

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

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Dedicado aos meus avós Alberto, Alice, e Albina, e à memória do meu avô Apolinário.

Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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Resumo

A certificação de aeronavegabilidade para impacto de aves avalia tipicamente a estrutura num estado livre de tensões, negligenciando as cargas operacionais preexistentes em fases críticas de voo. Esta dissertação aborda esta lacuna através do desenvolvimento de uma ferramenta numérica integrada para investigar a influência do pré-carregamento aerodinâmico na resposta ao impacto a alta velocidade em dispositivos hipersustentadores do bordo de fuga. Para garantir a comparabilidade desta investigação, aplicaram-se simulações numéricas num modelo de flap estrutural e dimensionalmente análogo ao de uma aeronave de grande porte, sob condições de impacto estabelecidas pelas normas internacionais de aeronavegabilidade.

A simulação utiliza um esquema de acoplamento implícito-explícito em LS-DYNA. As distribuições estáticas de pressão aerodinâmica, obtidas através de modelos de dinâmica de fluidos computacional (CFD) de elevada fidelidade, são mapeadas no domínio estrutural e inicializadas através de rampas de carregamento transitórias para estabelecer o estado de pré-esforço antes do impacto. Em paralelo, uma simulação de pré-carregamento estático por relaxação dinâmica serve de validação numérica, garantindo que a inicialização transitória atinge um estado de tensão fisicamente significativo e demonstrando que a abordagem estática constitui uma aproximação válida e mais simples. A subestrutura do flap é governada por um modelo de material elastoplástico para capturar o comportamento estrutural a alta velocidade.

Os resultados obtidos neste trabalho evidenciam que os ambientes operacionais introduzem variáveis determinísticas ausentes nas abordagens convencionais. Isto sugere que as futuras diretrizes virtuais de "Certificação por Análise" devem adotar metodologias aeroestruturais acopladas de modo a garantir uma maior fidelidade.

Palavras-chave: Colisão com Aves, Impacto de Alta Velocidade, Estruturas Pré-carregadas, Modelação em Elementos Finitos, Carregamento Aerodinâmico

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.

The results obtained in this work 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

Contents

Acknowledgments	vii
Resumo	ix
Abstract	xi
List of Tables	xv
List of Figures	xvii
Nomenclature	xix
Glossary	xxiii
1 Introduction	1
1.1 Motivation	1
1.2 Research Context and Case Definition	4
1.3 Objectives	7
1.4 Thesis Outline	8
2 Bird Strike Damage Assessment	9
2.1 Foreign Object Debris	9
2.2 Soft Body Impact Mechanics	12
2.3 Bird Strike Testing	14
2.3.1 Early Experimental Work	14
2.3.2 Testing Methods and Certification Context	16
2.3.3 Avian vs. Surrogate Projectiles	17
2.4 Impact Simulation Modelling	21
2.4.1 Numerical Representation of Soft Body Projectiles	21
2.4.2 Material Models	25
2.4.3 Aerodynamic Static Loading	26
3 Case Implementation and Numerical Modelling	29
3.1 Flap Model Geometry and Numerical Meshing	29
3.2 Preload case	31
3.2.1 Flight Condition and Flow Pressure	33
3.2.2 Aerodynamic Loading via Pressure Mapping	35
3.3 Bird Model	37

3.4	Simulation Software (LS-DYNA)	38
3.4.1	Time Integration Schemes	40
3.4.2	Finite Element Model	41
3.4.3	Solid and Shell Element Formulations	43
3.4.4	Contact Modelling	45
3.4.5	Material Numerical Model	47
3.5	Damage Quantification	49
3.5.1	Geometric Damage Area (A_d)	49
3.5.2	Energy Dissipation and Balance	49
3.5.3	Virtual Strain Gauges and Peak History	50
4	Impact Response Under Aerodynamic Preloading	51
4.1	Problem Definition and Numerical Setup	51
4.1.1	Boundary Conditions	51
4.1.2	Initial Conditions of the Impact Event	52
4.1.3	Contact Formulations and Numerical Controls	52
4.2	Flap Structural Response under Static Aerodynamic Loading	52
4.2.1	Pre-Stress Characterization and Internal Force Mapping	55
4.2.2	Static Pre-load Verification via Dynamic Relaxation	57
4.3	Bird Strike Impact Response	59
4.3.1	Response with Aerodynamic Loading	59
4.3.2	Damage Assessment Summary	61
5	Conclusions and Outlook	63
5.1	Achievements	63
5.2	Future Work	64
	Bibliography	65

List of Tables

1.1	Certification categories relevant for commercial aviation aircraft in Europe and the USA.	5
2.1	Damage level categories with visual examples.	12
2.2	Bird strike requirements by aircraft component per EASA specifications.	16
3.1	Overview of aerodynamic CFD parameters.	34
3.2	Overview of SPH bird model parameters.	39
4.1	Boundary condition constraints at track stations.	51
4.2	Initial conditions for the impact scenario.	52
4.3	Quantitative correlation metrics between static dynamic relaxation (DR) initialization and explicit transient baseline end-state.	59

List of Figures

1.1	Examples of bird strike on aircraft wings	2
1.2	Annual trends in commercial flights and reported bird strikes in the USA (2000-2023). . .	3
1.3	Distribution of bird strikes across documented altitude bands in the USA (1990–2018). . .	3
1.4	Ultrasonic C-scan results of impacted composite plates with different states of preload. . .	4
1.5	Detailed view of the Airbus XFR1 high-lift systems.	6
2.1	Technical evidence from the Concorde Air France flight 4590 investigation.	11
2.2	Illustration of the shock response of a soft body impactor.	13
2.3	Typical pressure curve for a typical soft body impact on a rigid plate	14
2.4	Bird strike testing using a chicken gun (1973)	15
2.5	Schematic representation of a Hopkinson bar.	15
2.6	Artificial bird projectile response to impact on a Hopkinson bar.	18
2.7	Composite high-speed sequence of a bird projectile impact.	19
2.8	Response of a biofidelic surrogate bird projectile to impact.	20
2.9	Response of an ellipsoidal surrogate bird projectile to impact.	20
2.10	Different finite element modelling methods for soft body projectiles.	23
2.11	Schematic overview of SPH bird-strike simulation approach.	24
2.12	Dissimilar meshes for Aerodynamic and Structural Loading.	28
3.1	Detailed view of the Airbus XFR1 flaps.	30
3.2	Section view of the CFRP flap.	30
3.3	FEM model of the CFRP flap.	31
3.4	Detailed view of the FEM mesh structure.	32
3.5	Total aerodynamic force vector.	32
3.6	Side-by-side comparison of baseline CFD pressure distribution and mapped FEM loading. . .	36
3.7	Bird Model in LS-DYNA.	37
3.8	Side and front section views of the SPH bird.	38
3.9	Simplified simulation workflow.	40
3.10	FEM nomenclature	42
3.11	LS-DYNA Solid and Shell elements.	44
3.12	Thickness offsets in LS-DYNA	47

4.1	Global energy components and energy ratio for the aerodynamically loaded trailing-edge flap.	53
4.2	Aerodynamic deformation history of the nodes with the maximum deformation amplitude.	53
4.3	Combined boundary reaction force history.	54
4.4	Deformation history during the transient aerodynamic loading.	55
4.5	Effective von Mises strain history during the transient aerodynamic loading.	56
4.6	Reaction force history over the full 14.95 ms aerodynamic loading.	56
4.7	Comparison between full-detail and simplified aerodynamic loading configurations.	58
4.8	Comparison of static and transient pre-load deflection snapshots.	58
4.9	Global energy conservation and transformation history, documenting the transition from aerodynamic preloading to projectile impact	60
4.10	Total displacement of selected control nodes on the flap surface upon bird strike.	60
4.11	Transient displacement comparison between aerodynamic baseline and impact sequence.	61
4.12	Kinematic displacement bounds for coupled impact case.	62
4.13	Spatial mapping of kinematic tracking nodes on the structural mesh.	62

Nomenclature

Greek symbols

α	Angle of attack
∂b_1	Traction boundary of the spatial domain
∂b_2	Displacement boundary of the spatial domain
∂b_3	Interior boundary
δ	Variational operator representing a virtual change
δ_f	Flap deflection angle
$\delta\pi$	Virtual work variation
δx_i	Virtual displacement vector
$\dot{\epsilon}$	Strain rate
μ_s, μ_d	Coefficient of friction (static, dynamic)
Π^h	Particle approximation operator (SPH)
Π_{ij}	Artificial viscosity matrix (SPH)
ρ	Density
ρ_0	Initial density of soft-body impactor
σ	Cauchy stress tensor
ξ, η, ζ	Parametric coordinates of the parent element domain

Roman symbols

b	Body
c	Chord
C_L	Coefficient of lift
c_0	Speed of sound in elastic medium

C_D	Coefficient of drag
D	Diameter of soft-body impactor
D	Prescribed displacement vector
E_d	Deformation energy
E_k	Kinetic energy
F	Force
f	Body force density
k	Total number of nodes defining an individual finite element
L	Length of a soft-body impactor
M	Aircraft mass
M	Moment
m	Impactor mass
Ma	Mach number
N	Shape or interpolation functions
n	Normal vector
p	Pressure
p_H	Hugoniot pressure
p_S	Steady-flow pressure
q	Dynamic pressure
Re	Reynolds number
S	Wing surface area
s	Current boundary surface
T	Temperature
t	Surface traction vector
t_D	Total duration (soft-body impact)
U	Internal energy
u_0	Impactor speed
u_s	Hydrodynamic shock speed

V	(Aircraft) velocity
V	(Impactor) volume
v	Current spatial volume domain
V_C	Design cruise speed
W	External work
w	Weighting factor
$\ddot{x}$	Material acceleration (FEM)
$\dot{x}$	Material velocity (FEM)
X	Centre of aerodynamic moment (Aerodynamics)
X	Initial material coordinates (FEM)
x	Current coordinates (FEM)
y^+	Wall coordinate (CFD)

Subscripts

∞	Free-stream condition
α	Material (Reference) coordinate indices
c	Contact point (FEM)
flap	Relative to trailing-edge flap
i	Spatial (Current) coordinate indices
i, j	Neighbouring SPH particles
i, j, k	Computational indexes (Einstein notation)
max	Maximum
n	Normal component
ref	Reference condition
x, y, z	Cartesian components

Superscripts

$+/-$	Opposing contact surface interfaces
d	Number of space dimensions (SPH)
h	SPH smoothing length

Glossary

1D	One-Dimensional
AAIB	Air Accidents Investigation Branch
AdViCe	Advanced Methods for Virtual Certification
ALE	Arbitrary Lagrangian-Eulerian
ASSURE	Alliance for System Safety of UAS through Research Excellence
ASTM	American Society for Testing and Materials
AWG	LS-DYNA Aerospace Working Group
BEA	<i>Bureau d'Enquêtes et d'Analyses pour la Sécurité de l'Aviation Civile</i>
CFD	Computational Fluid Dynamics
CFL	Courant-Friedrichs-Lewy
CFR	Code of Federal Regulations
CFRP	Carbon Fibre Reinforced Polymer
CMF	Composite Multi-spar Flap
CS	Certification Specifications
DLR	<i>Deutsches Zentrum für Luft- und Raumfahrt</i>
DLRRAB	DLR Reinforced Artificial Bird
DR	Dynamic Relaxation
EASA	European Union Aviation Safety Agency
EOS	Equation of State
FAA	Federal Aviation Administration
FE	Finite Element
FEA	Finite Element Analysis
FEM	Finite Element Method
FOD	Foreign Object Debris
FSI	Fluid-Structure Interaction
HVI	High Velocity Impact
IB	Outboard
ICAO	International Civil Aviation Organization
LU-SGS	Lower-Upper Symmetric Gauss Seidel
MDO	Multidisciplinary Design Optimization

MTE	Moveable Trailing Edge
NN	Nearest Neighbour
OB	Outboard
OEM	Original Equipment Manufacturer
RANS	Reynolds-Averaged Navier-Stokes
RBF	Radial Basis Functions
SA	Spalart-Allmaras
SAE	Society of Automotive Engineers
SPH	Smooth Particle Hydrodynamics
SSD	Significant Standards Differences
UAS	Unmanned Air Systems
XFR1	eXternal Research Forum

Chapter 1

Introduction

The first documented case of bird strike in aviation dates back to September 1905, when Orville Wright's aircraft "Wright Flyer III" hit a bird while flying over a cornfield near Dayton, Ohio, USA, causing extensive damage to the aircraft but no human casualties. Over a century later, in January 2009, US Airways Flight 1549 witnessed "the miracle on the Hudson", an emergency ditch landing shortly after take-off at New York City's LaGuardia airport that would arguably become the most famous case of bird strike in history. Following a total engine failure caused by impact with a flock of Canada geese during the climbing phase, the pilots decided to glide the aircraft to a ditch landing, with all 155 passengers and crew surviving [1–3]. These incidents highlight the persistent vulnerability of aircraft structures to bird impacts, despite the chronological distance and significant engineering advances in materials and design [4]. 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.

This introduction provides an overview of the research conducted within this thesis. It outlines the motivation behind the study, reviews airworthiness regulations governing impact resilience, and details the specific aero-structural case study chosen for numerical investigation.

1.1 Motivation

Damage caused by collisions between aircraft and smaller foreign objects has posed a hazard since the dawn of aviation. These objects are named Foreign Object Debris (FOD) and can range from meteorological elements, like hail, to runway debris, such as tyre fragments. While this acronym is often used interchangeably in the industry and research literature to also describe the resulting foreign object damage, this thesis distinguishes between debris, the physical impactor, and damage, the structural consequence.

Among these scenarios, the leading cause is collision between an aircraft and a bird: a type of impact known as bird strike, accounting for over 90% of all reported cases of foreign object damage [5, 6]. Federal Aviation Administration (FAA) reports indicate a total of over 310 000 recorded bird strikes

between 1990 and 2024 in the USA or US-registered aircraft [7]. Forward facing aircraft components are particularly prone to such damage, such as the wind shield, radome, fuselage skin and wings, as well as engine fan blades and inlet, a special case named bird ingestion [5]. Figure 1.1 illustrates the structural consequences of a high-energy bird impact, contrasting localized leading-edge deformation (Fig. 1.1a) with a more severe case resulting in full skin penetration (Fig. 1.1b).



(a) Damaged wing leading edge of a BE-200 aircraft after impact with a Canada goose [7].

(b) Damaged wing leading edge of an aircraft (with full skin penetration) after impact with a large bird [8].

Figure 1.1: Examples of bird strike on aircraft wings.

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 the United States, mandatory reporting to the FAA provides a comprehensive time-series that illustrates a persistent upward trend in strike frequency (Fig. 1.2), despite the significant reduction of total flights during the 2020 COVID-19 pandemic. This growth is driven by several factors: growing avian populations, increasing global air traffic density, the deployment of quieter engines, and heightened emphasis on incident reporting [4]. While these incidents are almost always fatal for the bird, historical data indicates that only 6 to 7% of all reported aircraft impacts result in a negative operational effect [9]. Nevertheless, conservative estimates place the economic effects of bird strikes at more than US\$ 2.1 billion per year [10], 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 [9].

Beyond the frequency and economic impact of bird strikes, identifying the specific conditions under which these events occur is essential for risk mitigation. Key factors influencing the occurrence of strikes include altitude, time of day, environmental and seasonal conditions, geographical location, and specific aircraft characteristics [9, 11]. Bird strike events are mostly concentrated at lower altitudes, a distribution shown in Fig. 1.3. Although the overall probability of bird strike steadily decreases with altitude (Fig. 1.3a), a significant increase in the share of damaging bird strikes can be seen after a certain threshold (Fig. 1.3b).

Given that the vast majority of bird strike events occur at low altitudes, the associated structural consequences are highly dependent on the specific flight condition. Most incidents are reported during take-off, initial climb, approach, and landing [8, 12], phases during which high-lift devices are typically deployed. The extension of trailing-edge flaps significantly increases the aircraft's frontal surface

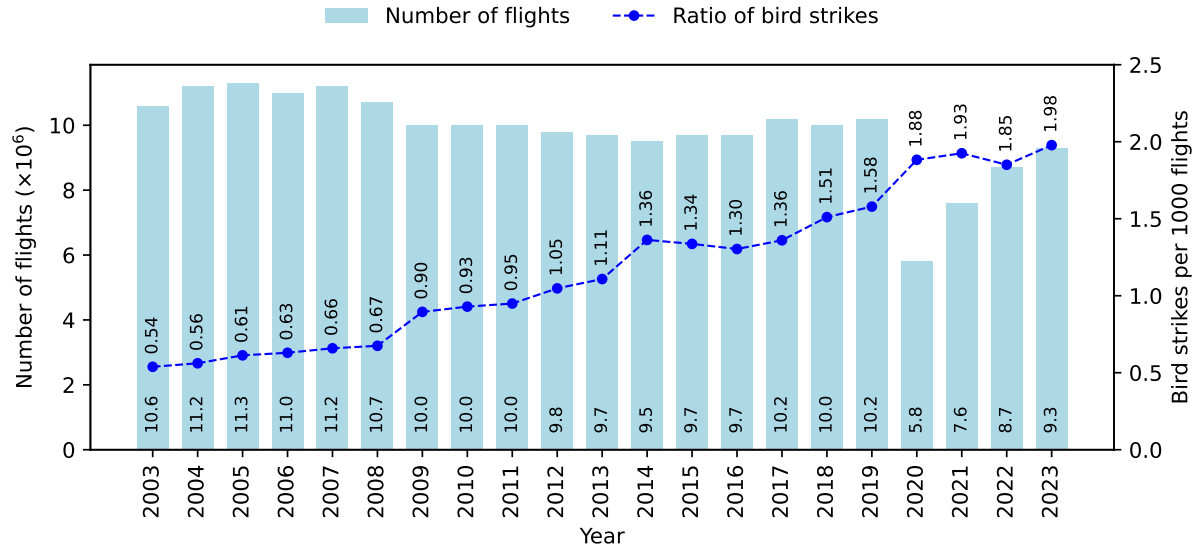


Figure 1.2: Annual trends in commercial flights and reported bird strikes in the USA (2000-2023). Adapted from [4], including data from FAA, US Bureau of Transportation Statistics.

