, where contours of the equivalent von Mises stress are shown. As illustrated, the kinetic energy of the hail impactor is sufficient to cause material failure throughout several skin finite elements, as predicted by the CEL as well as the SPH models. Consequently, penetration of the slat skin enables the intrusion of hail material that impacts the interior of the structure. As evident from Figure 3, the hail impactor material is more compact in the CEL analysis, causing more concentrated damage, leading to a smaller number of finite elements reaching the failure state. On the other hand, the hail material of the SPH model is distributed over a larger area, leading to a larger damaged area of the slat skin.

![Figure 4. Comparison of equivalent von Mises stress distribution [Pa].](image)
The structural damage states predicted by the isotopic plasticity and the Johnson-Cook models are very similar. To illustrate the strain rate effect on the deformation process, Figure 5 shows a comparison of the maximal node deflections predicted by using the CEL model and the two dissimilar material models. As shown, the very high strain rates lead to an increase of the yield strength resulting in a stiffer structural response.

![Comparison of maximal node deflections as predicted by the isotropic plasticity and the Johnson-Cook plasticity models.](image)

Figure 5. Comparison of maximal node deflections as predicted by the isotropic plasticity and the Johnson-Cook plasticity models.

5. Conclusion

The results presented in this work illustrate that the CEL and SPH, two soft-body impact modelling techniques available in Abaqus/Explicit, can both reliably predict the forces generated by the high-velocity hail impact. Although some discrepancies in the predicted contact forces exist, they are relatively small and depend on the analysed impact case (hail impactor diameter and initial velocity). A more pronounced difference between the CEL and SPH models is evident in the simulated impactor deformation process, where the hail material of the SPH impactor is distributed over a wider area compared to the more concentrated CEL impactor.

Despite these differences, the damaged state in the slat structure is simulated similarly by the CEL and SPH models, especially if penetration of the slat skin does not occur. The differences between the evaluated numerical techniques become more pronounced if slat skin penetration occurs due to the different deformation processes of the numerical impactors. Since the differences between the results obtained by the CEL and SPH models are not pronounced and considering the fact that the SPH approach is significantly more computationally efficient, it can be concluded that SPH is the more suitable approach to simulate the hail impact. However, experimental testing of the hail impact in the slat structure would be required to obtain a clear conclusion on the accuracy of the evaluated models in the slat structure impact simulations.

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