

Impact analysis and sensitivity study of trailing edge flaps under static preload

Filipe Ferreira da Costa Silva Valqueresma
filipevalqueresma@tecnico.ulisboa.pt

Instituto Superior Técnico, Universidade de Lisboa, Portugal

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Abstract

Airworthiness certification for bird strike resilience typically tests and simulates the aeronautical structure in an unloaded, stress-free state, neglecting pre-existing operational loads acting on components during critical flight phases. This dissertation addresses this gap by establishing an integrated numerical pipeline to investigate the influence of aerodynamic pre-stress on the high-velocity impact response of aircraft trailing-edge high-lift devices. In order to ensure research comparability, numerical simulations were implemented on a representative flap assembly, structurally and dimensionally analogous to that of a wide-body passenger aircraft, subjected to impact conditions mandated by international airworthiness standards. The simulation framework employs an implicit-explicit coupling scheme developed in LS-DYNA. Steady-state aerodynamic pressure distributions derived from high-fidelity computational fluid dynamics (CFD) are mapped onto the structural domain and initialized via transient loading ramps to establish the pre-stressed state prior to the soft-body impact event. In parallel, a standalone static pre-load simulation is executed via dynamic relaxation protocols to serve as a numerical validation baseline. This ensures that the transient initialization successfully achieves a physically significant stress state and demonstrates that the static approach constitutes a simpler, valid approximation of the pre-load environment. The high-lift flap substructure is governed by an elastoplastic material framework to accurately capture high-velocity structural behaviour. These findings highlight that operational environments introduce deterministic variables that are missing from conventional stress-free baselines, suggesting that next-generation virtual "Certification by Analysis" frameworks must adopt coupled aero-structural methodologies to ensure higher simulation fidelity.

Keywords: Bird Strike, High Velocity Impact, Preloaded Structures, Finite Element Modelling, Aerodynamic Loading

1. Introduction

Bird strikes have posed a persistent vulnerability to aircraft structures since the dawn of aviation, from Orville Wright's 1905 strike aboard the "*Wright Flyer III*" to the 2009 "Miracle on the Hudson", US Airways Flight 1549's ditch landing shortly after take-off at New York City's LaGuardia airport [1]. This research investigates the simulated structural response of an aeronautical component subjected to soft-body impact, explicitly incorporating the influence of aerodynamic pre-stress, a critical variable that remains largely unaddressed within current airworthiness certification frameworks.

1.1. Research Context

The global bird strike phenomenon is characterized by evolving statistical trends that encompass geographical occurrence mapping, substantial economic impact, and the evaluation of mitigation measures. In fact, conservative estimates place the

economic effects of bird strikes at more than US\$ 2.1 billion per year [2], while having caused 618 hull losses and 534 fatalities since the beginning of aviation (as of 11 November 2019), highlighting the very destructive impact associated with these incidents [3]. Bird strike events are mostly concentrated at lower altitudes (Fig. 1), during take-off, initial climb, approach, and landing phases. The extension of trailing-edge flaps significantly increases the aircraft's frontal surface area, thereby enhancing the susceptibility of these components to bird impacts during these critical flight stages.

From a structural mechanics perspective, bird strike is a high-velocity impact problem where the target's response depends highly on its initial state. Although conventional certification and testing often treat aircraft components as stress-free, the literature shows that preloaded structures exhibit a significantly different impact response compared to unloaded structures [4], as seen in Fig. 2. Specifi-

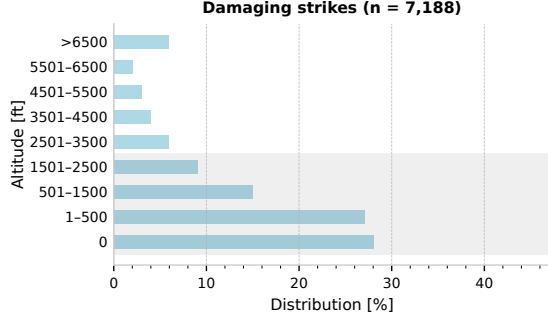


Figure 1: Distribution of damaging bird strikes across documented altitude bands in the USA (1990–2018). Adapted from [3].

cally, tensile preloads can reduce delamination extent by limiting bending deflection, whereas compressive preloads may increase delamination depending on the post-buckling regime.

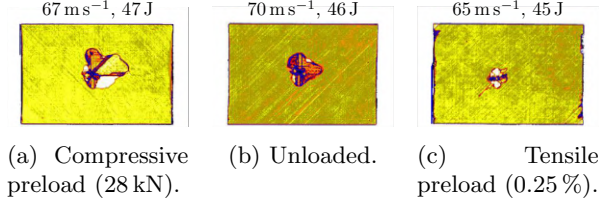


Figure 2: Selected ultrasonic C-scan results of impacted composite plates with different states of preload. Results are labelled with projectile impact speed and energy. Adapted from [4].

1.2. Objectives

A significant amount of bird strike modelling research is done in the context of aeronautical certification, such as to satisfy international Certification Standards (CS) and Code of Federal Regulations (CFR) requirements, laid out by the European Union Aviation Safety Agency (EASA) and Federal Aviation Administration (FAA) respectively. Current aircraft certification regulations require outer structures to be able to withstand impact of foreign objects during flight, ensuring that an impacted aircraft can continue to fly and land safely after such incidents. Throughout this study, EASA’s CS-25 - Large Aeroplanes [5] and its equivalent in the USA, the FAA’s 14 CFR Part 25 [6], are used as main references. Specifically, the central case discussed in this study is based on a high-velocity impact of a 4 lb (1.8 kg) bird on a trailing-edge flap, as prescribed by these regulations.