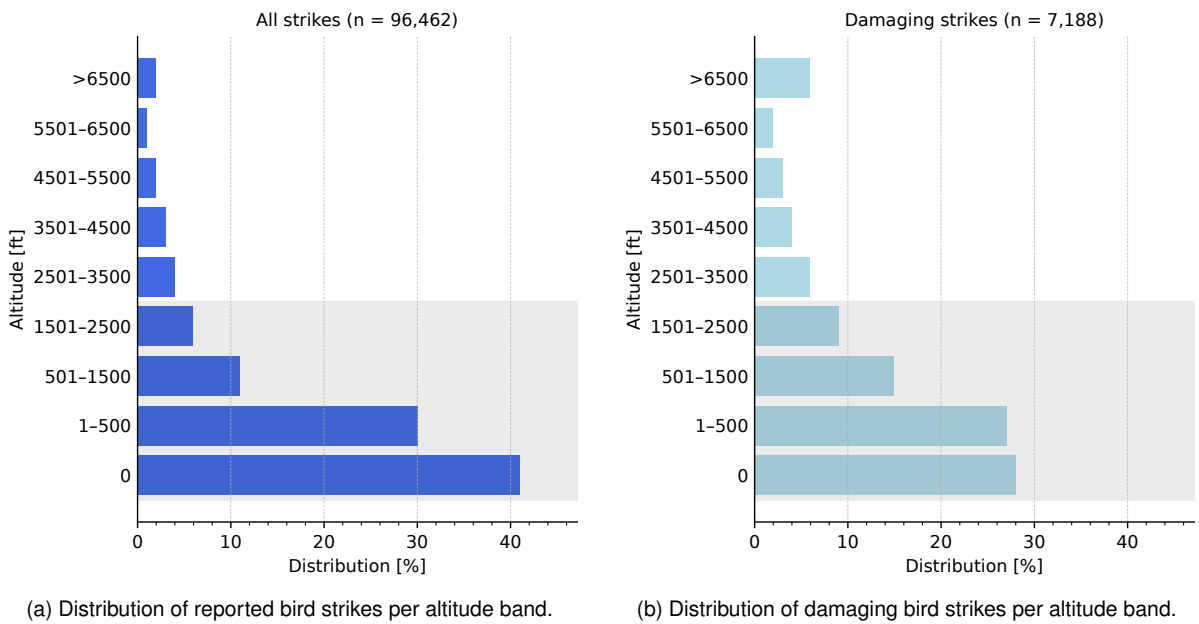


Figure 1.3: Distribution of bird strikes across documented altitude bands in the USA (1990–2018). Adapted from [9].

area, thereby enhancing the susceptibility of these components to bird impacts during these critical flight stages.

Bibliometric analysis of research on bird strike investigations has recently mapped the primary trends and topics across the field [4]. Existing literature is categorized into six major domains, consisting of three descriptive and analytical branches (Statistical Analysis, Bird Strike Impact Analysis, and Bird Strike Simulations) and three preventive and mitigatory branches (Sensors, Bird Movement Modelling, and Preventive/Mitigatory Measures). These domains encompass a diverse range of disciplines, extending from ornithology and statistics for modelling bird populations and migration patterns to control

theory and algorithm design for improving collision-avoidance systems [4]. The identification of 25 research gaps in the literature highlights the ongoing vitality and relevance of bird strike investigation. Among these, enhancing the fidelity of numerical models to better support virtual certification remains a significant priority.

From a structural mechanics perspective, bird strike is a High Velocity Impact (HVI) problem where the target's response depends highly on its initial state. While conventional certification and testing often treat aircraft components as stress-free, literature shows that preloaded structures exhibit a significantly different impact response compared to unloaded structures [13, 14], as seen in Fig. 1.4.

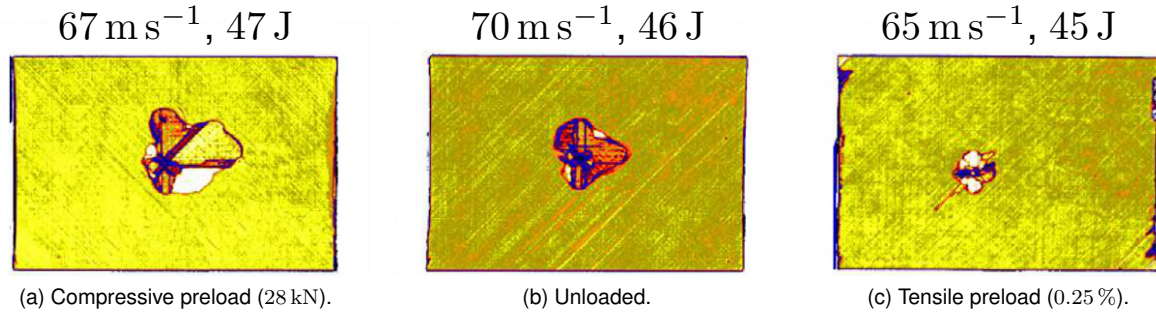


Figure 1.4: Selected ultrasonic C-scan results of impacted composite plates with different states of preload. Results are labelled with projectile impact speed and energy. Adapted from [14].

Experimental and numerical studies have demonstrated that static preloads significantly alter damage propagation, energy absorption, and failure morphology in composite structures. Specifically, tensile preloads can reduce delamination extent by limiting bending deflection, whereas compressive preloads may increase delamination depending on the post-buckling regime [15]. Despite this, aerodynamic loading, the primary source of in-flight pre-stress, is frequently neglected in standard bird strike certification processes. This thesis aims to bridge this gap by investigating the influence of operational aerodynamic loads on the structural response of trailing-edge flaps during a bird strike event.

1.2 Research Context and Case Definition

A significant amount of bird strike modelling research is done in the context of aeronautical certification, such as to satisfy international Certification Specifications (CS) and Code of Federal Regulations (CFR) requirements. This section describes the reasoning behind the case definition and its relationship to ongoing broader research. Details about the definition and characterisation of load cases are further discussed in Chapter 2.

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. In Europe, these airworthiness requirements are laid out by the European Union Aviation Safety Agency (EASA), while in the United States aircraft are certified by FAA regulations. Throughout this thesis, EASA's CS-25 - Large Aeroplanes is used as main reference [16]. In the USA, these requirements are included in FAA's 14 CFR Part 25 [17]. Safety requirements regarding engines (and

the adjacent topic of Bird Ingestion) are, despite some similarities, covered by EASA CS-E, a document beyond the scope of this thesis [18].

Table 1.1: Certification categories relevant for commercial aviation aircraft in Europe and the USA. Adapted from [9].

EASA (Europe)	FAA (USA)
CS-23 Normal Aeroplanes: aeroplanes with a passenger-seating configuration of 19 or less and a maximum certified take-off mass of 8618 kg (19 000 lbs) or less	14 CFR Part 23 Normal Category Airplanes: airplanes with a passenger-seating configuration of 19 or less and a maximum take-off weight of 19 000 lbs or less.
CS-25 Large Aeroplanes: turbine-powered aeroplanes of more than 5700 kg (12 500 lbs) maximum certified take-off weight, excluding commuter airplanes which are covered by the category Normal Aeroplanes	14 CFR Part 25 Transport Category Aircraft: multi-engine airplanes with more than 19 seats or a maximum take-off weight greater than 19 000 lbs.

While extensive harmonization efforts have resulted in largely overlapping requirements, a subset of Significant Standards Differences (SSD) is maintained within the bilateral aviation safety agreements. These differences identify specific areas where one authority's stringency exceeds the other's, potentially requiring additional testing or design changes for an aircraft to achieve global airworthiness.

In the specific context of bird strike resilience, the FAA requirements often serve as the limiting design factor for the empennage. While EASA mandates resilience to a 4 lb (1.8 kg) bird impact for all airframe structures, including the empennage, the FAA specifies a more severe 8 lb (3.6 kg) bird impact specifically for empennage components. Consequently, both agencies compile specific SSD lists to document where compliance with one jurisdiction's regulations does not automatically satisfy the more stringent requirements of the other [19, 20].

Specific requirements for bird strike damage are addressed in EASA CS 25.631 [16] and discussed in further detail in Section 2.3.2. Historically, compliance has relied on rigorous physical testing using either real avian carcasses or surrogate projectiles designed to emulate their mass, geometry, and hydrodynamic behaviour, as discussed further in Section 2.3. Although effective, these experimental procedures are resource-intensive and limit flexibility during the iterative design phases.

In response to these limitations, computational methods in aerospace design have reached a maturity level that offers enhanced cost-effectiveness and development speed. These virtual tools allow for rapid exploration of design configurations and the identification of structural vulnerabilities. According to EASA CSs, compliance may be demonstrated entirely through analysis, provided it is supported by tests on representative structures of similar design [16]. Consequently, contemporary research focuses on complementing or partially replacing physical testing with validated numerical simulations. Ensuring the accuracy and reliability of these methods remains a critical challenge for broader regulatory acceptance. This objective is central to the Advanced Methods for Virtual Certification (AdViCe) project [21], which seeks to promote simulation-based certification by increasing the reliability of numerically generated data. Managed by the *Deutsches Zentrum für Luft- und Raumfahrt* (DLR), the German Aerospace Center, this project leverages expertise across multiple research domains. The present study was con-

ducted within the DLR Institute of Structures and Design, in Stuttgart, which specializes in the impact behaviour of lightweight structures.

Despite the growing maturity of computational impact methods, a significant gap remains in current certification-relevant modelling: the omission of aerodynamic preloading. Although most simulations typically treat structures as initially stress-free, real-world bird strikes occur during flight phases where control surfaces are under substantial aerodynamic loading [22]. This discrepancy is particularly critical for high-lift devices, such as slats (leading edge) and flaps (trailing edge), which are deployed during the low-altitude take-off and landing phases where bird populations are most prevalent.

In these configurations, high-lift devices are tasked with increasing the lift coefficient, C_L , beyond the clean wing maximum, $C_{L_{\max}}$, to enable lower take-off and approach speeds. During take-off, they increase lift and reduce stall speed; during landing, the additional drag produced by the deflected surfaces enables a steeper descent and lower approach speed. Additionally, since most aircraft use partial-span flaps, their deployment modifies the spanwise lift distribution, which further increases lift-induced drag. Therefore, the deployment of these devices subjects them to their most severe aerodynamic loading at the moment where the probability of a bird strike is highest.

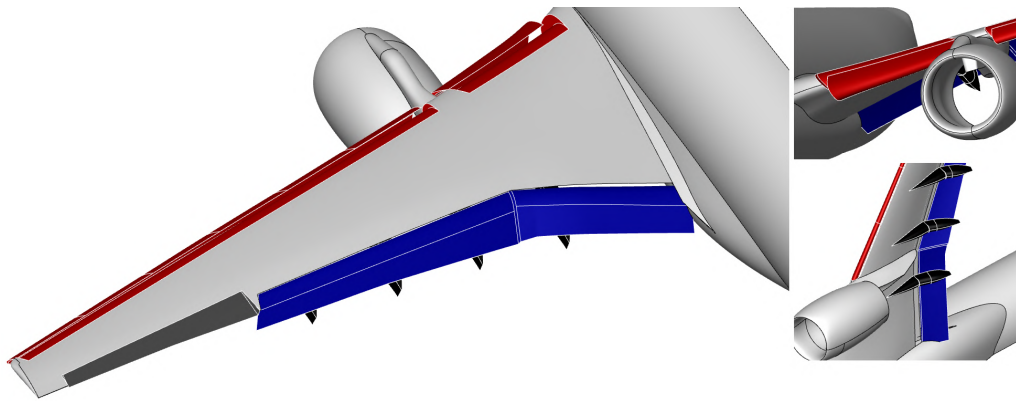


Figure 1.5: Detailed view of the high-lift systems of the Airbus eXternal Research Forum (XFR1): slats (red) and flaps (blue). [23].

Among the various high-lift architectures, the Fowler flap (depicted in blue in Fig. 1.5) represents a relevant case for this thesis due to both its widespread usage and complex kinematic behaviour. Unlike simple hinged surfaces, a Fowler flap achieves lift enhancement through a combination of rearward translation, which increases effective wing area and chord, and downward rotation, which increases camber [24]. As the flap slides along its tracks, a slot is created between the main wing and the flap leading edge, allowing high-energy air to re-energize the boundary layer over the flap, delaying flow separation and maintaining lift at high angles of attack. From a structural standpoint, however, this extension increases the flap's frontal surface area and its vulnerability to bird impact [25], while the resulting slot effect and camber increase generate an increased pressure loading that constitutes the crucial feature discussed in this thesis.

The selection of critical load cases for bird strike analysis is increasingly informed by high-fidelity aerodynamic assessments of the operational flight envelope. Recent research used Computational Fluid Dynamics (CFD) to determine the aerodynamic forces acting on the trailing edge flaps of the

Airbus eXternal Research Forum (XFR1) research aircraft across various flight phases. Although the highest aerodynamic forces occur during landing at maximum speeds, a landing configuration at minimum speed is equally critical due to a significantly larger exposed impact area. These findings [25] provide the technical background for investigating the interaction between high-lift deployment and strike vulnerability in this dissertation.

Building upon this technical reasoning, the focal case study for this dissertation applies a structurally analogous flap model that serves as an equivalent to the inboard trailing-edge flap of the Airbus XFR1 platform. While previous research prioritized the aerodynamic and CFD aspects of this configuration in high-deflection states [25], this study shifts the focus entirely toward a transient Finite Element Method (FEM) evaluation. Configured at a maximum landing deflection, this analogue model serves as the focal case study for the investigation. This choice aims to represent a worst-case scenario from both a geometric and aerodynamic perspective: it offers a significant frontal area for impact while simultaneously generating a highly intense pre-stress during the landing phase. The selected case aims to serve as a reference point for investigating the influence of operational flight environments on resilience to bird strike, establishing a general methodology for an integrated approach to airworthiness certification.

1.3 Objectives

This thesis addresses the following research question: "How does aerodynamic loading influence the impact response of a wing flap?"

The main objective of this work is to analyse how aerodynamic loading affects the impact behaviour of a trailing edge flap representative of a typical commercial aircraft, in a bird strike scenario. In doing so, this study also proposes a framework for computing the aerodynamic loads and their effects in a FEM setting.

To achieve this, the study employs computational simulations to examine the effect of selected structural and loading parameters. The work is organised in the following stages:

- Model a static load on a trailing edge flap, representative of an aerodynamic load in a typical flight condition;
- Characterise the structural behaviour of the trailing edge flap under the preloading;
- Simulate impact of a projectile against the preloaded structure;
- Evaluate and characterise damage to the structure, assessing damage modes and magnitude;
- Assess the influence of different flight conditions or impact variables, comparing against the baseline simple impact case.

Ultimately, this work aims to contribute to the broader effort to improve the reliability of simulation-based predictions for certification-relevant bird strike scenarios.

1.4 Thesis Outline

This thesis is structured as follows:

Chapter 2 establishes the theoretical foundations of this thesis. It begins with a general overview of the different engineering domains involved and introduces the broader context of FOD before moving onto the specific case of high-velocity bird strike events. The chapter then discusses the phenomenon of bird strike across aeronautical certification processes and academic literature, posing the problem through the complementary perspectives of physical experimental testing and numerical simulation to contextualize the framework developed in this work. Considerations about the modelling of aerodynamic loads within a FEM setting are also discussed.

Chapter 3 narrows the discussion to the specific formulation of the case studied in this thesis, detailing the numerical formulation, mesh discretization, boundary conditions, and fluid-structure coupling mechanics of the trailing edge flap assembly studied in this work.

Chapter 4 discusses the different simulated cases of bird strike and compiles the gathered data. This chapter presents visualizations of total deflection and simulated forces on the aeronautical structure, and relates the effects of aerodynamic parameters to these damage metrics.

Finally, Chapter 5 summarises the conclusions drawn from this study, provides a critical analysis of the computational method and the results, and highlights significant achievements. An overview of prospective directions for future work is also provided.

Chapter 2

Bird Strike Damage Assessment

The numerical analysis of bird strike events requires the integration of multiple engineering disciplines, ranging from high-strain-rate structural dynamics to fluid-structure interaction. While frequently driven by the requirements of aeronautical certification, these computational methods serve as fundamental tools for scientific investigation and for reducing reliance on costly physical testing during structural design phases.

This chapter provides a brief historical overview and establishes the theoretical foundations of these core disciplines: specifically, the physics of foreign object debris (Section 2.1), the mechanics of soft-body impact (Section 2.2), the evolution of experimental testing (Section 2.3), and the numerical representation of these impacts (Section 2.4), in order to provide the framework for the subsequent investigation. The modelling of materials is also discussed, with a focus on composite and isotropic materials in aerospace applications. Furthermore, this chapter addresses the incorporation of aerodynamic loading, a parameter that is frequently neglected in conventional impact studies.

2.1 Foreign Object Debris

Foreign object damage refers to any structural or functional impairment of an aircraft resulting from an impact with an external object, collectively termed FOD. Bird strikes represent the most hazardous form of airborne debris, but various other projectiles from both airborne and ground-based origins can compromise aircraft safety. These threats are typically classified by their source: airborne debris includes biological entities, meteorological elements such as hail and volcanic ash, and Unmanned Air Systems (UAS), while ground-based debris may consist of runway gravel, metallic fragments, tyre pieces, or maintenance tools.

The mitigation of these hazards depends significantly on the origin of the debris. Although airborne objects remain largely beyond direct human control, ground-origin damage is substantially reduced through rigorous airfield maintenance and the implementation of comprehensive control programmes. Under the primary oversight of the airport authority, these programmes rely on the cooperation of all airside users, including flight crews, ground-handling agents, and maintenance contractors, to ensure

effective prevention. Aligned with International Civil Aviation Organization (ICAO) standards, such initiatives require systematic inspections, personnel training, and coordinated monitoring [26]. Current regulations require at least one daily daylight inspection of manoeuvring areas, although high-traffic airports often perform multiple surveys per shift using specialized vehicles equipped with high-intensity lighting, high-definition cameras, and detection systems with magnetic bars for the simultaneous collection of metallic fragments.

Regardless of the type of debris, the severity of an impact depends mainly on the kinetic energy of the object, which scales with the square of velocity. Consequently, even small masses can transfer substantial energy when colliding at flight speed. The kinetic energy E_k of a projectile is given by

$$E_k = \frac{1}{2}mV^2, \quad (2.1)$$

where m is the mass, V is the relative velocity of the projectile, which, considering the different orders of magnitude, is usually approximated to the aircraft speed. Since velocity scales quadratically, energy levels increase rapidly with flight speed.

The total kinetic energy of the projectile is, however, not synonymous with the energy available to cause structural damage. To satisfy the conservation of linear momentum for a perfectly inelastic collision, a portion of the initial kinetic energy is retained as residual kinetic energy of the combined aircraft-debris system. The actual energy dissipated through material deformation, fracture, and structural damage, formally known as the deformation energy E_d , is thus expressed as:

$$E_d = \frac{\frac{1}{2}mV^2}{1 + \frac{m}{M}} = \frac{E_k}{1 + \frac{m}{M}}, \quad (2.2)$$

where M is the mass of the aircraft structure.

In scenarios involving commercial transport aircraft, the mass of the aircraft is orders of magnitude larger than the projectile ($M \gg m$). As such, the mass ratio m/M approaches zero, meaning the denominator approaches unity ($1 + \frac{m}{M} \approx 1$). Under these conditions, virtually 100% of the projectile's relative kinetic energy is converted into structural deformation ($E_d \approx E_k$).

For comparison, a large bird with a mass of 3.6 kg impacting a structure at 250 m s^{-1} releases an energy exceeding 100 kJ, roughly equivalent to that of a small car collision, concentrated over a few square centimetres and a few milliseconds. Such levels of transient loading can easily puncture thin skins or initiate delamination in composite structures.

A significant instance of ground-origin FOD is the 2000 Concorde accident at Paris Charles de Gaulle Airport [27]. During take-off, the aircraft's landing gear encountered a metal strip (Fig. 2.1a) that had fallen from a preceding aircraft. The resulting high-pressure tyre burst (Fig. 2.1b) projected a large rubber fragment against the underside of the wing. Although the fragment did not penetrate the wing skin, the high-energy impact generated a hydrodynamic shock wave within the internal fuel tank, leading to a structural rupture and catastrophic fire. All 109 occupants died, and the Certificates of Airworthiness for Concorde were suspended following the independent investigation by France's *Bureau d'Enquêtes et d'Analyses pour la Sécurité de l'Aviation Civile* (BEA) and the United Kingdom's Air Accidents Investiga-

tion Branch (AAIB). The investigation concluded that this fragment weighing less than 1 kg initiated the sequence, highlighting the extreme vulnerability of thin-walled aero-structures to high-velocity foreign object impacts.



Figure 2.1: Technical evidence from the Concorde Air France flight 4590 investigation, illustrating the primary FOD and the reconstructed damage initiation sequence [27].

In addition to biological threats, the proliferation of small UAS near airports over the last decades has introduced a distinct category of airborne hazard. While the kinetic energy of a small drone may be comparable to that of a medium-sized bird, the structural consequences of an impact differ significantly due to the presence of rigid, high-density components such as lithium-polymer batteries and electric motors. Unlike the soft-body hydrodynamic behaviour of avian tissue, these elements act as rigid impactors that do not dissipate energy through fluid-like spreading [28]. Consequently, UAS collisions are characterised by higher peak forces and more localised structural penetration, presenting a considerably different challenge compared to traditional bird-strike certification standards.

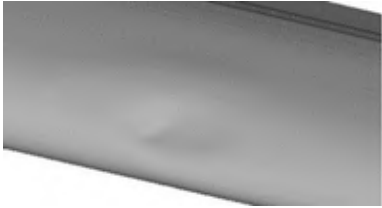
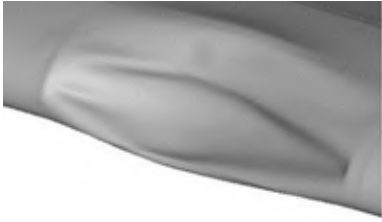
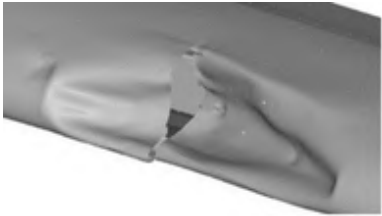
To address and mitigate these unique risks, the EASA Drone Collision Task Force outlines a strategy based on developing validated analytical models for drone components, conducting specialized risk assessments for lithium battery hazards, and establishing impact severity thresholds for critical aircraft structures [28].

To standardize the assessment of these collision events, the Alliance for System Safety of UAS through Research Excellence (ASSURE), the FAA's Center of Excellence for UAS Research, developed a classification system for aircraft-to-UAS impact damage [29]. This framework, summarized in Tab. 2.1, categorizes the severity of the interaction based on the resulting structural integrity:

Level 1 corresponds to a minimal amount of localized damage. Level 2 represents significant visible damage to the external surface of the aircraft with some internal component damage but with no appreciable skin rupture. Level 3 describes impact events where the outer surface of the aircraft is compromised in a way that could allow ingress of foreign objects into the airframe, with some damage to substructure. Finally, Level 4 indicates damage that includes all of the preceding aspects as well as extensive damage to internal components and possibly compromising damage to primary structure.

From an engineering standpoint, the transition from Level 2 (surface damage) to Level 3 (structural penetration) represents a critical threshold in airworthiness. In bird strikes, this transition is often driven

Table 2.1: Damage level categories with visual examples. Adapted from [29].

Severity	Description	Example
Level 1	• Airframe undamaged. • Small deformations.	
Level 2	• Extensive permanent deformation. • Some deformation in internal structure. • No failure of skin.	
Level 3	• Skin fracture. • Penetration of a least one component into the airframe.	
Level 4	• Penetration of UAS (FOD) into airframe. • Failure of primary structure.	

by the total kinetic energy exceeding the material's rupture strain over a wide area. For the trailing-edge flaps considered in this work, this penetration threshold is not static, as the presence of aerodynamic preloading creates a pre-existing stress state in the composite skin and substructure. Consequently, understanding the interaction between these external loads and the impact event is vital for predicting whether a given strike will result in a manageable Level 1-2 repair or a flight-critical Level 3-4 failure.

2.2 Soft Body Impact Mechanics

The structural response during a bird strike is determined by the projectile's behaviour, which is classified into five categories based on impact velocity: elastic, plastic, hydrodynamic, sonic, or explosive [30]. In an elastic collision, internal stresses remain significantly below the material strength of the projectile, resulting in a rebound governed by a coefficient of restitution. As velocity increases, plastic deformation initiates until internal stresses exceed the projectile's ultimate strength, causing it to behave in a manner analogous to fluid flow. In this hydrodynamic regime, the impactor response is governed by

material density rather than structural stiffness. Given the typical velocities involved in aeronautical bird strikes, the impact occurs within this hydrodynamic domain, where the bird is treated as a soft body due to internal stresses overwhelming its inherent material strength. Further increases in velocity would take the impactor response into sonic or explosive regimes, out of the scope of the bird strike problem.

An impact in the hydrodynamic regime is described by four main stages [31], as depicted in Fig. 2.2: Initial shock at contact, shock decay, steady flow, and pressure decay.

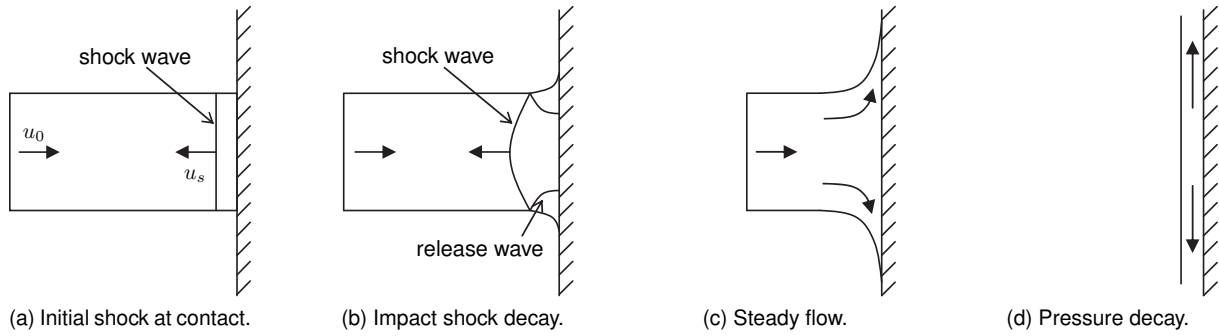


Figure 2.2: Illustration of the shock response of a soft body impactor. Adapted from [5].

Approximating the impactor as a cylinder, the flow across the generated shock can be considered One-Dimensional (1D), adiabatic, and irreversible: when the impactor, travelling at velocity u_0 , strikes a rigid surface (Fig. 2.2a), the material at the contact point is brought almost instantaneously to rest, which generates a shock wave propagating into the projectile at velocity u_s , with its front oriented parallel to the target surface and travelling perpendicular to it [32].

This creates a strong pressure gradient develops at the impact interface between the shocked material and the free outer surface of the projectile. This gradient accelerates material outward, forming a release wave that travels back toward the centre of impact and interacts with the incoming shock wave. As a result, the very high initial pressure peak at the centre of contact, the Hugoniot pressure p_H ,

$$p_H = \rho_0 c_0 u_0 , \quad (2.3)$$

where ρ_0 is the initial density of the projectile and c_0 is the speed of sound in the elastic medium, lasts only a fraction of a microsecond. After repeated reflections of these release waves, the flow within the projectile evolves toward a quasi-steady state (Fig. 2.2c), characterised by approximately constant pressure, p_S , and particle velocity.

This steady-flow pressure p_S can be estimated by the Bernoulli relationship,

$$p_S = \frac{1}{2} \rho_0 u_0^2 , \quad (2.4)$$

and the total duration, t_D , of the impact can be approximated by the time taken by the projectile to traverse its own length L :

$$t_D = \frac{L}{u_0} . \quad (2.5)$$

During the steady-flow phase, the shock wave is progressively weakened by successive release-wave interactions until both the projectile and its pressure trace decay to zero (Fig. 2.2d). A typical pressure-time history for such an impact is shown in Fig. 2.3, where the initial peak corresponds to the Hugoniot pressure.

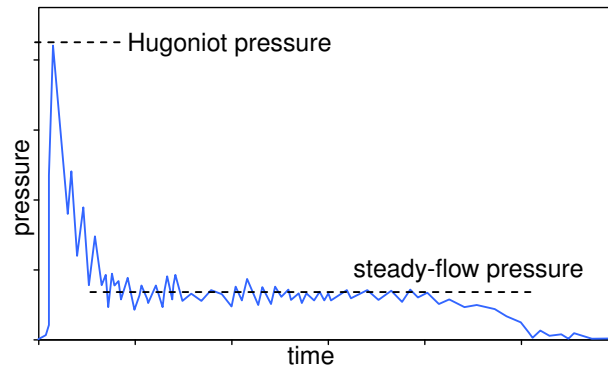


Figure 2.3: Typical pressure curve for a typical soft body impact on a rigid plate, highlighting the transient Hugoniot peak pressure and the subsequent steady-state stagnation phase. Adapted from [5].

The establishment of a steady-flow regime depends on the length-to-diameter ratio of the projectile. For very short impactors, the event concludes before steady flow development; therefore, a ratio of around 2 is generally recommended for representative testing.

2.3 Bird Strike Testing

Empirical evidence is needed to translate the statistical hazards of bird strikes into measurable metrics and airworthy structural designs. While the aerospace industry is increasingly moving toward certification by analysis, physical testing continues to be the primary method for demonstrating compliance with EASA and FAA requirements [33]. In addition to validating certification, these tests also serve the dual purpose of providing data for calibrating and validating numerical models for research purposes.

2.3.1 Early Experimental Work

The origins of systematic bird strike testing date back to 1942, with pioneering investigations conducted by the predecessor of the modern-day FAA. Early research focused predominantly on aircraft transparencies (windshields), which were identified as the most safety-critical components due to their exposure and role in maintaining pilot visibility. Statistical data from 1950 confirmed this vulnerability, showing that approximately one third of the 473 documented strikes at the time occurred on the windshield area [34].

The technical foundation for modern testing was established through the development of the compressed-air chicken gun (Fig. 2.4). This device allowed for the acceleration of bird projectiles to representative flight velocities, with structural responses captured on film and early wire-break measurement systems.

A significant inflection occurred in the 1970s with the characterization of bird material as a low-strength, fluid-like projectile during high-velocity impacts. Methodologies were developed to launch

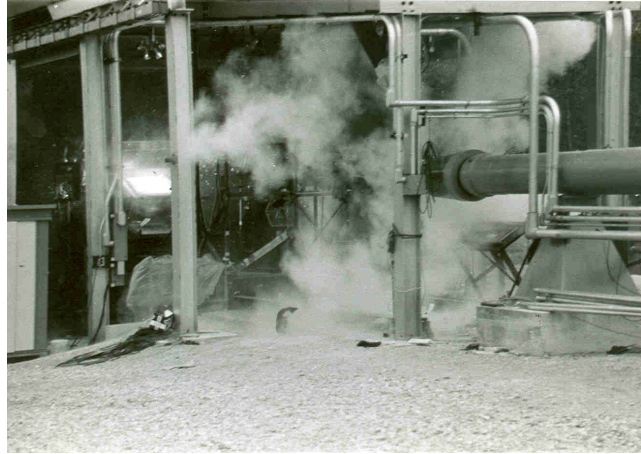


Figure 2.4: Bird strike testing using a chicken gun (1973). [Source: US Air Force]

projectiles at velocities up to 350 m s^{-1} against rigid flat aluminium plates to isolate the pressure-time histories of the impact [35], generating an extensive dataset which served as empirical basis for the analytical and numerical models that followed.

While earlier studies prioritized structural damage, research later shifted significantly toward the hydrodynamic behaviour of the projectile itself. This involved validating unsteady hydrodynamic models against various biological and synthetic materials to ensure the projectile strength was negligible compared to the generated impact pressures. These experiments established that 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 [36]. To further quantify these highly transient forces, experimental setups used Hopkinson bar measurements to derive non-dimensionalized total force-time histories [31].

The core measurement principle of the Hopkinson bar transducer configuration (Fig. 2.5) relies on the assumption that a soft-body projectile striking the axial face of the bar generates a purely one-dimensional, planar, compressive elastic wave within the medium [37]. Isolating this wave allowed for the early identification of a classic four-stage impact process, initiated by a high-pressure shock phase governed by Hugoniot relations, as explored in Section 2.4.

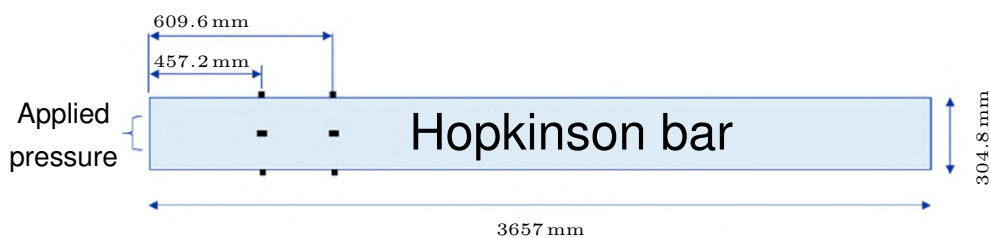


Figure 2.5: Schematic representation of a Hopkinson bar with locations of strain gauges. Adapted from [37].

Critically, these studies demonstrated that while the temporal and spatial distribution of impact pressure scales linearly with bird dimensions, the magnitude of the peak pressure is independent of bird mass and primarily dependent on impact velocity and material density [38]. This finding remains a

cornerstone of bird strike modelling, and justifies the use of standardized surrogate projectiles across different mass categories.

However, the widespread reliance on these legacy datasets for numerical benchmarking has been subject to scrutiny. Critical reviews indicate that the piezoelectric quartz sensors used in the original experiments lacked adequate acceleration compensation and possessed a resonance frequency of approximately 300 kHz [5]. These instrumental limitations likely introduced unphysical oscillations and overshoots into the historical pressure-time curves. Furthermore, uncertainties regarding experimental parameters, such as the exact gun-to-target distance and the deformation state of the projectile at the moment of impact, require a cautious approach when using these early quantitative results for modern high-fidelity validation.

While physical testing dominated the first decades of bird strike research, the late 20th century saw the first attempts toward digital prediction. A pivotal development in this shift was the implementation of explicit finite element techniques capable of resolving non-linear material behaviour and high-rate structural dynamics [39]. This computational advance allowed researchers to directly model the impacting body within the finite element framework. Crucially, these early analytical methods introduced advanced treatments for laminated shell constructions, enabling the simulation of multi-layered aircraft transparencies without the need for discrete element modelling of every interlayer. This established the foundation for modern virtual certification, demonstrating that numerical simulations could accurately reproduce standard test problems and complex airframe interactions, such as those observed in F-16 bird strike events.

2.3.2 Testing Methods and Certification Context

Bird-strike tests are conducted both for scientific research and for aircraft certification. The certification standards mentioned in Section 1.2, EASA CS-25 and FAA 14 CFR Part 25, do not prescribe a specific test setup, but rather define the required outcome: critical components, such as windshields, leading edges, and empennage surfaces, must withstand impacts of specified bird masses at representative flight velocities, ensuring continued safe flight and landing. Consequently, industry practice relies on the well-established gun-test setup to reproduce these impacts under controlled conditions.

The EASA certification documents specify different requirements for each part, those of which that apply to bird strike are summarized in Tab. 2.2.

Table 2.2: EASA bird strike requirements by aircraft component [16], adapted from [9].

Aircraft Component	EASA Requirement
Windshield	Required to withstand the impact of a 4 lb (1.8 kg) bird at operational speed without penetration (CS 25.775, 25.631).
Empennage and Wing	In case of penetration, no critical damage may be introduced, assuring a continued safe flight and landing after impact. Compliance has to be proven for 4 lb (1.8 kg) birds impacting all the structure, including the wing (CS 25.571, 25.631).