Historically, compliance has relied on rigorous physical testing using either real avian carcasses or surrogate projectiles designed to emulate them. Although effective, these experimental procedures are resource-intensive and limit flexibility during the it-

erative design phases. Consequently, contemporary research focuses on complementing or partially replacing physical testing with validated numerical simulations.

This study, conducted within the German Aerospace Center (DLR) Institute of Structures and Design under the Advanced Methods for Virtual Certification (AdViCe) project, addresses a gap in current simulation baselines: while standard models treat structures as initially stress-free, real-world bird strikes occur while control surfaces experience substantial aerodynamic pressures [7]. The primary objective of this work is to analyse how these representative aerodynamic preloads alter the high-velocity impact behaviour of a commercial aircraft trailing-edge flap.

2. Bird Strike Damage Assessment

The initial kinetic energy E_k of a projectile relative to an aircraft scales quadratically with speed and is governed by:

$$E_k = \frac{1}{2}mV^2, \quad (1)$$

where m represents projectile mass and V is the relative impact velocity, which is typically approximated to the aircraft’s flight speed.

To satisfy the conservation of linear momentum in a perfectly inelastic collision where the projectile fragments and spreads across the target surface, the actual deformation energy E_d dissipated through material rupture and structural failure is expressed as:

$$E_d = \frac{\frac{1}{2}mV^2}{1 + \frac{m}{M}} = \frac{E_k}{1 + \frac{m}{M}}, \quad (2)$$

where M represents the mass of the primary aircraft structure. In transport-category aviation, because the structural mass of the airframe is multiple orders of magnitude larger than the projectile ($M \gg m$), the mass ratio m/M approaches zero. Consequently, virtually 100% of the initial relative kinetic energy is converted into structural deformation ($E_d \approx E_k$).

In bird strikes at velocities exceeding 100 m s⁻¹, the strength of the bird tissue becomes negligible compared to the generated impact pressures, allowing the impact to be modelled using hydrodynamic theory [8].

The resulting fluid-structure interaction follows a well-defined four-stage shock sequence initiated by a transient high-pressure shock phase governed by Hugoniot relations. The initial peak shock pressure p_H is expressed as:

$$p_H = \rho_0 c_0 u_0 \quad (3)$$

where ρ_0 is the initial density, c_0 is the acoustic speed of the projectile, and u_0 is the initial impact

velocity. This microsecond-long peak is rapidly attenuated by release waves originating from the free boundaries, transitioning the material flow into a quasi-steady stagnation phase. A typical pressure-time history for such an impact is shown in Fig. 3, where the initial peak corresponds to the Hugoniot pressure.

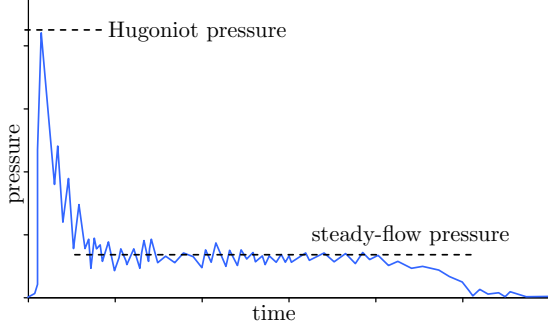


Figure 3: Typical pressure curve for a typical soft body impact on a rigid plate. Adapted from [9].

2.1. Bird Strike Testing

Empirical evidence is needed to translate the statistical hazards of bird strikes into measurable metrics and airworthy structural designs, as such, physical testing continues to be the primary method for demonstrating compliance with EASA and FAA requirements. In addition to validating certification, these tests also serve the dual purpose of providing data for calibrating and validating numerical models for research purposes.

The origins of systematic bird strike testing date back to 1942, with pioneering investigations conducted by the predecessor of the modern-day FAA. Currently, and despite some variability within the field, bird strike testing follows technical protocols formalized by organizations such as the American Society of Testing and Materials and the Society of Automotive Engineers. Specifically, the ASTM F330 prescribes the use of a smooth-bore compressed-gas gun to fire a domestic chicken carcass at velocities exceeding 334 m s^{-1} (650 kt) [10]. In contrast, SAE AS6940 provides a specialized methodology for the quantification of impact forces, employing an instrumented aluminium bar known as a Hopkinson bar to measure the highly-transient force history of impact [11].

Discussions surrounding the choice of projectile revolve around the trade-off between biological fidelity and experimental repeatability. Contemporary aerospace research, however, focuses increasingly in resorting to validated synthetic surrogates.

Despite the recognised advantages of using artificial bird projectiles, a universally accepted standard dummy bird has yet to be established. Several formulations for synthetic birds exist across insti-

tutions and manufacturers, governed by two fundamentally distinct architectural philosophies (Fig. 4): biofidelic projectiles, which seek to replicate the internal macro-structural heterogeneity of a real bird; and simplified geometries, which prioritize geometric abstraction to maximize mathematical and experimental repeatability.

In this research, a numerical model of an ellipsoidal surrogate bird such as that of Fig. 4 is used.