- **Velocity:** Components must withstand the impact of a specified bird mass at the most critical velocity between the design cruise speed, V_C , at sea level, or $0.85 \cdot V_C$ at 8000 ft.
- **Mass:** Ranges from 1.8 kg (4 lb) for general airframe structures to 3.6 kg (8 lb) for empennage surfaces.

The usual experimental setup (Fig. 2.4) uses a gas cannon and a sabot, a lightweight carrier that seals the barrel and protects the projectile's geometry during acceleration. Just before impact, the sabot is stopped by a stripping mechanism, allowing the bird to continue toward the target in free flight. Modern instrumentation typically includes high-speed video, strain gauges, and piezoelectric transducers.

Although authorities such as EASA and FAA define high-level airworthiness requirements, the practical standardization of these compliance tests relies on technical protocols formalized by organizations such as the American Society for Testing and Materials (ASTM) and the Society of Automotive Engineers (SAE). Specifically, the ASTM F330 serves as the primary standard for the structural certification of aerospace transparencies [40]. The standard prescribes a smooth-bore compressed-gas gun to fire a domestic chicken carcass at velocities exceeding 334 m s^{-1} (650 kt).

In contrast, SAE AS6940 provides a specialized methodology for the quantification of impact forces, serving as the foundation for modern certification by analysis [41]. Recognizing that standard transducers often fail to capture the transient high-frequency shock phase of a soft-body impact, this standard employs the previously discussed Hopkinson bar. In this configuration, the aluminium bar acts as a precision force transducer, using high-sensitivity semiconductor strain gauges affixed to its surface to record the passing elastic wave and back-calculate a precise force history.

Because these strain transducers must be located relatively close to the impacted face of the bar to minimize wave dispersion, questions have historically been raised regarding whether the assumption of true one-dimensional wave propagation holds before the stress state fully uniforms across the cross-section. However, recent numerical and experimental research has successfully validated this configuration [37]. Their findings confirm that for the transient frequencies expected in bird impacts up to operational velocities of approximately 300 m s^{-1} , the large-diameter Hopkinson bar test provides an acceptable method for measuring impact forces and directly comparing the hydrodynamic response of real and surrogate avian projectiles, through tests such as that represented in Fig. 2.6 [37].

2.3.3 Avian vs. Surrogate Projectiles

Discussions surrounding the choice of projectile revolve around the trade-off between biological fidelity and experimental repeatability. Traditional certification tests for aircraft components use real birds, most commonly dead or sedated chicken and ducks. In fact, ASTM F330 prescribes the use of real bird carcasses, ensuring that the heterogeneous anatomical structure (bones and internal tissue) of the actual threat is represented [40].

Conversely, SAE AS6940 highlights the role of physical surrogates, named simulants, in developing repeatable scientific datasets [41]. Because biological carcasses introduce significant variability in density and geometry, simulants like gelatin or soft polymers are often preferred for research and model

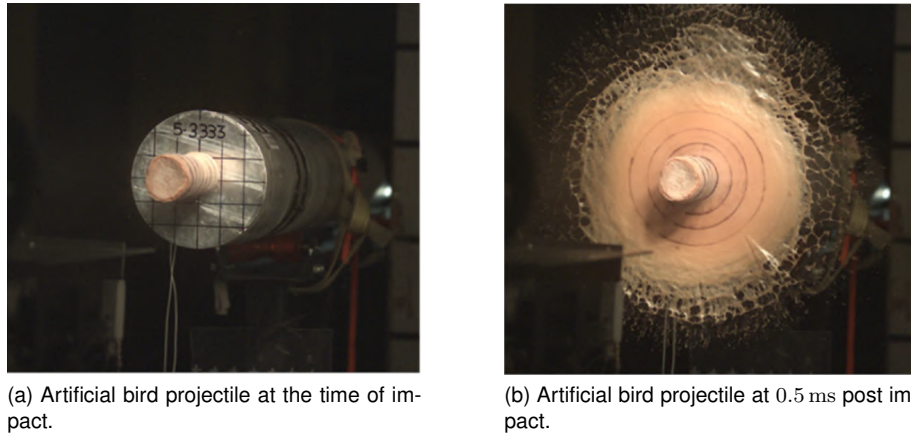


Figure 2.6: Artificial bird projectile response to impact on a Hopkinson bar. Adapted from [37].

validation. A critical feature of this high-fidelity testing is the measurement of the breakup pattern after impact. Using high-speed photography to track the radial spread of debris across a reference grid, researchers can quantify the overall area and average velocity of the fragmented material. This data provides an important benchmark for Smooth Particle Hydrodynamics (SPH) simulations, in that comparison allows the numerical particles to replicate the correct momentum transfer and spatial distribution of the real impact event.

Avian Projectiles

The use of real birds as projectiles offers the clear advantage of biological fidelity, since their heterogeneous composition and anatomical structure closely resemble the actual threat. However, this approach comes at the expense of both repeatability and representativeness. Since airworthiness certification standards specify only the nominal projectile mass (such as the standard 4 lb or 8 lb requirements) rather than bird species or precise dimensions, substantial variability is introduced into the experiment, which in turn has a significant influence on the local pressure distribution and damage patterns. The irregular shape of the bird also complicates aiming accuracy, making it difficult to ensure that the impact occurs precisely at the intended location [33].

To control these variations, real bird projectiles must be rigorously packaged and accommodated according to guidelines such as ASTM F320 [40]. This protocol prescribes the biological carcass to be enclosed within a specialized carrier, known as a sabot. This packaging serves a dual purpose: it seals the gun barrel to maintain uniform pressure distribution during gas expansion, while stabilizing the flexible carcass during the rapid acceleration phase. Upon exiting the gun, the sabot is mechanically arrested or deflected by a sabot stripper, allowing only the avian projectile to proceed forward.

Additionally, the preparation of the biological tissue introduces other types of constraints. Carcasses must be flash-frozen shortly after death to prevent decomposition, which alters its shear strength and viscosity. The subsequent thawing process must be monitored with high precision, since incomplete thawing may leave a solid ice core within the projectile, artificially turning the localized impact forces into a hard-body regime rather than hydrodynamic fluid spreading. However, overheating or multiple freeze-

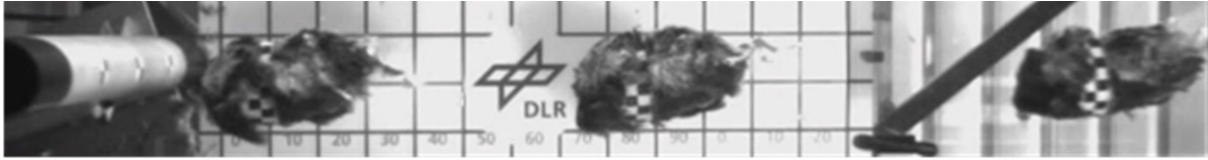


Figure 2.7: Composite high-speed camera sequence illustrating the trajectory and free-flight state of a bird projectile prior to target impact [42].

thaw cycles degrade cellular walls and drastically reduce the stagnation pressure generated during the initial shock impact.

These logistical limitations, along with the search for data repeatability in testing, highlight why contemporary aerospace research focuses on replacing biological carcasses with validated synthetic surrogates.

Surrogate Projectiles

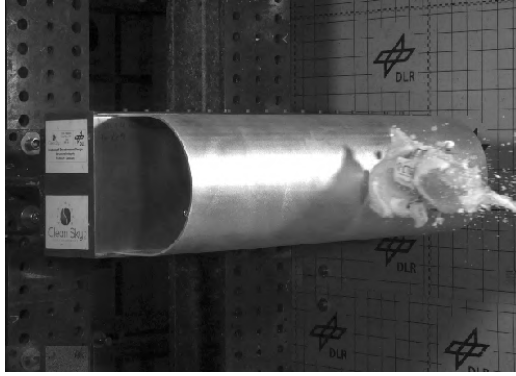
In practice, these drawbacks have led to the increasing adoption of artificial birds, generally made of gelatin or water–gel mixtures tuned to match the density ($\rho \approx 950 \text{ kg m}^{-3}$) and mechanical response of real avian tissue [36]. The use of standardised artificial birds brings several advantages: improved reproducibility of results, easier handling and storage, lower cost, and the elimination of ethical concerns associated with sedating or euthanising animals for testing [33].

Despite the recognised advantages of using artificial bird projectiles, a universally accepted standard dummy bird has yet to be established, although recent initiatives have moved toward greater harmonisation. Several formulations for synthetic birds exist across institutions and manufacturers, but these have not been systematically validated over a broad range of impact conditions. Their variability relative to real birds remains insufficiently quantified and, as a result, such surrogates are not yet approved as full replacements for real birds in certification testing by regulatory bodies such as the EASA and FAA.

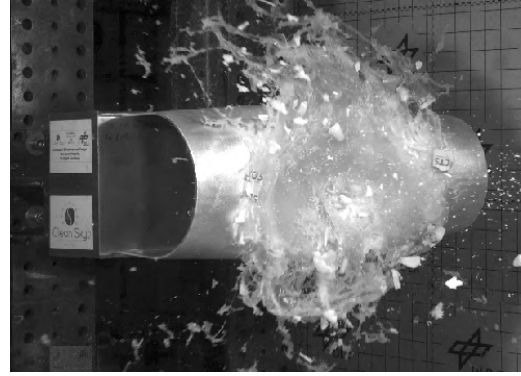
In practice, the development of these artificial projectiles is governed by two fundamentally distinct architectural philosophies, each presenting a unique trade-off between geometric fidelity and numerical repeatability [42].

Biofidelic Projectiles: This approach seeks to replicate the internal macro-structural heterogeneity of a real bird. These impactors feature moulded ballistic gelatin to represent muscle tissue and integrated polyamide or composite inserts to simulate the rigid mechanics of bones, and artificial internal cavities to emulate the lungs and air sacs. Certain biofidelic models are often tailored to represent specific avian species profiles, such as geese or chicken [43]. However, this high structural fidelity may reintroduce the same experimental difficulties of the real bird case: localized manufacturing tolerances can cause asymmetry in the internal mass distribution, altering the projectile orientation and lowering aiming accuracy during deployment.

Simplified Geometries (e.g. Ellipsoidal): On the other hand, the vast majority of bird strike testing applications prioritize geometric abstraction to maximize mathematical and experimental repeatability.



(a) Biofidelic projectile at the time of impact.



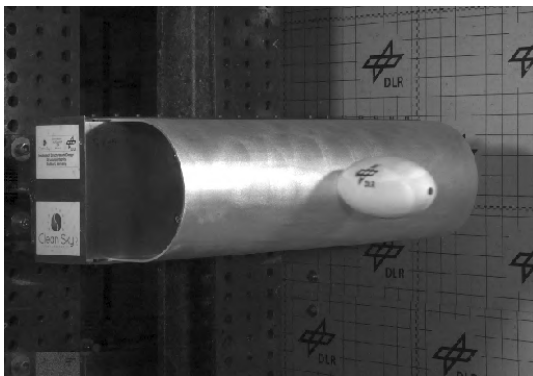
(b) Biofidelic projectile briefly after the time of impact.

Figure 2.8: Response of a biofidelic surrogate bird projectile to impact. Adapted from [44].

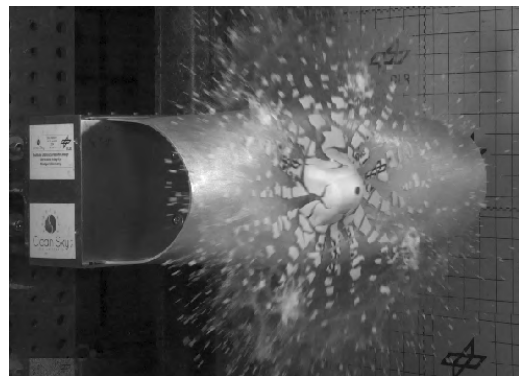
Here, the surrogate is manufactured as either a perfectly homogeneous, flat- or hemispherical-ended cylinder, or an ellipsoid. These projectiles allow to isolate the structural response of the target from variability. Comparative experimental studies have demonstrated that despite its geometric simplicity, the standard ellipsoidal projectile provides a valid approximation of the total integrated force history and momentum transfer generated by biological tissue, validating its usage as a highly effective baseline for parametric structural sweeps [42, 45].

Ultimately, both philosophies maintain distinct uses within the ecosystem of aerospace structural certification. While biofidelic surrogates allow investigating more complex, localized failure modes, simplified ellipsoidal geometries remain the superior choice for numerical sensitivity studies, such as evaluating the macro aero-structural behaviour of preloaded trailing-edge flaps.

The computational bird model used in this work is based on one of such ellipsoidal formulations, the DLR Reinforced Artificial Bird (DLRRAB).



(a) Ellipsoidal projectile at the time of impact.



(b) Ellipsoidal projectile briefly after the time of impact.

Figure 2.9: Response of an ellipsoidal surrogate bird projectile to impact. Adapted from [44].

2.4 Impact Simulation Modelling

Bird strike simulations are one of the main load cases which use Finite Element Analysis (FEA) in aeronautics, along with water ditching or drop tests for crashworthiness [5]. This section reviews numerical approaches used to analyse soft-body impacts on aircraft structures and how they complement or reduce the need for testing. Emphasis is placed on methods applicable to deformable bird-like projectiles and airframe components, including material modelling. The section closes by outlining how static aerodynamic loads are incorporated as preloads prior to impact.

The use of numerical simulation as a primary or exclusive means of certification is currently a maturing field. A notable example is the certification of the Moveable Trailing Edge (MTE) of the Boeing 787 Dreamliner, reported by researchers from Hawker de Havilland, then the sole supplier [46]. Their work demonstrated an improved certification approach that relied almost entirely on computational methods, without directly employing testing or semi-empirical formulations, achieving “dramatic improvements in bird-strike resistance” while reducing some of the excessive conservatism of traditional design rules.

Numerical investigations into the bird strike resilience of wing components have previously focused on the damage prediction of trailing-edge flap structures using Lagrangian formulations [22]. This study established methodologies for predicting failure in composite skins and honeycomb cores, highlighting the catastrophic potential of energy transfer in sandwich constructions. While providing a proven framework for assessing internal structural damage and material failure modes, these models typically represent the impact event in a stress-free state, omitting the operational aerodynamic loads that characterise real-world flight phases.

Simulating a bird strike presents several additional challenges. The deformable nature of the projectile makes it a Fluid-Structure Interaction (FSI) problem, requiring the impactor to be modelled as a fluid rather than as a solid body. Representing this behaviour accurately is essential for studying pressure propagation and structural response, as discussed in Section 2.4.1. Further complexity arises from the use of composite materials in modern aircraft structures: unlike metallic components with well-defined plastic behaviour, composites exhibit multiple damage mechanisms, such as matrix cracking, fibre failure, and delamination, which must be represented through suitable material models and failure criteria (Section 2.4.2). Finally, the present study introduces an additional level of coupling by incorporating a static aerodynamic preload prior to impact. This requires transferring distributed pressure fields from aerodynamic simulations onto the finite element model, a process described in Section 2.4.3.

2.4.1 Numerical Representation of Soft Body Projectiles

For several decades, numerical simulations have complemented and replaced physical testing with both biological and surrogate impactors, offering a highly efficient and repeatable framework. Extensive reviews of the research literature [5, 32] demonstrate that despite significant advancements in soft impactor modelling, the field remains characterized by distinct methodological approaches. These branches differ primarily in the numerical representation of the projectile, which range from classical Lagrangian formulations to meshless methods, as well as regarding the coupling strategies on the inter-

action with the rigid structure.

The numerical representation of a soft body projectile and its interaction with a target structure can be categorized into two primary families: mesh-based and meshless methods. Each approach offers distinct advantages and limitations regarding computational cost, mesh stability, and the ability to capture large material deformations.

Traditionally, the aerospace industry has relied on mesh-based formulations where the physical domain is discretized into a network of finite elements. These are further divided based on the relationship between the computational grid and the material motion:

- **Lagrangian Formulation:** The mesh is fixed to the material and deforms with it (Fig. 2.10a). While excellent for tracking structural boundaries and representing solid materials, it is highly susceptible to element inversion and negative volume errors during the extreme distortions characteristic of bird strikes.
- **Eulerian Formulation:** The mesh remains fixed in space while the material flows through the elements (Fig. 2.10b). This eliminates mesh distortion issues but complicates the tracking of the projectile-target interface.
- **Arbitrary Lagrangian-Eulerian (ALE):** A hybrid approach where the mesh can move independently of the material (Fig. 2.10c). ALE aims to combine the boundary-tracking precision of Lagrangian methods with the distortion-handling capabilities of Eulerian solvers, though it often incurs a higher computational cost and increased algorithmic complexity.

To overcome the inherent restrictions of a pre-set grid, mesh-free approaches represent the domain through a collection of points or particles (Fig. 2.10d). By using interpolation functions to estimate solutions between nodes, these techniques handle complicated geometries and fragmentation without the need for remeshing or mesh-matching at the interface. Among these, SPH has emerged as the most widely used alternative for high-strain-rate fluid-structure interactions, offering a computationally effective complement to traditional FEA.

Smooth Particle Hydrodynamics (SPH)

SPH is a meshless Lagrangian particle method widely adopted to overcome the limitations of other models. Originally developed for astrophysical problems in 1977 [47], SPH has evolved into a standard tool for continuum mechanics involving fluid-like behaviour and high-strain-rate structural dynamics. This method is commonly favoured in bird strike research since it allows to model extreme distortions while eliminating material interface problems [46]. Since it is a Lagrangian technique, SPH can be linked to standard FEM formulations.

The adoption of meshless methods, namely SPH, is supported by parametric studies demonstrating their ability to capture the fluid-like behaviour of avian projectiles [48]. Research in this area has shown that the structural response of the target is highly sensitive to the initial state of the projectile, specifically regarding impact orientation (pitch and yaw) and the precise calibration of contact algorithms. These

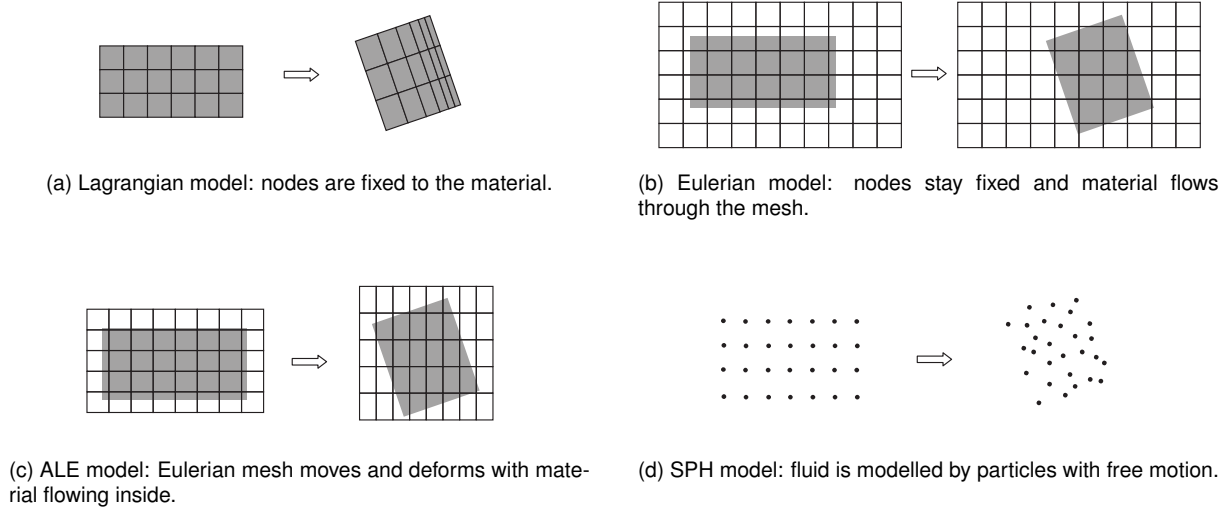


Figure 2.10: Different finite element modelling methods for soft body projectiles. Adapted from [5].

findings highlight the need for high-fidelity modelling to capture the non-linear pressure distributions and energy absorption variations that occur during the milliseconds of duration of a soft-body impact.

In addition, comparative studies between traditional Lagrangian solvers and meshless methods have validated the effectiveness of SPH for bird strike on hybrid wing leading edges, demonstrating that particle-based approaches are superior in capturing the high-speed interaction and subsequent disintegration of the projectile upon hitting multi-layered targets [49]. These investigations, validated against experimental datasets involving large avian masses, promote the adoption of SPH as a reliable numerical tool for the virtual certification of composite airframe components [49].

The core philosophy of SPH is based on the interpolation of field variables over a set of discrete points, known as particles, which carry material properties such as mass, velocity, and internal energy, as opposed of a solid element mesh. To ensure consistency with the numerical implementation used in this study, further discussed in chapter 3, the mathematical framework and notations presented in this section adhere, when possible, to the conventions established in the LS-DYNA Theory Manual [50], while also following other sources [51].

SPH is built upon the particle approximation of a function $f(x)$, denoted as $\Pi^h f(x)$, defined in continuous form by the integral:

$$\Pi^h f(x) = \int f(y)W(x - y, h)dy , \quad (2.6)$$

where W is the kernel function and h is the smoothing length. The kernel function $W(\mathbf{x}, h)$ is defined using a dimensionless function θ by the following relation:

$$W(\mathbf{x}, h) = \frac{1}{h(\mathbf{x})^d} \theta(\mathbf{x}) . \quad (2.7)$$

In this formulation, d represents the number of space dimensions, and h is the smoothing length, which varies in both time and space to maintain numerical stability during material deformation.

For the approximation to be physically consistent, the kernel function W must be a centrally peaked function. The most common smoothing kernel used in the SPH community, and the default in the LS-DYNA environment, is the cubic B-spline. This kernel is defined by choosing θ as a piecewise function:

$$\theta(u) = C \times \begin{cases} 1 - \frac{3}{2}u^2 + \frac{3}{4}u^3 & \text{for } 0 \leq |u| \leq 1 \\ \frac{1}{4}(2 - |u|)^3 & \text{for } 1 \leq |u| \leq 2 \\ 0 & \text{for } 2 < |u| \end{cases} \quad (2.8)$$

where u is the normalized distance between particles ($u = \frac{|x-y|}{h}$) and C is a normalization constant that ensures the integral of the kernel equals unity over the support domain. This compact support ensures that only neighbouring particles within the distance $2h$ contribute to the properties of a given particle, significantly optimising computational efficiency.

In the discrete SPH framework (Fig. 2.11), 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,

$$f(\mathbf{x}_i) \approx \sum_{j=1}^N \frac{m_j}{\rho_j} f(\mathbf{x}_j) W(\mathbf{x}_i - \mathbf{x}_j, h), \quad (2.9)$$

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 .

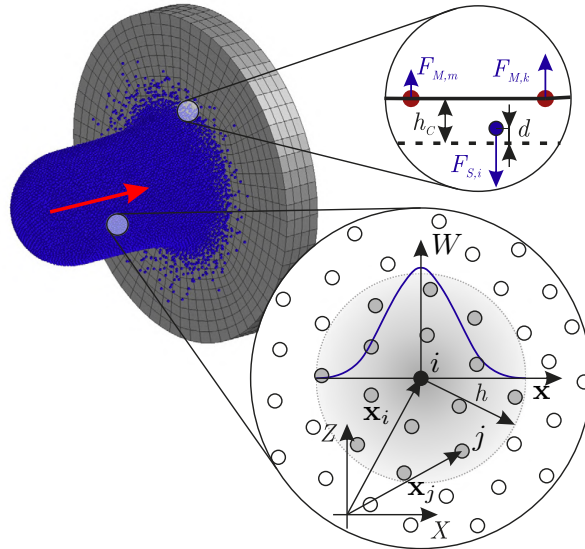


Figure 2.11: Schematic overview of SPH bird-strike simulation approach. Adapted from [51].

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

$$\frac{d\rho_i}{dt} = \rho_i \sum_{j=1}^N \frac{m_j}{\rho_j} (\mathbf{v}_i - \mathbf{v}_j) \cdot \nabla_i W_{ij}, \quad (\text{Mass Conservation}) \quad (2.10a)$$

$$\frac{d\mathbf{v}_i}{dt} = - \sum_{j=1}^N m_j \left(\frac{p_i}{\rho_i^2} + \frac{p_j}{\rho_j^2} + \Pi_{ij} \right) \cdot \nabla_i W_{ij} + \mathbf{g}_i, \quad (\text{Momentum Conservation}) \quad (2.10b)$$

$$\frac{du_i}{dt} = \frac{1}{2} \sum_{j=1}^N m_j \left(\frac{p_i}{\rho_i^2} + \frac{p_j}{\rho_j^2} + \Pi_{ij} \right) (\mathbf{v}_i - \mathbf{v}_j) \cdot \nabla_i W_{ij}, \quad (\text{Energy Conservation}) \quad (2.10c)$$

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 [51].

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.

These equations are closed by an Equation of State (EOS) which defines the value for pressure, p , as further explained in Sec. 3.3.

2.4.2 Material Models

The use of Carbon Fibre Reinforced Polymer (CFRP) has become a cornerstone of modern aerospace structures, particularly for primary load-carrying components and high-lift devices such as trailing-edge flaps. Their adoption is driven by exceptional weight-specific stiffness, high strength-to-weight ratios, and superior fatigue resistance compared to traditional aluminium alloys [14, 52]. Beyond these structural advantages, composites offer significant flexibility in material selection and high reliability in fabrication reproducibility. However, their inherent susceptibility to impact damage remains a matter of continued concern [53]. Unlike ductile metals that typically dissipate impact energy through elastic-plastic strain and shear plugging, the heterogeneous nature of composites introduces a complex array of failure mechanisms that can severely reduce residual structural integrity [53, 54].

The response of a composite structure is primarily dictated by the impact velocity regime. While large-mass, low-velocity impacts, typically occurring below 10 m s^{-1} from tool drops or handling, result in a quasi-static global structural response, bird strikes fall within the high-velocity or ballistic regime [53]. Materials behave differently under these high strain-rate loadings compared to quasi-static conditions: in the ballistic regime, the material behaviour is governed by localized stress wave propagation rather than global structural vibration [53]. High-velocity impacts are characterized by localized damage, including fibre rupture and fibre blow-out at the exit site in cases of full penetration [14].

Intralaminar failure refers to the damage mechanisms occurring within a single composite ply. To accurately simulate a bird strike on a composite flap, the numerical model must account for different interactive modes: Fibre Tension/Compression, when brittle rupture or kinking of the reinforcement fibres; and Matrix Cracking, consisting of failures parallel to the fibres due to transverse or shear loading.

In numerical frameworks such as Abaqus/Explicit, these modes are typically governed by orthotropic

constitutive laws combined with specialized failure criteria, such as Hashin or Puck [55]. These criteria identify damage initiation based on directional stress components, allowing the model to degrade the material stiffness according to the specific mode of failure encountered.

Interlaminar damage, or delamination, is often the most critical failure mode in HVIs. This separation of plies results in a significant loss of flexural stiffness and can grow under subsequent operational loads [14, 54]. This fracture process is highly complex; without accounting for delamination, the predictive capabilities of progressive failure analyses remain severely limited [54].

To capture this, modern simulations use a stacked shell modelling technique with cohesive elements placed at the ply interfaces [55]. These interfaces are governed by a Traction-Separation Law. As impact energy is absorbed, these elements track the softening of the interface until the fracture energy is exhausted, at which point the plies physically disconnect. This method is essential for capturing the hidden internal damage that characterizes the composite impact response.

A central objective of this thesis is assessing how these damage modes interact with pre-existing aerodynamic stress states. Research has demonstrated that preloading significantly alters the impact footprint and resultant damage extent [13, 14, 55, 56]:

- Tensile Preload: Generally leads to a reduced extent of delamination by limiting the bending deflection of the plate during the impact event
- Compressive Preload: Increases the extent of delamination due to amplified bending deflections
- Intralaminar Effects: Preloading has been observed to increase the extent of matrix cracking in specific plies compared to the unloaded case

Given that bird strikes on flaps occur while the component is under high lift-induced pressure, capturing these shifts is an important requirement for airworthiness assessments. This requires an implicit–explicit coupling approach: the steady-state aerodynamic load is first solved (implicit) and subsequently imported as a pre-stress state for the high-speed impact event (explicit) [14].

While progressive composite failure models provide valuable information, they significantly increase both setup and computational complexities, as well as making the model more prone to human modelling error, severe numerical instabilities and contact convergence failures. 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 [57].

2.4.3 Aerodynamic Static Loading

Recent advancements in coupled analysis suggest that the traditional uncoupled approach to impact modelling may fail to capture critical physics in thin-walled aerodynamic components. By implementing an integrated Structural–CFD methodology, research has demonstrated that pre-existing aerodynamic load states significantly influence the transient response of composite structures subjected to HVIs. This methodology acknowledges that the steady-state pressure field acting on a surface prior to impact

effectively alters the initial stress-strain state of the material, resulting in a measurable shift in the failure threshold compared to traditional stress-free simulations [58].

By establishing the initial stress state as a primary driver of failure, this body of work justifies the transition away from standard simulations toward the sequential aerodynamic-structural approach implemented in this thesis.

Aerodynamic pressures arise from the interaction between airflow and the aircraft's outer surfaces, acting as continuous loads governed by parameters such as flight speed, angle of attack, flap deflection, and Mach and Reynolds numbers. In steady, trimmed flight, these pressures generate distributed forces that deform the control surface prior to the impact event. The inclusion of this preload can be represented by the superposition of steady-state aerodynamic stress ($\sigma_{ij}^{\text{aero}}$) and transient impact stress ($\sigma_{ij}^{\text{impact}}$):

$$\sigma_{ij}^{\text{total}}(t) = \sigma_{ij}^{\text{aero}} + \sigma_{ij}^{\text{impact}}(t) . \quad (2.11)$$

Because aerodynamic pressures and structural deformations are mutually dependent (the deflection of a surface modifies local flow, which alters the pressure field) the problem is inherently a type of FSI [59]. In static load transfer problems, this coupling is typically categorized into two paradigms:

- Forward Coupling: Aerodynamic pressures obtained from a fixed aerodynamic shape (via CFD or wind tunnel data) are mapped to the structure without iterative feedback from structural deformation.
- Full Coupling: An iterative process where the structure deforms under load, the new shape is re-analysed aerodynamically, and the cycle continues until convergence.

For the preload assessment in this study, forward coupling is considered sufficient. Given the high stiffness of the composite flap assemblies, only moderate deflections occur, meaning aeroelastic feedback remains negligible in the context of the subsequent high-energy impact [25].

The exchange of data between the fluid and structural domains is non-trivial due to the fundamental differences in mesh requirements for flow and structural solvers [60–62]. Aerodynamic meshes are typically surface-based and unstructured, whereas structural models use shell elements that are often structured or regionally refined (Fig. 2.12) This requires the mapping procedures to overcome several challenges [63]:

- Coordinate Systems: Origins, rotations, and scaling must be precisely aligned to prevent spatial offsets;
- Fidelity Levels: CFD meshes may represent the entire aircraft, whereas the FEM model focuses on local components such as an individual flap, and thus often relies on meshes of differing levels of fidelity;
- Discretization: Information transfer between non-matching meshes requires interpolation algorithms that ensure load and moment conservation.

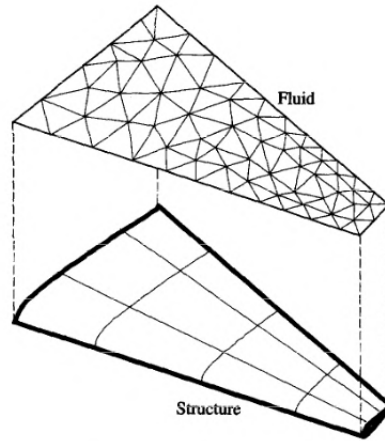


Figure 2.12: Dissimilar meshes for Aerodynamic and Structural Loading. Adapted from [59].

Methods based on Radial Basis Functions (RBF) [60], specifically those using thin plate splines, are often favoured for their high accuracy and efficiency in handling these non-matching discrete interfaces. When the coupling framework is not built upon a weak formulation, one in which the governing partial differential equations are integrated to naturally enforce energy conservation at the boundary, the nature of the data transfer must be explicitly defined. In such cases, a consistent interpolation approach is usually preferred over a conservative one to avoid unphysical oscillations in the pressure field received by the structure. A conservative method aims to guarantee the exact conservation of global integral quantities, such as ensuring that the net integrated fluid force equals the net structural force, which can introduce localized pressure spikes or numerical artifacts on non-matching grids. Conversely, a consistent method ensures that a uniform constant state (such as a uniform pressure field) is preserved exactly during the transfer without spatial distortion, maintaining local gradient fidelity at the expense of minor global conservation discrepancies.

The inclusion of aerodynamic preloading allows for an assessment of whether the pre-stressed configuration modifies local stiffness, deformation modes, or damage extent upon impact. Consequently, for the flap assembly discussed in this thesis, the aerodynamic loading represents an initial condition as well as a sensitivity parameter, critical for understanding the real in-flight structural state during a bird strike event.

Chapter 3

Case Implementation and Numerical Modelling

Multidisciplinary Design Optimization (MDO) studies that account for impact resilience must balance structural integrity against aerodynamic efficiency. Sensitivity studies conducted within these frameworks explore the influence of different parameters such as geometry, structural topology, skin thickness, and material failure thresholds, as well as projectile kinematic variables such as impact location and orientation. This thesis adopts an investigative approach with parallels to that of typical MDO research [15, 58, 64, 65], though not aimed at optimization, and applies sensitivity analysis methods to evaluate how variations in the aerodynamic environment influence the structural response of a flap during a bird strike event. This methodology moves from simple structural impact analysis onto a sequential aero-structural sensitivity study, where the aerodynamic scenario defined in CFD simulations serves as initial state for the transient dynamic simulation.

This chapter discusses the implementation of the simulated case in a FEM framework and the numerical setup of the problem. Section 3.1 presents the flap model used in the simulations, and Section 3.2 explores the process of approximating aerodynamic loading data obtained via CFD simulations and translating it into FEM static loads to apply to the flap. The SPH formulation of the bird impactor is described in Section 3.3. The FEM software used in the simulations for this thesis is presented in Section 3.4, and the metrics used for damage assessment are laid out in Section 3.5.

3.1 Flap Model Geometry and Numerical Meshing

The evaluation of bird strike resilience requires a structural target that is both standardized to ensure research comparability and representative of modern aerospace manufacturing 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 XRF1 research platform [25]. The XRF1 provides a high-fidelity, wide-body twin-engine configuration, analogous to an Airbus A330 airframe, thus ensuring that the transient dynamic results

are directly relevant to the current generation of transport aircraft and fully compatible with international research frameworks such as the AdViCe project.

The investigation focuses specifically on a segment of the Outboard (OB) trailing edge flap (indicated in red in Fig. 3.1), specifically the segment between the 3rd and 4th support tracks. The high-lift system of the XFR1 is a complete assembly comprising the leading-edge slats and trailing-edge flaps, the latter of which are responsible for the significant aerodynamic lift enhancement during the approach and landing phases.

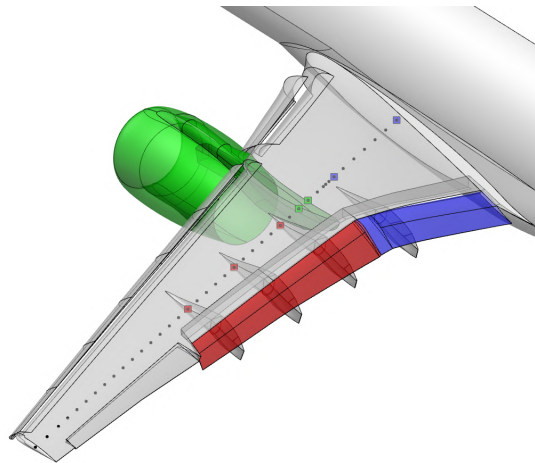


Figure 3.1: Detailed view of the Airbus XFR1 flaps, with OB flaps indicated in red [23].