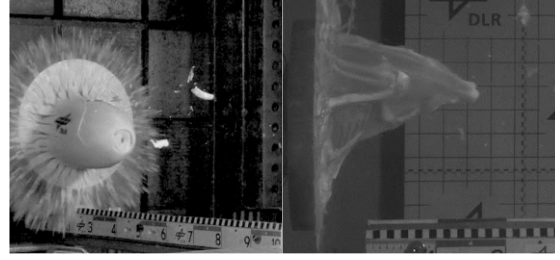


Figure 4: Composite image of an ellipsoidal projectile (left) and a biofidelic projectile (right) during impact testing. Adapted from [12].

2.2. Impact Simulation Modelling

Simulating the extreme material distortions, and fluid-like splashing of hydrodynamic soft-body impacts presents severe challenges to classical grid-based computational methods.

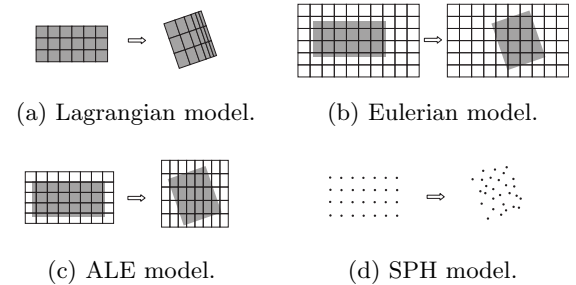


Figure 5: Different finite element modelling methods for soft body projectiles. Adapted from [9].

While spatial discretization using standard mesh-based Lagrangian solvers tracks solid structural boundaries with high accuracy, it is highly susceptible to severe element distortion and negative volume errors when applied to the soft impactor, which in turn introduce artificial numerical stiffening into the solver.

Conversely, purely Eulerian methods eliminate grid distortion by allowing material to flow through a fixed spatial mesh, but they introduce significant algorithmic complexity and high computational costs when tracking the high-frequency, moving projectile-target interface.

To exploit the benefits of both regimes without their numerical limitations, this study uses a mesh-

less particle-based architecture: Smoothed Particle Hydrodynamics (SPH). The continuous spatial domain of the surrogate bird projectile is discretized into a finite collection of moving particles, which carry individual discrete material properties including mass, velocity, density, and internal energy.

The SPH framework replaces the continuous field functions $f(x)$ through integral kernel interpolation over a localized support domain:

$$\Pi^h f(x) = \int f(y)W(x-y, h)dy, \quad (4)$$

where W is a piecewise cubic centrally peaked B-spline smoothing kernel function, and h represents the smoothing length, which varies in both time and space to maintain numerical stability during material deformation.

In the discrete SPH framework, the continuous integral is replaced by a summation over the particles within the support domain. By introducing the explicit spatial coordinates of a specific target particle i as $\mathbf{x}_i$, and its neighbours j as $\mathbf{x}_j$, the continuous integral step is discretized,

$$f(\mathbf{x}_i) \approx \sum_{j=1}^N \frac{m_j}{\rho_j} f(\mathbf{x}_j)W(\mathbf{x}_i - \mathbf{x}_j, h), \quad (5)$$

approximating the value of f at position $\mathbf{x}_i$ by a summation at the neighbouring positions, weighted by particle volume $\frac{m_j}{\rho_j}$ and the kernel function W .

The hydrodynamic behaviour of a bird model is characterized by solving the Euler equations of mass, momentum and energy conservation, in their SPH formulation:

Mass:

$$\frac{d\rho_i}{dt} = \rho_i \sum_{j=1}^N \frac{m_j}{\rho_j} (\mathbf{v}_i - \mathbf{v}_j) \cdot \nabla_i W_{ij} \quad (6a)$$

Momentum:

$$\frac{d\mathbf{v}_i}{dt} = - \sum_{j=1}^N m_j \left(\frac{p_i}{\rho_i^2} + \frac{p_j}{\rho_j^2} + \Pi_{ij} \right) \nabla_i W_{ij} + \mathbf{g}_i \quad (6b)$$

Energy:

$$\frac{du_i}{dt} = \frac{1}{2} \sum_{j=1}^N m_j \left(\frac{p_i}{\rho_i^2} + \frac{p_j}{\rho_j^2} + \Pi_{ij} \right) (\mathbf{v}_i - \mathbf{v}_j) \cdot \nabla_i W_{ij} \quad (6c)$$

where ρ is density, m is particle mass, $\mathbf{v}$ is the velocity vector, p is pressure, u is specific internal energy,

Π is an artificial viscosity tensor, $\mathbf{g}$ is a vector of external body forces accelerations such as gravity, and ∇W is the gradient of the kernel function.

The term Π_{ij} , the artificial viscosity, represents a numerical stabilization factor required to capture shock waves and prevent unphysical particle penetration during high-velocity impacts.

2.3. Damage Modelling and Aerodynamic Mapping

The structural components of the commercial trailing-edge flap analysed in this study are manufactured from high-performance Carbon Fibre Reinforced Polymers (CFRP), chosen for their exceptional weight-specific stiffness and strength. However, to ensure higher numerical stability and more experimental reliability when isolating the influence of aerodynamic pre-stress, this study implements a high-fidelity elastoplastic material framework tailored for ductile aerospace alloys.

The structural stress state throughout the impact event is defined via linear superposition:

$$\sigma_{ij}^{\text{total}}(t) = \sigma_{ij}^{\text{aero}} + \sigma_{ij}^{\text{impact}}(t). \quad (7)$$

Because the structural rigidity of the commercial flap box assembly limits overall deflections under operational pressures, forward aerodynamic-to-structural load mapping is utilized. This methodology captures the alterations in structural stiffness and changes in the material failure energy thresholds accurately, omitting the excessive computational cost of a fully coupled, iterative aeroelastic solver framework.