The structural FEM model represents a high-performance composite assembly, a Composite Multi-spar Flap (CMF), using 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.3.2. The flap is connected to the aircraft's main wing via a dedicated track mechanism. These tracks are responsible for the flap's kinematics and serve as the primary boundary conditions, transferring the aerodynamic and impact loads into the wing's rear spar [66].

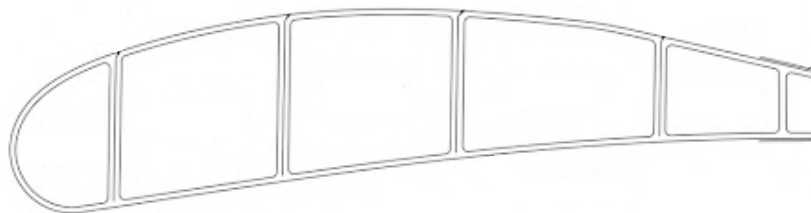


Figure 3.2: Section view of the CFRP flap. Adapted from [66].

The discretization of the flap was performed within an explicit finite element framework to capture the transient high-strain-rate response of the impact. A hybrid meshing approach was adopted to balance computational economy with physical accuracy:

- Skin and Surfaces (TSHELL): The outer aerodynamic skins and internal spar/rib webs were modelled using Thick Shell (TSHELL) elements. These elements are particularly effective for represent-

ing composite plies, as they account for thickness-wise stress distributions and out-of-plane shear, which are critical during failure modes associated with bird strikes.

- Internal Components and Resins (SOLID): The internal bonding areas, thick reinforcements, and resin-rich zones were modelled using eight-node hexahedron solid elements. This allows for a 3D representation of the stress state in areas where the plane-stress assumption of traditional thin shells would be invalid.

The resulting FEM model (Fig. 3.3) provides a high-resolution target for both the steady-state aerodynamic preload and the subsequent SPH bird impact.

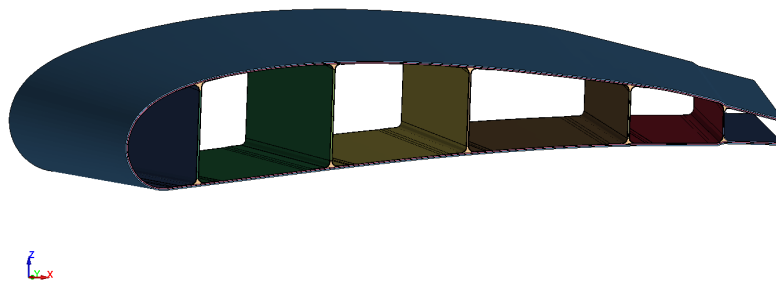


Figure 3.3: FEM model of the CFRP flap.

While the structural model is geometrically and architecturally a composite assembly, for the scope of this investigative thesis, the material properties were assigned as isotropic Aluminium.

By using a well-characterized isotropic material on a "composite-ready" geometry (Fig. 3.4), this study establishes a structural baseline on a simpler case while ensuring total flexibility to increase complexity in further work. This approach isolates the influence of the aerodynamic preload from the failure uncertainties associated with composite delamination or matrix cracking. This simplification ensures that the observed sensitivities in the bird strike response are a direct result of the aero-structural coupling rather than material modelling artifacts. The model remains material-ready, allowing for the future integration of specific CFRP ply sequences within the established framework.

To ensure that the transfer of aerodynamic loads was not overly sensitive to the structural mesh resolution, a mapping sensitivity study was conducted. By varying the spatial resolution from 25 000 individual patches down to a 250-patch grid (5×20 panels), it was observed that global metrics, such as tip deflection and peak internal stress, varied by less than 10%. This suggests that the structural response allows reasonable coarsening of the pressure distribution without losing accuracy, justifying the use of a computationally efficient mapping approach for the subsequent parametric studies.

3.2 Preload case

The evaluation of vulnerability to bird strike requires a representative operational baseline. In this thesis, the landing configuration is identified as the critical scenario, as the full extension of high-lift

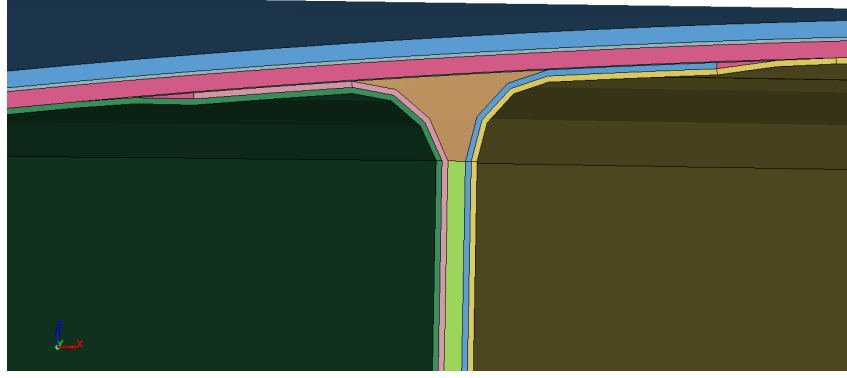


Figure 3.4: Detailed view of the FEM mesh structure, displaying both solid (e.g. the resin matrix, in light brown and light green) and shell elements (e.g. the skin element, in blue).

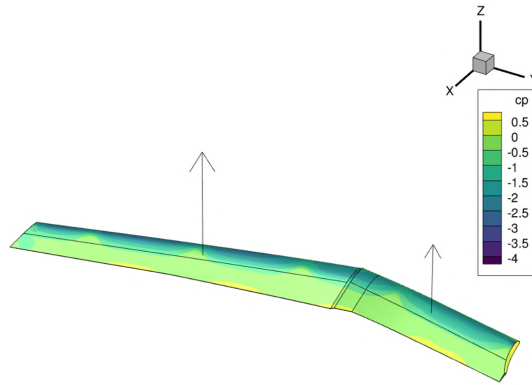


Figure 3.5: Total aerodynamic force vector [25].

devices maximizes both the frontal impact area and the aerodynamic pre-stress on the flap structure.

The reference preload case is detailed in Tab. 3.1 and corresponds to a flight speed of approximately 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. To evaluate the influence of varying flight conditions without the prohibitive cost of multiple iterative CFD runs, a template-based scaling approach is adopted. The reference pressure distribution (p_{ref}) is scaled with the dynamic pressure ($q_\infty = \frac{1}{2} \rho V^2$) to represent different airspeeds. Small empirical adjustments are then applied to ensure the total integrated lift and hinge moments remain physically consistent with the target flight condition. Given that the high-lift configuration remains geometrically static ($\delta_f = 40^\circ$) and within the same Mach regime, the pressure distribution and separation patterns are assumed to remain qualitatively similar, a methodology consistent with recent coupled structural–CFD investigations. This approach preserves the characteristic span- and chord-wise variation while ensuring physically consistent overall loading.

Section 3.2.1 describes the flight condition and specifies the operational parameters and the high-fidelity CFD computations used to characterize the loading on the wing flap. Section 3.2.2 formalizes the subsequent approximation and mapping procedures required to integrate these pressures into the

structural solver, establishing the pre-stressed initial state necessary for the transient impact analysis.

3.2.1 Flight Condition and Flow Pressure

The baseline aerodynamic pressure distribution applied in this work was kindly provided by the Institute of Aerodynamics and Flow Technology at DLR within the cooperation framework of the AdViCe project. The dataset corresponds to a steady flow solution representative of the selected flight condition, which was computed using the DLR TAU code [67], solving the Reynolds-Averaged Navier-Stokes (RANS) equations. This ensures that viscous effects, particularly the boundary layer behaviour on the multi-element airfoil, are captured in the pressure distribution. Although the complete aerodynamic simulation lies outside the scope of this thesis, the main assumptions and parameters behind the supplied pressure field are documented in this section, which aims not to validate the CFD computations, but to provide sufficient context for understanding the origin and applicability of the aerodynamic loads used throughout the numerical framework.

Overview of CFD simulation parameters and main results

Table 3.1 summarises the key characteristics of the CFD configuration. These data form the basis for the pressure-to-structure mapping procedure, from which the static preload state is established prior to the impact simulations. The delivered aerodynamic field consists of surface coordinates and associated pressure coefficients and dimensional pressures, exported in tabular form and subsequently applied onto the structural mesh.

The raw CFD output provided absolute static pressures. For the structural application, further detailed in Section 3.2.2, these were converted to gauge aerodynamic loads using the freestream dynamic pressure (q_∞) defined in Tab. 3.1, effectively isolating the aerodynamic lift and drag forces from the ambient atmospheric pressure.

The DLR-TAU software system

TAU is a CFD software system for aerospace applications, developed by DLR for internal use, but also widely present in the research and industry ecosystems in Europe [67]. The TAU system is engineered to solve the compressible RANS equations over complex three-dimensional geometries across a vast operational range, spanning from low-speed subsonic flows (critical for the high-lift configurations analysed in this study) to hypersonic regimes, and employs hybrid unstructured grids composed of tetrahedrons, pyramids, prisms, and hexahedrons. Its modular architecture facilitates ease of maintenance and reuse, allowing individual modules to operate as standalone utilities or within a Python-based scripting framework for automated inter-module communication and high flexibility in parallel computing environments. These paragraphs provide an overview of TAU's structure and capabilities which closely follows published research or conference presentations by its authors [68–70].

The numerical framework of TAU relies on a pre-processing phase that converts the primary mesh into a dual-grid structure. This vertex-centred, edge-based data structure makes the solver essentially

Table 3.1: Overview of the CFD setup used to generate the aerodynamic pressure field applied as structural preload.

	Parameter	Symbol	Value
Numerical Setup	Flow solver	-	DLR TAU (Release 2012.2.0)
	Governing equations	-	RANS (Steady)
	Turbulence model	-	One-equation Spalart-Allmaras
	Mesh type	-	Hybrid
Freestream Conditions	Mach number	Ma_∞	0.195 268
	Reference Density	ρ_∞	0.903 33 kg m ⁻³
	Static Temperature	T_∞	287.85 K
	Reference velocity	V	66.4148 m s ⁻¹
	Dynamic Pressure	$q_\infty (\frac{1}{2}\rho V^2)$	1992.1946 Pa
Flight Condition	Angle of attack	α	7°
	Flap deflection angle	δ_f	40°
	Reynolds number	Re	14 066 000
Reference Values	Reference Area	S	61.2 m ²
	Reference Chord	c_{ref}	4.1935 m
	Moment Ref. Point	X_{ref}	(18.85 m, 0 m, 0.7 m))
Integrated Loads	Flap segment Z-Force	$F_{z_{flap}}$	1.746 490 kN
	Flap segment Y-Moment	$M_{y_{flap}}$	-5.112 003 N m
Mesh	Total cell count	N_{cells}	65 096 185
	Surface Mesh Nodes count	$N_{surface\ nodes}$	$\approx 1.24 \times 10^5$
	Typical near-wall y^+	y^+	1.9

independent of the primary element types, using normal vectors to represent the metrics of the auxiliary cells. Spatial discretization of inviscid terms is achieved through second-order central schemes or various upwind schemes using linear reconstruction, while viscous terms are resolved with a second-order central scheme. To overcome the strict Courant-Friedrichs-Lewy (CFL) limitations associated with explicit time-stepping in large-scale applications, the solver incorporates an implicit approximate factorization scheme. Specifically, the Lower-Upper Symmetric Gauss Seidel (LU-SGS) method is employed, since its low memory requirements and computational efficiency allow for parallelization with relative ease. Compared to traditional explicit Runge-Kutta methods, the LU-SGS scheme ensures numerical stability and robustness with significantly reduced time-step restrictions, which is essential for achieving converged pressure distributions on complex high-lift surfaces.

High-lift aerodynamics are dominated by adverse pressure gradients and potential flow separation, demanding rigorous turbulence modelling. TAU contains an extensive library of RANS models, such as one-equation closures like Spalart-Allmaras (SA) for attached flows, two-equation $k - \omega$ based models, and Reynolds-Stress models. Efficiency in these simulations is further enhanced by model-specific "universal" wall functions, which maintain accuracy across a wide range of wall coordinate y^+ values while reducing computational memory and time requirements by up to 40% and 75%, respectively.

While TAU supports various transition prediction modules, including automated linear stability analysis methods, the current research adopts a fully turbulent approach. This choice is physically justified

by the high Reynolds numbers characteristic of the landing phase and the aerodynamic slot between the main wing and the flap. This slot acts as a powerful source of turbulence, effectively tripping the boundary layer instantly, and causing transition to occur near the leading edge, thereby using a fully turbulent assumption appropriate for predicting global structural loads.

To accommodate geometric variations or structural responses in coupled simulations, TAU incorporates an algebraic grid deformation tool. Unlike iterative solutions based on linear elasticity, this tool uses an advancing front technique to transport surface displacements and rotations into the grid interior. For large deformations, such as wing tip deflections that might cause cell collapse, a volume spline algorithm is employed to repair the mesh by rebuilding affected regions as images of the original cells. This allows the system to handle significant structural movements with negligible computational overhead, making it a powerful utility for aeroelastic optimization.

In the context of this dissertation, TAU serves as a high-fidelity "load generator." It provides the deterministic, converged aerodynamic environment that defines the initial stressed state of the structural mesh, which is subsequently mapped onto the LS-DYNA framework for transient impact analysis.

3.2.2 Aerodynamic Loading via Pressure Mapping

The transfer of aerodynamic pressures from the CFD grid to the structural finite-element surface is a non-matching interface problem in fluid–structure interaction. In the present study, the DLR TAU surface mesh, optimized for boundary layer resolution, is significantly finer and topologically different from the LS-DYNA structural mesh of the flap. Past work [59] has proposed conservative load-transfer schemes based on virtual-work equivalence, which guarantee momentum and energy conservation across the interface. While these are critical for two-way aeroelastic coupling, the present work focuses on establishing a deterministic pre-stressed initial state, allowing for a more localized interpolation approach.

In the present work, a simplified one-way mapping is adopted: CFD pressures are interpolated onto the flap skin mesh and applied as piecewise-constant surface loads through the LS-DYNA keyword `*LOAD_SEGMENT`. This approach is formally non-conservative [59], but is considered adequate here because the aerodynamic field is steady, the fluid mesh is finer than the structural mesh, and the deformation under static preload remains moderate. The objective is not to resolve aeroelastic coupling but to establish a representative pre-stressed state prior to bird impact.

In the transfer of information between the CFD data points and the FEM segments, two primary spatial interpolation categories were considered:

1. Nearest Neighbour (NN) Interpolation: A zero-order approach where each structural segment receives the pressure value of the closest CFD node. While computationally efficient for highly unstructured data, it can introduce non-physical discontinuities in the pressure field if the structural mesh is too coarse.
2. Radial Basis Functions (RBF): A more sophisticated scattered-data interpolation method that uses a sum of basis functions (e.g., thin-plate splines or multiquadrics) to create a smooth, continuous

pressure surface. RBF is highly accurate but involves solving a global system of equations, which can be computationally prohibitive.

In this dissertation, 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:

$$P_{\text{seg}} = \frac{\sum_{i=1}^n w_i P_i^{\text{CFD}}}{\sum_{i=1}^n w_i}, \quad (3.1)$$

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.

To ensure the numerical stability of the structural response, a sensitivity study was conducted regarding the mapping resolution. The analysis compared a high-fidelity mapping with the full CFD vertex cloud (approximately 25 000 points) against a reduced-order mapping of 250 patches.

The additional complexity of a fully conservative, two-way load-transfer implementation is not justified, as the primary objective is the characterization of the structural response under a representative, steady-state aerodynamic pre-stress, and the structural deformations induced by these aerodynamic loads are negligible.

To verify the fidelity of the data transmission pipeline across the fluid-structure interface, a direct spatial correlation analysis was executed. Figure 3.6 establishes a side-by-side comparison between the raw, continuous source pressure fields extracted from the CFD grid environment (.csv) against the localized discretized pressure loads compiled into the structural finite element solver input cards (.k).

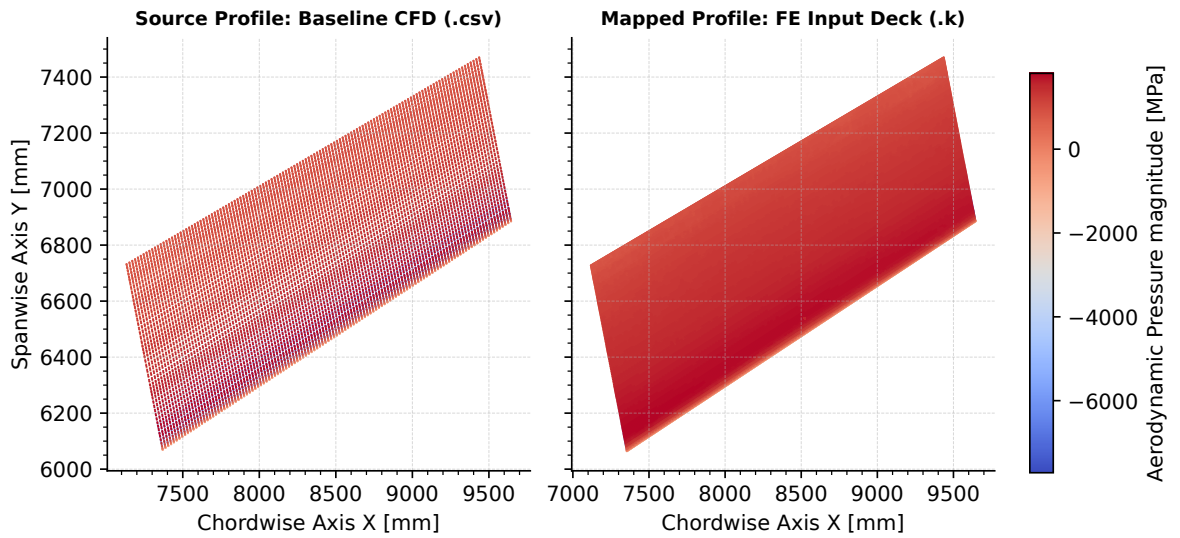


Figure 3.6: Side-by-side validation mapping comparing the baseline CFD source pressure distributions against the mapped structural finite element segment constraints.

The side-by-side projection validates the spatial interpolation framework. The planform layout, leading-

edge curvature, and trailing-edge taper match identically between the two data arrays, confirming no spatial coordinate transformations or rotational scaling errors occurred during file compilation.

Furthermore, the distribution of the pressure scale mirrors the baseline envelope, demonstrating that the high-pressure gradients on the lower surface and the suction zones on the upper surface were appropriately mapped onto the faces of the corresponding structural shell elements. This layout serves as verification that the structural initial conditions are accurately grounded in the physics of the design flight state.

3.3 Bird Model

The numerical characterization of the bird is a critical component of the impact simulation. As discussed earlier in Chapter 2, at the velocities associated with take-off and landing (exceeding 60 m s^{-1}), the bird behaves essentially as a fluid projectile. This section details the geometric definition, and the numerical and constitutive formulations of the substitute bird used in this study. Table 3.2 summarizes the main parameters.



Figure 3.7: Bird Model in LS-DYNA.

To ensure reproducibility and compliance with aerospace certification standards, a standardized surrogate bird geometry is used (Fig. 3.7). While real birds have complex heterogeneous structures (such as flesh, air sacs, and bone), experimental and numerical studies have shown that a homogeneous projectile of appropriate density adequately captures the momentum transfer and pressure peaks during impact.

As seen in Figure 3.7, the bird is modelled as an ellipsoid with a length-to-diameter (L/D) ratio of 2.0. This shape is preferred over a simpler shapes such as a flat-ended cylinder to avoid non-physical pressure spikes at the initial contact moment. The total mass is set to the standard certification value of 1.814 kg (4lb), which aims to represent the most frequent certification-relevant bird for impact on wing and empennage structures. The density is assumed to be $\rho = 980 \text{ kg m}^{-3}$, approximating a mixture of water and air, and its SPH particle-based representation is illustrated in Figure 3.7.

While the theoretical foundation of the SPH method is detailed in Section 2.4.1, its implementation for the bird strike scenario requires specific discretization and material characterization. The projectile is discretized into approximately 72 363 particles with an initial spacing of [X] mm. To ensure a stable

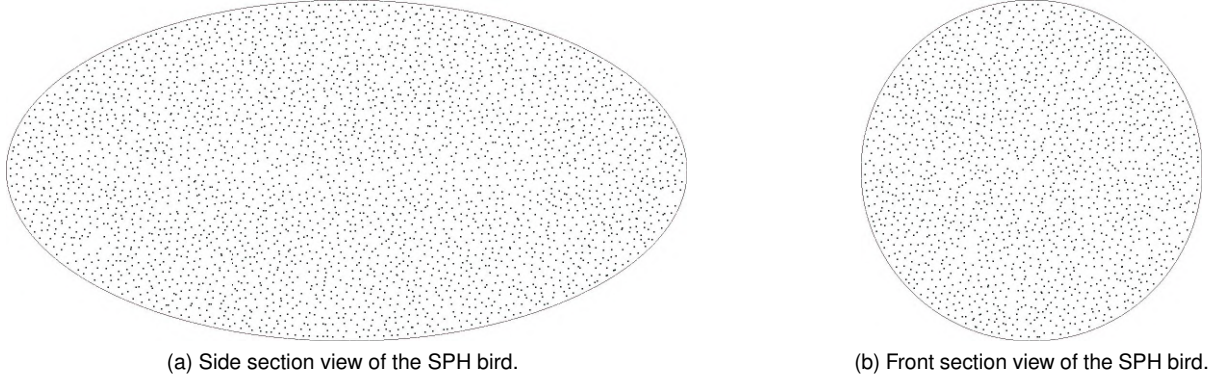


Figure 3.8: Side and front section views of the SPH bird.

interaction with the structural mesh, a variable smoothing length is used, constrained by the $HMIN$ and $HMAX$ parameters to prevent numerical instability during the high-compression phase of the impact.

Since the bird behaves as a fluid during impact, it is modelled using the `*MAT_NULL` keyword in LS-DYNA. This material model possesses no shear strength and requires an Equation of State (EOS) to define the relationship between pressure, density, and internal energy.

In this study, the bird is modelled using a Polynomial fitted pressure equation [71, 72], one of the most common types of EOS for this type of application,

$$p = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3, \quad (3.2)$$

in which μ is the non-dimensional mass density changing ratio of the bird tissue and the remaining coefficients are defined as

$$\begin{aligned} C_0 &= 0 \\ C_1 &= \rho_0 c_0^2 \\ C_2 &= (2k - 1)C_1 \\ C_3 &= (k - 1)(3k - 1)C_1 \end{aligned} \quad (3.3)$$

where C_0 denotes the initial equilibrium pressure and k is a material constant, here taken to represent the properties of gelatin as a first approximation.

By defining these parameters accurately, the numerical model captures the Hugoniot pressure peak as well as the subsequent Stagnation phase, where the bird flows across the structure as a steady liquid jet.

3.4 Simulation Software (LS-DYNA)

The dynamic analysis in this study was conducted using LS-DYNA, a multi-physics, general-purpose 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

Table 3.2: Overview of SPH bird model parameters used in simulation.

	Parameter	Symbol	Value
Geometry	Geometry type	-	Ellipsoidal
	Length	L	244.350 mm
	Diameter	D	122.175 mm
Mass Properties	Total mass	m	1.814 kg
	Volume	V	0.001 90 m ³
	Density	ρ	950 kg m ⁻³
SPH Discretization	Number of particles	N	72 363
	Particle spacing	Δx	2.977 mm
	Kernel radius	h	3.572 mm
	Particle mass	m_p	25.068 mg
Equation of State	EOS type	-	*EOS.LINEAR.POLYNOMIAL
	Coefficients	(C_1, C_2, C_3)	(2.25, 6.00, 10.00)

core strength lies in its explicit time integration methodology. This makes it the industry standard for aerospace certification and research involving High Velocity Impact (HVI) events, such as bird strikes, where the resolution of high-frequency shock propagation and material failure is critical. This section explores the FEM implementation of the research for this thesis. The mathematical derivations throughout this section follow the conventions and nomenclature from the LS-DYNA Theory Manual [50].

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 [73]. A standard simulation workflow requires the definition of a constitutive material model, a discretized spatial geometry (the finite element mesh), an element kinematic formulation, contact interfaces between interacting parts, and a temporal integration scheme [74].

User interaction with the solver environment is mediated via LS-PrePost, a free integrated pre- and post-processing companion software used to manipulate finite element meshes, prescribe boundary conditions, and define contact cards. During execution, the solver computes the transient structural response and outputs the solution into two primary data streams: `.d3plot` files, which contain the full spatial visualization of the deformed domain, and `.binout` files, which store time-history variables for any user-defined output requests. In this study, these outputs are post-processed through a combination of LS-PrePost and external data-extraction pipelines, developed in Python via the LASSO library [75]. This workflow is schematized in Fig. 3.9.

LS-DYNA uses a vast spatial discretization library. This includes a wide range of element formulations: four node tetrahedron and eight node solid elements, two node beam elements, three and four node shell elements, eight node solid shell elements, truss elements, membrane elements, discrete elements, and rigid bodies. For the high-lift configuration analysed here, the main focus is the software's ability to handle Thick Shells (TSHELL) and high-order solid elements, which is used for capturing the out-of-plane shear and bending-torsion coupling characteristic of the flap's internal substructure.

The treatment of the interaction between the bird projectile and the flap skin is managed through

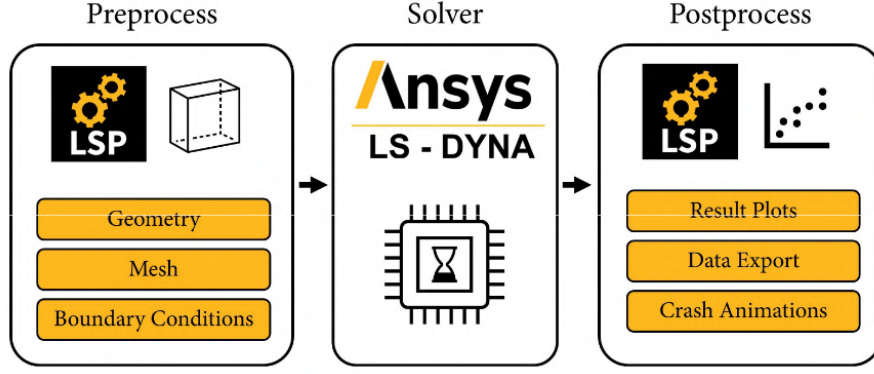


Figure 3.9: Simulation workflow. Adapted from [76].

a specialized contact-impact algorithm (detailed in Section 3.4.4). LS-DYNA employs penalty-based contact methods that allow for the efficient resolution of non-matching interfaces, even when subject to extreme deformations.

To represent the wide variety of physical behaviours present in this problem, the software couples standard structural constitutive equations with hydrodynamic equations of state (EOS). This specialized multi-physics framework allows for the simultaneous modelling of the classical behaviour of the isotropic metallic components (Aluminium) alongside the hydrodynamic behaviour of the SPH bird projectile.

3.4.1 Time Integration Schemes

LS-DYNA governs the dynamic structural response by solving the semi-discrete equations of motion at time step n [50, 76]:

$$\mathbf{M}\mathbf{a}^n = \mathbf{P}^n - \mathbf{F}^n + \mathbf{H}^n \quad (3.4)$$

where $\mathbf{M}$ is the diagonal mass matrix, $\mathbf{a}^n$ is the global nodal acceleration vector, $\mathbf{P}^n$ represents the external and body force load vector, $\mathbf{F}^n$ is the internal stress divergence vector, and $\mathbf{H}^n$ is the hourglass resistance vector.

To advance the state of the system (t^{n+1}), LS-DYNA implements an explicit central difference time integration scheme with half-step velocity formulations [50]. The solution sequence progresses through the following algorithmic updates:

$$\mathbf{a}^n = \mathbf{M}^{-1} (\mathbf{P}^n - \mathbf{F}^n + \mathbf{H}^n) \quad (3.5)$$

$$\mathbf{v}^{n+\frac{1}{2}} = \mathbf{v}^{n-\frac{1}{2}} + \mathbf{a}^n \Delta t^n \quad (3.6)$$

$$\mathbf{u}^{n+1} = \mathbf{u}^n + \mathbf{v}^{n+\frac{1}{2}} \Delta t^{n+\frac{1}{2}} \quad (3.7)$$

where $\mathbf{v}$ and $\mathbf{u}$ are the global nodal velocity and displacement vectors, respectively. The intermediate

time step increment $\Delta t^{n+\frac{1}{2}}$ is evaluated as the mean of the adjacent steps:

$$\Delta t^{n+1/2} = \frac{\Delta t^n + \Delta t^{n+1}}{2} \quad (3.8)$$

Following the displacement computation, the nodal geometry is updated relative to the initial reference coordinates $\mathbf{x}^0$:

$$\mathbf{x}^{n+1} = \mathbf{x}^0 + \mathbf{u}^{n+1} \quad (3.9)$$

Implicit Schemes:

Iteratively solve for static or quasi-static equilibrium equations at each step using much larger time increments to reduce overall computational intervals:

$$\mathbf{K}\mathbf{u}_{n+1} = \mathbf{F}_{ext,n+1} \quad (3.10)$$

Implicit Schemes:

Iteratively solve the nonlinear equations of structural equilibrium at each discrete time step, allowing for significantly larger time increments (Δt) to reduce the total number of computational cycles:

$$\mathbf{M}\mathbf{a}^{n+1} + \mathbf{F}^{n+1}(\mathbf{u}^{n+1}) = \mathbf{P}^{n+1} \quad (3.11)$$

where the internal force vector $\mathbf{F}^{n+1}$ varies as a nonlinear function of the updated displacement state $\mathbf{u}^{n+1}$. In purely static or heavily damped quasi-static simulations, the inertial terms are minimized, and iterations are performed to drive the residual force vector to zero within a predefined convergence tolerance. This strategy requires the formation and inversion of a global tangent stiffness matrix ($\mathbf{K}_t = \partial \mathbf{F} / \partial \mathbf{u}$), making each step computationally expensive but unconditionally stable, thus completely bypassing the strict time step limits imposed by the explicit stability criterion.

Dynamic Relaxation: LS-DYNA provides a built-in Dynamic Relaxation functionality, which applies fictitious damping to an explicit simulation loop. This allows the transient system to settle efficiently into a steady-state equilibrium, commonly utilized for initializing static pre-loads (such as bolting or gravity) prior to running a highly dynamic explicit analysis.

3.4.2 Finite Element Model

LS-DYNA is based on a Lagrangian formulation, where a mesh is superimposed on the reference volume and tracks properties over time. Taking Fig. 3.10 as example, this section derives the FEM formulation of a generic time-dependent deformation, for which a point in b initially at X_α ($\alpha = 1, 2, 3$) in a fixed rectangular Cartesian coordinate system moves to a point x_i ($i = 1, 2, 3$) in the same coordinate system.

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

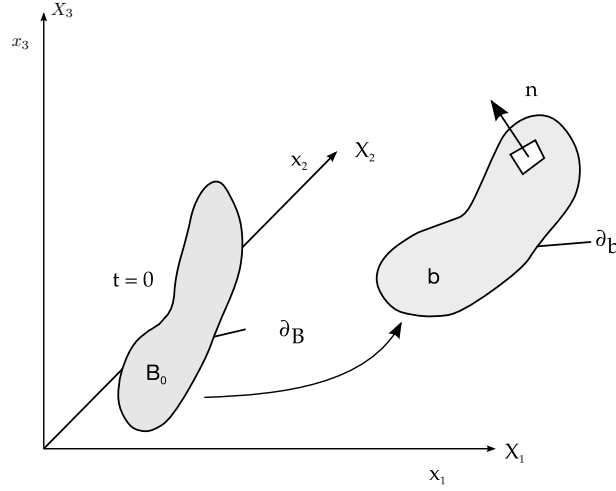


Figure 3.10: FEM nomenclature [50].

$$\sigma_{ij,j} + \rho f_i = \rho \ddot{x}_i, \quad (3.12)$$

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. 3.12) is solved while satisfying the boundary conditions:

$$\sigma_{ij} n_j = t_i(t), \quad \text{on boundary } \partial b_1 \text{ (Traction);} \quad (3.13a)$$

$$x_i(X_\alpha, t) = D_i(t), \quad \text{on boundary } \partial b_2 \text{ (Displacement);} \quad (3.13b)$$

$$(\sigma_{ij}^+ - \sigma_{ij}^-) n_i = 0, \quad \text{along internal boundary } \partial b_3 \text{ (Contact discontinuity), when } x_i^+ \neq x_i^-. \quad (3.13c)$$

The discretization process relies on the principle of virtual work, which transforms the differential governing equations into an integral form suitable for numerical integration, the weak formulation of the momentum equation,

$$\delta\pi = \int_v \rho \ddot{x}_i \delta x_i dv + \int_v \sigma_{ij} \delta x_{i,j} dv - \int_v \rho f_i \delta x_i dv - \int_{\partial b_1} t_i \delta x_i ds = 0, \quad (3.14)$$

where $\delta\pi$ represents the virtual work variation, δx_i is the arbitrary virtual displacement field, and $\delta x_{i,j}$ represents its spatial gradient. The integrations are evaluated over the current domain volume v and its traction boundary surface ∂b_1 , corresponding to the differential volume element dv and differential surface element ds , respectively.

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.,

$$x_i(X_\alpha, t) = x_i(X_\alpha(\xi, \eta, \zeta), t) = \sum_{j=1}^k N_j(\xi, \eta, \zeta) x_i^j(t), \quad (3.15)$$

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. Since each shape function possesses a finite support, its influence is strictly confined to the elements sharing its associated node. Because the interpolation within any given element depends exclusively on its own local nodal values, localized expressions such as Equation 3.15 remain computationally independent from the rest of the global mesh.

Hourglassing

A significant challenge in explicit finite element analysis is the trade-off between computational efficiency and numerical stability. By default, many of the element formulations in LS-DYNA use reduced integration (one-point quadrature). While this reduces the computational effort by nearly an order of magnitude, it introduces a numerical artifact known as hourglassing.

Hourglass modes are non-physical, zero-energy deformation modes that arise because the displacement field at the nodes results in zero strain at the single central integration point. Consequently, the element's internal force vector becomes blind to these specific deformations, leaving the element with no stiffness to resist them. If left uncorrected, these oscillations can propagate through the mesh, leading to a total loss of solution accuracy or premature simulation termination.

The stiffness matrix of a fully integrated 8-node solid element has a rank of 18 (representing its 24 degrees of freedom minus 6 rigid body modes). However, a one-point integrated element has a rank of only 6, where the remaining 12 modes are hourglass modes. For the velocity field $\dot{x}_i$ the strain rate $\dot{\epsilon}_{ij}$ is calculated at the integration point. In an hourglass mode, the nodal velocities are such that:

$$\dot{\epsilon}_{ij} = \sum_{k=1}^8 B_{ijk} \dot{x}_k = 0. \quad (3.16)$$

Despite a non-zero velocity field, the resulting strain rate is zero, meaning no internal energy is absorbed by the element during this deformation.

In the current flap model, the selection of the hourglass control type and the scaling factor Q_{HG} is balanced to ensure that the hourglass energy remains below 5% of the total internal energy, a standard validation metric in aerospace impact engineering to ensure that numerical damping does not overshadow the physical material response.

3.4.3 Solid and Shell Element Formulations

The structural discretization of the flap relies on a combination of shell and solid elements, chosen to represent the distinct geometric scales of the assembly. In finite element theory, shell elements

are used for structures where the thickness is significantly smaller than the longitudinal dimensions, allowing for a reduction in the total degrees of freedom by employing kinematic assumptions about the stress distribution through the thickness. On the other hand, solid elements are required for the internal substructure and resin-rich zones where the stress state is inherently three-dimensional and out-of-plane effects are significant.