3. Case Implementation and Numerical Modelling

Evaluating bird strike resilience requires a structural target that is both standardized to ensure comparability and representative of modern aerospace standards. This study uses a particular geometric representation of a trailing-edge high-lift flap assembly corresponding to a typical passenger aircraft, similar to the Airbus A330, which allows to match structural characteristics of the Airbus eXternal Research Forum (XRF1) research platform.

The investigation focuses specifically on a segment of the outboard trailing edge flap.

3.1. Model Geometry

The structural FEM model represents a high-performance composite assembly, a Composite Multispar Flap (CMF), utilizing a Carbon Fibre Reinforced Polymer (CFRP) skin as the primary load-bearing surface. This design features a co-cured CFRP outer skin integrated directly with a multi-cell internal substructure consisting of 5 longitudinal web spars, as seen in Fig.6. The flap is connected to the aircraft's main wing via a dedicated track mechanism. These tracks are responsi-

ble for the flap's kinematics and serve as the primary boundary conditions, transferring the aerodynamic and impact loads into the wing's rear spar [13].



Figure 6: Section view of the CFRP flap. Adapted from [13].

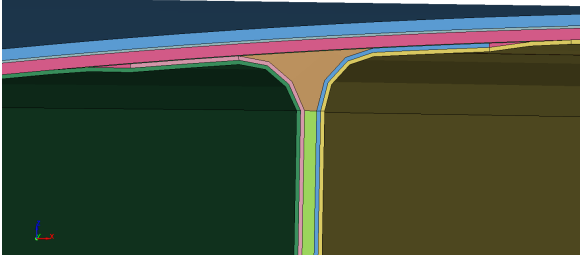


Figure 7: Detailed view of the FEM mesh structure, displaying both solid (e.g. the resin matrix, in light brown and light green) and shell elements (e.g. the skin element, in blue).

3.2. Preload Case

The evaluation of bird strike vulnerability requires a representative operational baseline. In this study, the landing configuration is identified as the critical scenario, as the full extension of high-lift devices highly exacerbates both the frontal impact area and the aerodynamic pre-stress on the flap structure.

The reference case corresponds to a flight speed of 66 m s^{-1} at a flap deflection of 40° and an angle of attack (α) of 7° . At this high-lift setting, the aerodynamic load is dominated by a strong suction peak at the flap's leading edge, induced by the accelerated flow through the slot between the main wing and the flap. This pressure field constitutes the baseline against which all subsequent results are compared.

The dataset for the baseline aerodynamic pressure distribution applied in this work corresponds to a steady flow solution representative of the selected flight condition, which was computed using the DLR TAU code [14].

In this study, a hybrid interpolation methodology was adopted. The pressure values at the CFD vertices are exported from the TAU solver and subsequently mapped onto the structural flap skin. The implementation uses the `*LOAD_SEGMENT` keyword in LS-DYNA, where the aerodynamic pressure is applied as a piecewise-constant surface traction acting

normal to the face of each shell or solid element.

The pressure for each structural segment P_{seg} is determined by calculating the weighted average of the n closest aerodynamic points:

$$P_{\text{seg}} = \frac{\sum_{i=1}^n w_i P_i^{\text{CFD}}}{\sum_{i=1}^n w_i}, \quad (8)$$

where w_i is an inverse-distance weighting factor. This approach ensures that localized suction peaks, particularly those at the flap leading edge, are not smoothed out by the coarser structural discretization.

3.3. Bird Model

The numerical characterization of the bird is a critical component of the impact simulation. At the velocities associated with take-off and landing (exceeding 60 m s^{-1}), the bird behaves essentially as a fluid projectile. To ensure reproducibility and compliance with aerospace certification standards, a standardized surrogate bird geometry is used (Fig. 8). The bird is modelled as an ellipsoid with a length-to-diameter (L/D) ratio of 2.0. The total mass is set to the standard certification value of 1.814 kg (4 lb) and the density is assumed to be $\rho = 980 \text{ kg m}^{-3}$, approximating a mixture of water and air.



Figure 8: Bird Model in LS-DYNA.

3.4. FEM Simulation

The dynamic analysis in this study was conducted using LS-DYNA, a multi-physics, general-purpose Finite Element Analysis (FEA) software package optimized for the simulation of large-deformation, non-linear structural responses. While the software also incorporates an implicit solver for quasi-static and thermal applications, its core strength lies in its explicit time integration methodology. This makes it the industry standard for aerospace certification. The execution of an LS-DYNA simulation is governed by a text-based keyword input system, which constitutes a highly modular, human-readable interface for defining the problem parameters, known as keyword cards.

The FEA framework seeks to solve the momentum equation, derived from Newton's Second Law:

$$\sigma_{ij,j} + \rho f_i = \rho \ddot{x}_i, \quad (9)$$

where, using the Einstein notation (a summation is implied for each repeated index), σ is the Cauchy stress and the ij, j subscript denotes covariant differentiation, ρ is the current density, f is the body force density and $\ddot{x}$ is acceleration.

For high-energy impacts, this is coupled with mass conservation and the energy equation to track global energy balance and global stability.

The momentum equation (Eq. 9) is solved while satisfying the boundary conditions:

$$\begin{aligned} &\textit{Traction Boundary } (\partial b_1): \\ &\sigma_{ij}n_j = t_i(t) \end{aligned} \quad (10a)$$

$$\begin{aligned} &\textit{Displacement Boundary } (\partial b_2): \\ &x_i(X_\alpha, t) = D_i(t) \end{aligned} \quad (10b)$$

$$\begin{aligned} &\textit{Contact Discontinuity } (\partial b_3): \\ &(\sigma_{ij}^+ - \sigma_{ij}^-)n_i = 0 \\ &\text{for } x_i^+ \neq x_i^- \end{aligned} \quad (10c)$$

In the finite element method, spatial discretization is achieved by superimposing a mesh of elements interconnected at nodal points onto the reference configuration. While this spatial discretization introduces an approximation to the true continuous solution, the discrete kinematic field within any given isoparametric element is explicitly defined by tracking its nodes through time, i.e.,

$$x_i(X_\alpha, t) = x_i(X_\alpha(\xi, \eta, \zeta), t) = \sum_{j=1}^k N_j(\xi, \eta, \zeta) x_i^j(t), \quad (11)$$

where N_j are the shape (interpolation) functions defined in the parametric coordinate system (ξ, η, ζ) , k is the number of nodal points defining the element, and x_i^j is the transient coordinate of the j^{th} node in the i^{th} direction.

3.5. Damage Quantification

The final stage of the implementation framework involves defining the quantitative metrics used to evaluate the structural response and the influence of aerodynamic preloads. This study employs three primary numerical metrics to compare the sensitivity across different flight conditions.

To capture the transient structural response, "Virtual Strain Gauges" are implemented at critical locations: the impact centroid, the leading-edge attachment points, and the flap tracks. These are represented by specific history-tracking nodes.

4. Impact Response under Aerodynamic Preloading

This section presents the results of the simulated cases and discusses the effects of aerodynamic loading on the simulated response of the bird strike impact.

Before proceeding to the impact analysis, the baseline flight condition is evaluated. This section defines the initial state of the flap before the bird enters the computational domain.

4.1. Boundary Conditions

To capture the true structural response of the inboard trailing-edge flap, the boundary conditions must accurately reflect the kinematic constraints of the deployment mechanism. As established, the flap is supported by two distinct track fairing stations along its span. In the explicit finite element model, these interfaces are represented by constraining specific nodal subsets at the track attachment locations.

Boundary conditions are enforced by constraining all translational degrees of freedom (X, Y, Z) at the inboard and outboard track stations to structurally represent the fixed joints of the track mechanism, respectively.

The bird strike scenario is modelled as a normal, symmetrical impact on the leading edge of the flap skin. The initial position of the SPH projectile is shown in the computational domain. The key parameters governing the initial state of the impactor are defined as follows:

Table 1: Initial conditions for the impact scenario.

Parameter	Value	Context
Impact Velocity	66 m s ⁻¹	Final approach speed.
Impact Angle	47°	Maximum flap deflection.
Spanwise Position	Mid-span	Centered

Since the bird projectile is modelled in SPH, a meshless particle-based approach, while the flap is modelled as a typical structure based on SOLID and TSHELL elements, the contact formulation is especially relevant for this problem. The *CONTACT_AUTOMATIC_NODES_TO_SURFACE card is employed to handle the FSI in this simulation. A static friction coefficient of $\mu_s = 0.01$ and a dynamic friction coefficient of $\mu_d = 0.009$ are applied to capture the tangential sliding of the bird splash across the pre-tensioned skin. To prevent internal element penetration during localized buckling or folding after impact, a *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE key-

word is active across the structural components of the flap substructure.

4.2. Flap Structural Response under Static Aerodynamic Loading

The initial phase of the investigation focused on evaluating the numerical stability and structural response of the trailing edge flap under the mapped aerodynamic load envelope.

As observed in the vertical displacement profiles of the history nodes (Fig. 9), the structural domain does not achieve a static steady-state equilibrium within the designated 14.95 ms window.

This behaviour represents the characteristic transient dynamic response of a highly flexible, thin-walled aerospace assembly subjected to a rapid aerodynamic loading ramp. The finite duration of the force application acts as a dynamic excitation, triggering the structural bending modes of the internal CFRP network.

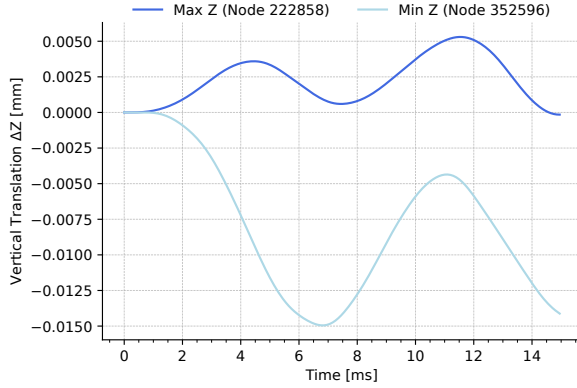


Figure 9: Deformation history of the nodes with the maximum positive and negative resultant deformation.

The fact that the wing tip continues to oscillate at the terminal point of the simulation indicates that the structural inertial forces have not yet been fully dissipated by material or numerical damping. A longer simulation window would be required to observe the asymptotic relaxation into a pure static equilibrium. This simulation, however, successfully serves its primary objective: verifying the structural integrity of the FE mesh and characterizing the early-stage transient kinematic flexing of the flap model before an impact wave is introduced.

To verify that the aerodynamic pressure field is correctly integrated across the structural surface, the global boundary reaction forces were extracted from the single-point constraints (`spcforc`). Figure 10 isolates the total resultant reaction force vector acting in the vertical (Z) direction across the primary hinge and actuator attachment points.

The vertical reaction load climbs in direct pro-

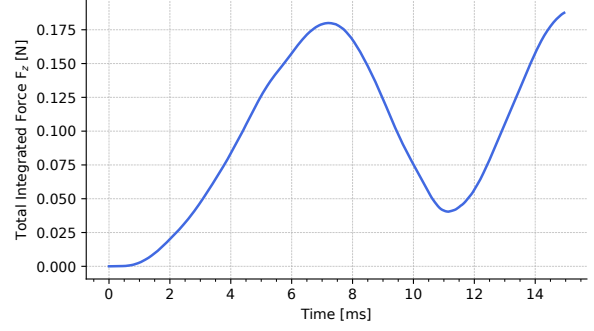


Figure 10: Combined vertical boundary resultant reaction force history showing the cumulative load transfer to the support mounts during the aerodynamic pressure ramp.

portion to the applied aerodynamic pressure envelope. At the terminal point of the load ramp ($t = 14.95$ ms), the integrated reaction force reaches a peak magnitude of ≈ 0.175 N. This cumulative load directly counterbalances the distributed lift profile mapped onto the flap skin.

The qualitative profile of the reaction curve appears exactly as intended, climbing in direct proportion to the aerodynamic pressure ramp and capturing the transient structural oscillations. However, from a quantitative standpoint, the absolute peak reaction force reaches a terminal value of only 0.175 N. This magnitude is severely underestimated and clearly unphysical for an operational commercial aircraft trailing edge surface.

The structural response of the model flap assembly under transient aerodynamic loading is evaluated across selected time steps to verify the numerical stability of the load-mapping pipeline before introducing the impact event. Figure 11 illustrates the evolution of the global displacement field at four distinct time steps spanning the initialization sequence ($t = 3, 6, 12, 15$). The maximum displacement is consistently observed at the mid-span section, specifically concentrated near the trailing edge. This localized compliance matches analytical expectations for high-lift aerodynamic topologies.

Complementing the displacement global tracking, Fig. 12 details the corresponding contour histories of the effective von Mises strain distribution. Overall, the structure remains well within its elastic regime, demonstrating a low strain profile across the spatial domain that guarantees the baseline integrity of the initial loading methodology. Despite the globalized nature of the fluid pressure distribution, the effective strain contours clearly outline the internal layout of the composite spars. This structural print reflects the discrete stiffness transitions occurring at the junctions where the flexible skin is bonded directly to the highly rigid inter-

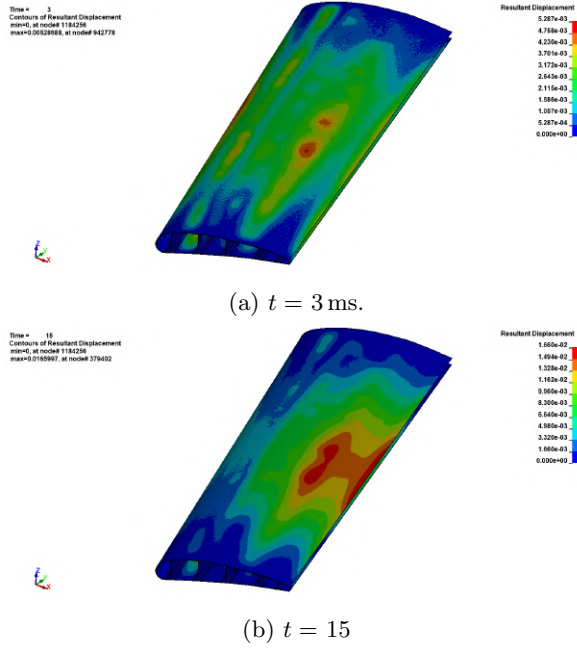


Figure 11: Visualization of the deformation history during the transient aerodynamic loading.

nal web cells. Peak strain values are localized at the track mechanism interfaces where the model is structurally constrained. Because these attachment tracks serve as the primary boundary conditions responsible for transferring all lifting forces into the wing's rear spar architecture, these localized strain concentrations physically validate the model's load-path.

To establish a numerical baseline and verify the convergence integrity of the load-mapping pipeline, an independent simulation case was performed using the Dynamic Relaxation (DR) capability available in LS-DYNA. During the DR phase, artificial numerical damping is introduced to dissipate kinetic energy generated by the application of the aerodynamic pressure field. As the transient oscillations decay, the structure progressively approaches a state of static equilibrium in which the internal structural forces balance the applied external loads. The resulting deformed and pre-stressed configuration provides a reference solution for assessing the accuracy and consistency of the mapped aerodynamic loading.

The primary objective of this static analysis was to verify the transient initialization procedure employed in the preceding simulation. The deformation field obtained through DR was compared with the final state of the transient aerodynamic loading sequence presented in Section ?? . Acceptable agreement was observed in the overall displacement distribution, peak displacement magnitude, and stress levels within the flap structure. The comparison

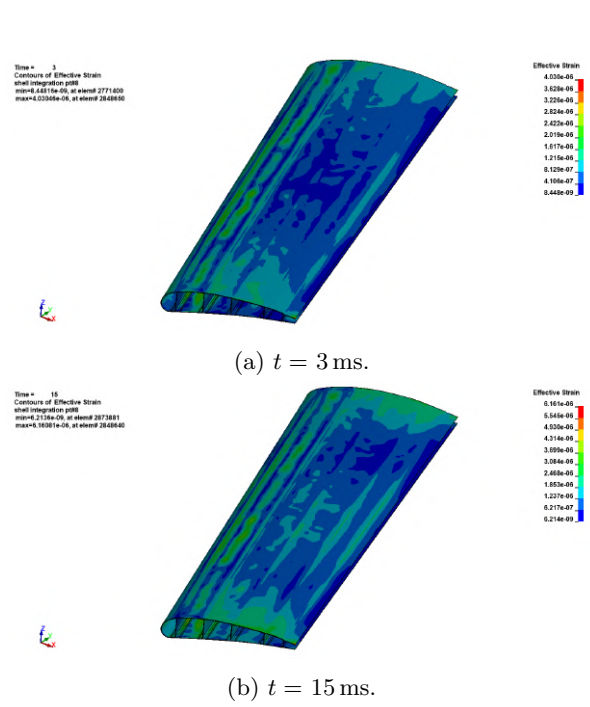


Figure 12: Visualization of the effective von Mises strain history during the transient aerodynamic loading.

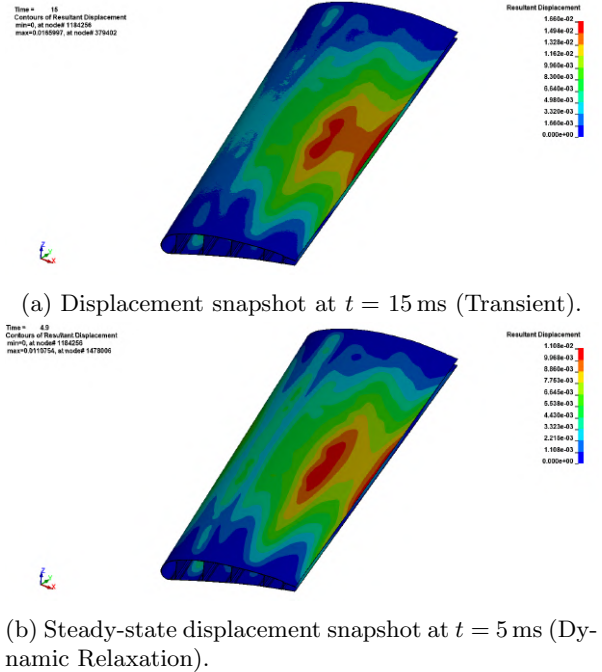


Figure 13: Static displacement field achieved via dynamic relaxation, confirming architectural alignment with the transient quasi-static snapshots.

demonstrates that the transient initialization procedure produces a similar global structural response to that predicted by the DR analysis.

4.3. Response with Aerodynamic Loading

In this simulation, the trailing edge flap assembly is first subjected to the complete 11.50 ms aerodynamic loading before undergoing a high-velocity soft-body projectile impact from $t = 11.50$ ms to 20.00 ms.

The global system energy tracks were captured via the explicit solver’s global statistical repository (`glstat`). Figure 14 maps the complete energy transformation profile across the entire 20.00 ms computational window, highlighting the clear distinction between the quasi-static loading phase and the dynamic impact sequence.

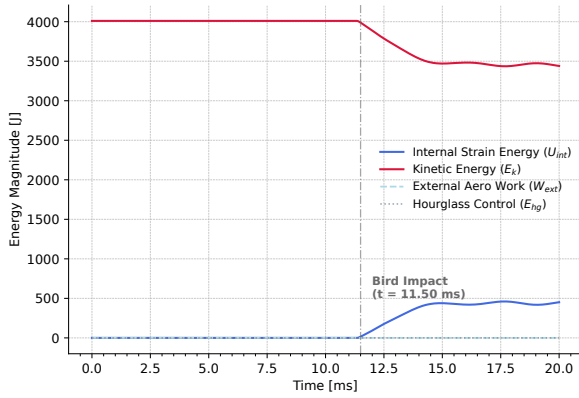


Figure 14: Global energy conservation and transformation history for Case 4, documenting the transition from aerodynamic preloading to projectile impact at $t = 11.50$ ms.

From $t = 0$ ms to 11.50 ms, the system operates within the aerodynamic ramp regime. The internal strain energy (U) scales upward continuously, perfectly balancing the work injected by the fluid-structure load interface (W). During this phase, global kinetic energy (E_k) remains bounded at near-zero baselines, confirming that the loading profile was introduced without triggering premature unphysical explosive shock waves.

5. Conclusions and Outlook

This dissertation has presented a comprehensive numerical investigation into the transient structural response of a high-lift trailing-edge flap assembly subjected to high-velocity soft-body impacts. By connecting decoupled fluid-domain characterizations and explicit structural dynamics, this research successfully established a simulation pipeline to include approximated aerodynamic loads while evaluating structural vulnerability in critical flight phases.

The main milestones and original contributions achieved throughout this research project are summarized as follows:

- **Development of an integrated implicit–explicit coupling pipeline:** established a functional data-transfer and mapping pipeline that imports steady-state aerodynamic pressure fields derived from high-fidelity CFD solvers into an explicit Lagrangian framework (LS-DYNA). This workflow utilizes a quasi-static initialization phase that applies mapped load segments linearly over time, achieving a stable, pre-stressed equilibrium without exciting non-physical transient structural oscillations.
- **Global Load Balance and Mapping Verification:** Developed an automated data-extraction and post-processing pipeline using Python and the LASSO library to audit the fidelity of the load-transfer interface.
- **Contributions to Airworthiness Frameworks:** Provided a scalable, standardized modelling framework using an equivalent benchmark flap geometry structurally analogous to the Airbus XRF1 platform. This decoupled implementation delivers a baseline that may contribute to the aerospace industry’s “Certification by Analysis” guidelines, as it progresses towards the virtual evaluation of emerging airborne hazards under realistic operational stress environments.

While the core numerical pipeline was successfully established and verified, the final simulation matrix encountered technical constraints that limit the range of cross-case comparability. In specific baseline scenarios, most notably the isolated projectile impact without aerodynamic pre-stress, solver termination occurred midway through the event sequence. Consequently, certain time-history data streams and spatial visualization files (`.d3plot`) could not be fully compiled for every proposed simulation of the initial parametric matrix.

These numerical limitations establish a clear, structured roadmap for immediate future work. Employing this validated coupling pipeline within a broader, more highly refined simulation matrix, while also potentially introducing advanced element formulations or material models, will allow future research to generate a more comprehensive set of aero-structural impact visualizations.

5.1. Future Work

Based on the established pipeline and its current limitations, three distinct paths for future research are identified:

1. Advanced Composite Material Models: Transitioning from the current isotropic baseline to high-fidelity CFRP material cards. Furthermore, implementing Cohesive Zone Modelling (CZM) or tie-break contacts will allow researchers to investigate inter-laminar delamination and debonding between the skin and the spars.
2. Higher-Fidelity Fluid-Structure Interaction (FSI): Progressing from one-way sequential mapping to two-way partitioned FSI, where the structural deformation during the impact event actively influences the local aerodynamic pressure field. This includes assessing unsteady aerodynamic effects and gust loads using time-accurate Reynolds-Averaged Navier-Stokes (RANS) simulations to capture the influence of dynamic flow fluctuations on the impact response.
3. Experimental Validation and Correlation: Conducting physical gas-gun experimental tests on representative multi-spar flap segments to validate the numerical damage morphology and strain-time histories obtained in LS-DYNA. This will enable refinement of the SPH bird model through correlation with experimental high-speed imagery to ensure the Hugoniot peak shock pressure (p_H) and steady-state flow phases are captured accurately.

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References

- [1] Elaheh Sabziyan Varnousfaderani and Syed A. M. Shihab. Bird strikes in aviation: A systematic review for informing future directions. *Aerospace Science and Technology*, 163:110303, August 2025. ISSN 1270-9638. doi:10.1016/j.ast.2025.110303.
- [2] John R. Allan. The Costs of Bird Strikes and Bird Strike Prevention. In *Human Conflicts with Wildlife: 2002 Symposium*, Lincoln, Nebraska, USA, August 2000.
- [3] Isabel C. Metz, Joost Ellerbroek, Thorsten Mühlhausen, Dirk Kügler, and Jacco M. Hoekstra. The Bird Strike Challenge. *Aerospace*, 7(3):26, March 2020. ISSN 2226-4310. doi:10.3390/aerospace7030026.
- [4] S. Heimbs, T. Bergmann, D. Schueler, and N. Toso-Pentecôte. High velocity impact on preloaded composite plates. *Composite Structures*, 111:158–168, May 2014. ISSN 02638223. doi:10.1016/j.compstruct.2013.12.031.
- [5] European Union Aviation Safety Agency (EASA). Easy Access Rules for Large Aeroplanes (CS-25), January 2023. URL <https://www.easa.europa.eu/en/document-library/easy-access-rules/online-publications/easy-access-rules-large-aeroplanes-cs-25>.
- [6] Federal Aviation Administration (FAA). 14 CFR Part 25 – Airworthiness Standards: Transport Category Airplanes. URL <https://www.ecfr.gov/current/title-14/chapter-I/subchapter-C/part-25?toc=1>.
- [7] I. Smojver and D. Ivančević. Numerical simulation of bird strike damage prediction in airplane flap structure. *Composite Structures*, 92(9):2016–2026, August 2010. ISSN 02638223. doi:10.1016/j.compstruct.2009.12.006.
- [8] James S. Wilbeck. Impact Behavior of Low Strength Projectiles. Technical Report AFFDL-TR-77-134, US Air Force Flight Dynamics Laboratory, Dayton, Ohio, USA, July 1978.
- [9] Sebastian Heimbs. Computational methods for bird strike simulations: A review. *Computers & Structures*, 89(23):2093–2112, December 2011. ISSN 0045-7949. doi:10.1016/j.compstruc.2011.08.007.
- [10] American Society for Testing and Materials (ASTM). Standard Test Method for Bird Impact Testing of Aerospace Transparent Enclosures. F330-21.
- [11] Society of Automotive Engineers (SAE). Standard Test Method for Measuring Forces During Normal Impact of a Soft Projectile on a Rigid Flat Surface. AS6940, March 2021.
- [12] S. A. Ritt and P. Schimmelpfennig. Goose Type Artificial Bird - CTS Biofidelic Birdstrike Test. In *5. Dummy.Crashtest.Konferenz*, July 2025.
- [13] Alexis Staub. Damage Modelling of Integral Composite Flaps under Bird Strike. Internship Report IB 435 - 2012/24, German Aerospace Center (DLR), Stuttgart, Germany, August 2012.
- [14] German Aerospace Center (DLR). TAU - Unstructured computational fluid dynamics (CFD) solver for aerospace applications in research and industry in Germany and Europe, 2026. URL <https://www.dlr.de/en/as/research-and-transfer/software-solutions/aerodynamics/software-tau>.