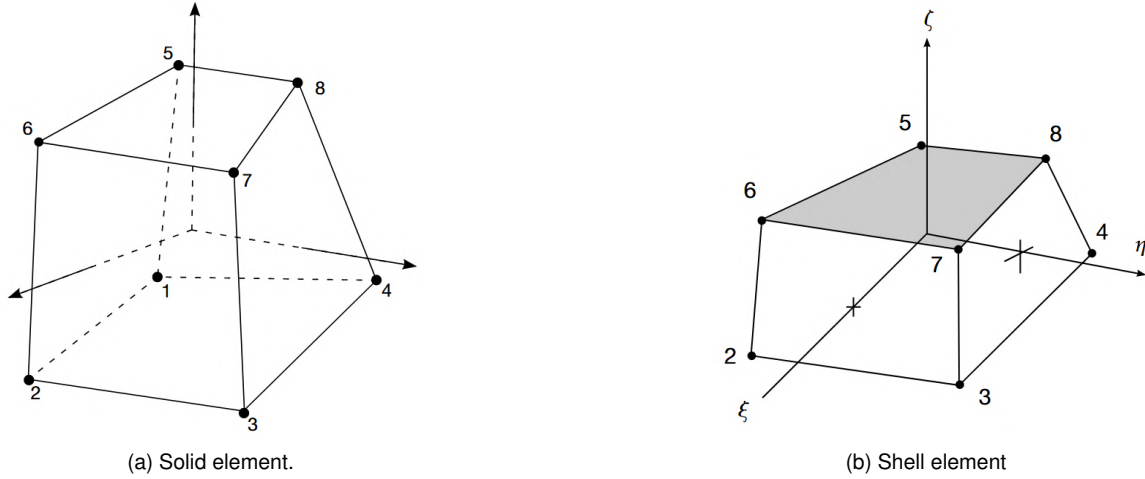


Figure 3.11: LS-DYNA Solid and Shell elements. Adapted from [50].

Solid Elements (8-Node Hexahedron): The internal resins and structural reinforcements are modelled using 8-node hexahedral (brick) elements. In this study, one-point integration (reduced integration) is employed for these elements to maximize computational efficiency. In high-velocity impact simulations with tens of thousands of elements, the cost of full integration (8-point) is often prohibitive. However, this efficiency requires the use of the hourglass control methods detailed in Section 3.4.2 to prevent the excitation of zero-energy modes.

Shell Elements ((TSHELL) Formulation): For the flap skin, this study uses Thick Shell elements. TSHELL elements allow for a more accurate representation of these through-thickness stresses. Composite-Ready Framework: While the current model uses an Aluminium baseline, the TSHELL formulation is inherently suited for laminated composites, as it allows for multiple integration points through the thickness to resolve the stress state of individual plies. The mapping from the parametric space (ξ, η, ζ) to the physical coordinates (x, y, z) follows the standard formulation:

$$x_i(\xi, \eta, \zeta) = \sum_{j=1}^n \phi_j(\xi, \eta, \zeta) x_i^j, \quad (3.17)$$

where ϕ_j are the shape functions for the 4-node or 8-node element.

3.4.4 Contact Modelling

In the simulation of HVI events, the computational treatment of sliding, impact, and penetration along the interface between the projectile and the target is of great importance. The mechanical interaction between the SPH bird particles and the structural target surfaces is governed by contact-impact algorithms implemented within the LS-DYNA explicit framework.

LS-DYNA provides three fundamental methods for handling these interfaces: the kinematic constraint method, the penalty method, and the distributed parameter method. The kinematic constraint method is primarily used for tied interfaces, and the distributed parameter method has been historically applied in specific interactions. The Penalty Method is the most widely adopted for high-velocity soft-body impacts.

In the penalty approach, normal interface springs are placed between any penetrating slave node and the master surface segments. Momentum is exactly conserved without the necessity of imposing artificial impact and release conditions.

Standard Penalty Formulation (SOFT=0) For the standard formulation, each slave node is checked for penetration through the master surface. If a slave node n_s has passed through the master segment that contains its closest contact point, penetration is indicated by the condition:

$$l = n_i \cdot [t - r(\xi_c, \eta_c)] < 0 \quad (3.18)$$

where t is the position vector of the slave node, $r(\xi_c, \eta_c)$ is the parametric representation of the master segment at its contact point, and $n_i(\xi_c, \eta_c)$ is the normal vector pointing outward from the master segment.

Once penetration is detected ($l < 0$), an interface force vector f_s is applied to the slave node:

$$f_s = -lk_i n_i . \quad (3.19)$$

An equivalent and opposite reaction force f_m^i is distributed to the four nodes ($i = 1, 2, 3, 4$) comprising the corresponding master segment via their basis/shape functions:

$$f_m^i = \phi_i(\xi_c, \eta_c) f_s . \quad (3.20)$$

The stiffness factor k_i for a given master segment S_i is determined by the material properties and geometry of the elements in contact. For brick and solid elements, k_i is expressed as:

$$k_i = \frac{f_{si} K_i A_i}{V_i} . \quad (3.21)$$

For shell and thick shell elements, the formulation incorporates the element diagonal:

$$k_i = \frac{f_{si} K_i A_i}{\max(\text{shell diagonal})} , \quad (3.22)$$

where K_i is the bulk modulus, V_i is the element volume, A_i is the face area of the master segment, and f_{si} is a user-defined stiffness scale factor, normally defaulting to 0.1.

Soft Constraint Penalty Formulation (SOFT=1) To prevent excessive penetration when soft bodies interact with rigid structures, alternative stiffness formulations are available. The Soft Constraint Penalty Formulation calculates an additional stability-based contact stiffness k_{cs} governed by the stability of the local masses:

$$k_{cs}(t) = 0.5 \cdot \text{SOFSCCL} \cdot m^* \cdot \left(\frac{1}{\Delta t_c(t)} \right)^2, \quad (3.23)$$

where SOFSCCL is a scaling factor, m^* is a function of the slave and master nodal masses, and Δt_c is the solution time step size. The algorithm adopts the maximum value between the stability stiffness and the standard penalty stiffness:

$$k_{\text{soft}=1} = \max\{k_{cs}, k_{\text{soft}=0}\}. \quad (3.24)$$

Segment-Based Penalty Formulation (SOFT=2) The segment-based penalty formulation replaces the standard node-to-segment algorithm with a segment-to-segment logic. The interface stiffness $k(t)$ uses direct segment masses rather than nodal masses:

$$k(t) = 0.5 \cdot \text{SLSFAC} \cdot \left(\frac{\text{SFS or SFM}}{2} \right) \cdot \frac{M_1 M_2}{M_1 + M_2} \cdot \left(\frac{1}{\Delta t(t)} \right)^2, \quad (3.25)$$

where M_1 and M_2 are the respective masses of the interacting segments, and SFS or SFM are the segment scale factors. This approach provides a significant advantage by preventing localized node-dropping through master segments, which is common in high-velocity soft-body impact simulations.

Coulomb Friction Treatment

Tangential resistance forces along the target-projectile boundary are governed via a Coulomb-based formulation. The interface yield force F_y limits the maximum tangential resistance:

$$F_y = \mu |f_n| \quad (3.26)$$

where $|f_n|$ is the normal interface force magnitude. A trial force $f^* = f^n - k\Delta e$ is evaluated against this threshold. The transitional friction coefficient μ scales exponentially between the static (μ_s) and dynamic (μ_d) states based on the relative sliding velocity $|v|$:

$$\mu = \mu_d + (\mu_s - \mu_d)e^{-c|v|}, \quad (3.27)$$

where c is the dynamic decay constant.

Shell Thickness Offsets and Initial Penetration Treatment

Since the structural discretization of the flap skin relies on thick-shell elements (TSHELL), the contact algorithm must account for the thickness of the elements rather than operating solely on the mid-surface.

The contact surfaces are projected outward from the mid-surface based on normal projection vectors (Fig. 3.12). Both the slave and master surfaces must be offset by an amount equal to half their respective total thicknesses:

$$\delta_{\text{offset}} = \frac{1}{2} t_{\text{shell}} . \quad (3.28)$$

Failure to accurately model this initial offset can introduce unphysical contact interpenetrations at the beginning of the simulation. Such initial interpenetrations generate severe numerical spikes and lead to an unphysical growth of negative contact energy. In the current numerical framework, the IGNORE parameter is set to ensure that initial penetrations are appropriately ignored or adjusted by moving the contact surface, preventing premature element erosion or unstable initial force spikes.

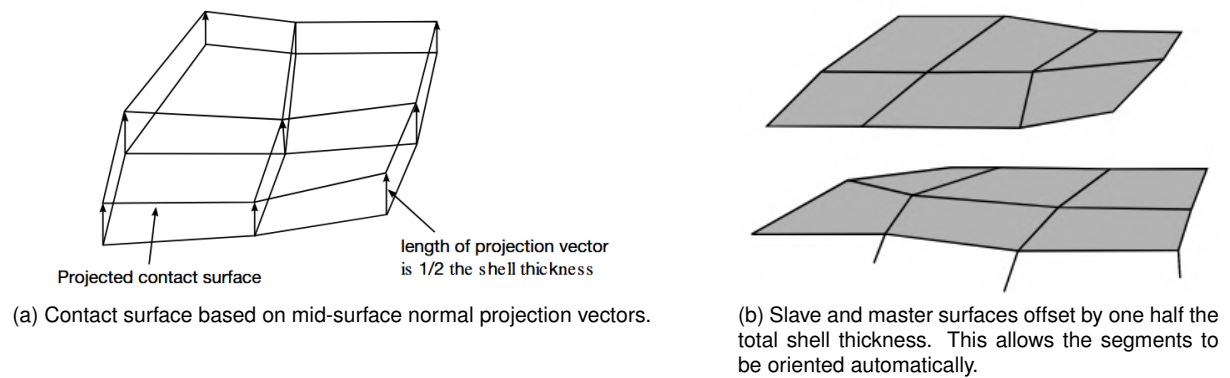


Figure 3.12: Thickness offsets in LS-DYNA. Adapted from [50].

3.4.5 Material Numerical Model

The selection of a constitutive model for HVI analysis must account for the highly non-linear behaviour of materials subjected to extreme strain rates and localized heating. In this dissertation, the material characterization of the flap structure follows the guidelines established by the LS-DYNA Aerospace Working Group (AWG). The AWG is a collaborative effort between major aerospace Original Equipment Manufacturers (OEMs) (such as Boeing and Airbus), the FAA, and researchers to standardize and validate material models specifically for the purpose of virtual certification and crashworthiness analysis.

While the flap is geometrically designed as a composite assembly, the current investigative phase uses an isotropic Aluminium baseline to isolate aerodynamic sensitivities. Within the LS-DYNA framework, two primary models are standard for such applications:

***MAT_024 (MAT_PIECEWISE_LINEAR_PLASTICITY):** A widely used model for aerospace structural analysis, due to its versatility and low computational requirements.

*MAT_024 accounts for strain-rate effects, relevant for high load speed cases. Several specification options are available, such as user-defined scaling curves, tabulated stress-strain curves, or simple scaling of the yield stress.

This was the selected material model for the initial simulations.

*MAT_224 (MAT_TABULATED_JOHNSON_COOK): Developed in conjunction with the FAA and the AWG [77], *MAT_224 is a tabulated model, meaning the user provides detailed experimental data for the failure surface as a function of stress triaxiality. This is critical for bird strikes because the stress state at the leading edge varies rapidly from pure tension to high-pressure compression during the impact.

The stress σ_{ij} is expressed as a function of strain ε_{ij} , strain rate $\dot{\varepsilon}_{ij}$, and temperature T :

$$\sigma_{ij} = \sigma_{ij}(\varepsilon_{ij}, \dot{\varepsilon}_{ij}, T) \quad (3.29)$$

In the plastic region, a von Mises type yield surface controls the material behaviour, expanding or contracting via strain hardening, rate dependencies, and thermal softening:

$$\sigma_{vm}(\sigma_{ij}) \leq \sigma_y(\varepsilon_{eff}^p, \dot{\varepsilon}_{eff}^p, T) = (\varepsilon_{eff}^p, \dot{\varepsilon}_{eff}^p, T) \quad (3.30)$$

where σ_{vm} is the von Mises stress, ε_{eff}^p is the equivalent plastic strain, and $\dot{\varepsilon}_{eff}^p$ is the equivalent plastic strain rate.

Plastic failure strain ε_{pf} is defined multiplicatively as a product of independent functions accounting for stress triaxiality τ , Lode parameter θ_L , plastic strain rate $\dot{\varepsilon}_p$, temperature T , and element size l_c :

$$\varepsilon_{pf} = f(\tau, \theta_L) g(\dot{\varepsilon}_p) h(T) i(l_c) \quad (3.31)$$

- **Triaxiality (τ):** Defined by the ratio of hydrostatic pressure p to von Mises stress σ_{vm} :

$$\tau = \frac{p}{\sigma_{vm}} \quad (3.32)$$

where $p = -\frac{\sigma_1 + \sigma_2 + \sigma_3}{3}$ and $\sigma_{vm} = \sqrt{\frac{3}{2}((\sigma_1 + p)^2 + (\sigma_2 + p)^2 + (\sigma_3 + p)^2)}$. A valid range of -1.0 to $+1.0$ is typical for impact simulations.

- **Lode Parameter (θ_L):** Boundaries the failure surface using principal deviatoric stresses s_1, s_2, s_3 , ranging between $[-1, 1]$:

$$\theta_L = \frac{27 s_1 s_2 s_3}{2 \sigma_{vm}^3} \quad (3.33)$$

- **Element Modeling:** Shell elements characterize failure strain purely as a function of triaxiality ($f(\tau)$ via a load curve). Solid elements require a full 3D failure surface boundary defined by both triaxiality and the Lode parameter ($f(\tau, \theta_L)$ via a table of curves generated through 3D curve-fitting of diverse material test specimens).

The built-in failure index in the *MAT_224 formulation is based on an accumulated damage parameter,

F , defined by the integration of plastic strain increments relative to the dynamic plastic failure strain:

$$F = \int \frac{\dot{\varepsilon}_p}{\varepsilon_{pf}} dt \quad (3.34)$$

where $\dot{\varepsilon}_p$ is the plastic strain rate and ε_{pf} is the continuously changing plastic failure strain. Elemental failure and subsequent deletion occur immediately when this built-in damage parameter reaches or exceeds unity ($F \geq 1$).

One of the primary advantages of the AWG-standardized models is the inclusion of built-in History Variables. These allow the analyst to extract critical data from the "black box" of the simulation, such as Effective Plastic Strain, to identify zones of permanent deformation, or triaxiality path, to understand if the skin failed due to bending-induced tension or shear-driven petalling.

By defining these parameters, the model ensures that the structural response is both visually realistic and numerically consistent with the standards required for aerospace structural integrity.

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 proposes three primary numerical metrics to compare the sensitivity across different flight conditions.

3.5.1 Geometric Damage Area (A_d)

The most direct measure of bird strike severity is the extent of the skin perforation. This is quantified by tracking the number of eroded elements, which are those that have reached the failure strain defined in Section 3.4.5. The total damage area A_d is calculated as:

$$A_d = \sum_{i=1}^{N_{\text{eroded}}} \text{Area}(e_i) \quad (3.35)$$

where N_{eroded} is the total count of failed elements. Comparing A_d between the "No-Load" and "High-Load" cases reveals whether the aerodynamic suction peak facilitates easier penetration by pre-tensioning the composite-equivalent skin.

3.5.2 Energy Dissipation and Balance

According to the LS-DYNA Theory Manual, monitoring the global energy balance is the primary method for ensuring simulation validity. For damage quantification, we focus on the Internal Energy (U) absorbed by the flap compared to the initial Kinetic Energy (E_k) of the bird. A "Damage Efficiency" metric is established to evaluate how much of the impact energy is dissipated through plastic deformation versus how much is retained by the projectile as it passes through the structure (residual velocity). The

energy balance is extracted from the GLSTAT and MATSUM files to ensure that the Hourglass Energy remains below the 5% threshold.

3.5.3 Virtual Strain Gauges and Peak History

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. The primary metric here is the Peak Strain Increment ($\Delta\epsilon$), defined as the difference between the maximum strain reached during the impact and the initial strain induced by the aerodynamic preload:

$$\Delta\epsilon = \epsilon_{\text{impact}}^{\text{max}} - \epsilon_{\text{aero}}^{\text{initial}} \quad (3.36)$$

This allows the study to isolate the dynamic shock from the static load, determining if the preload provides a stiffening effect or moves the material closer to its failure threshold.

Chapter 4

Impact Response Under Aerodynamic Preloading

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

4.1 Problem Definition and Numerical Setup

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.

4.1.1 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:

Table 4.1: Boundary condition constraints at track stations.

Boundary Station	Constraint Type	Structural Representation
Outboard (IB) Track	Translational (X, Y, Z)	Fixed joint of the track mechanism.
Outboard (OB) Track	Translational (X, Y, Z)	Fixed joint of the track mechanism.

The connection between the main spar and the tracks is modelled using rigid link assemblies via the `*CONSTRAINED_NODAL_SET` keyword in LS-DYNA. This prevents the non-physical distortion of the internal rib-to-spar joints while ensuring that the integrated vertical aerodynamic force, as well as the high-energy shock of the bird impact, is correctly transferred through the primary load path of the wing structure.

4.1.2 Initial Conditions of the Impact Event

The bird strike scenario is modelled as a normal, symmetrical impact on the leading edge of the flap skin. The key parameters governing the initial state of the impactor are defined as follows (Tab. 4.2):

Table 4.2: Initial conditions for the impact scenario.

Parameter	Value	Operational Context
Impact Velocity	66 m s^{-1}	Aligned with aircraft final approach speed.
Impact Angle	47°	Effective angle during maximum high-lift configuration deflection.
Spanwise Position	Mid-span	Aligned between track attachments .

4.1.3 Contact Formulations and Numerical Controls

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.

In order to prevent internal element penetration during localized buckling or folding after impact, a `*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE` keyword 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. Figure 4.1 displays the global energy conservation profile throughout the 14.95 ms simulation window.

The internal energy (U) exhibits an upward trend, mirroring the external work (W) applied by the fluid-structure interface. The global energy ratio remains bounded at 1.0, which confirms that the underlying element formulations and contact algorithms maintain strict numerical stability, introducing no significant non-physical energy dissipation or artificial stiffening into the system mesh.

As observed in the vertical displacement profiles of the history nodes (Fig. 4.2), 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.

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

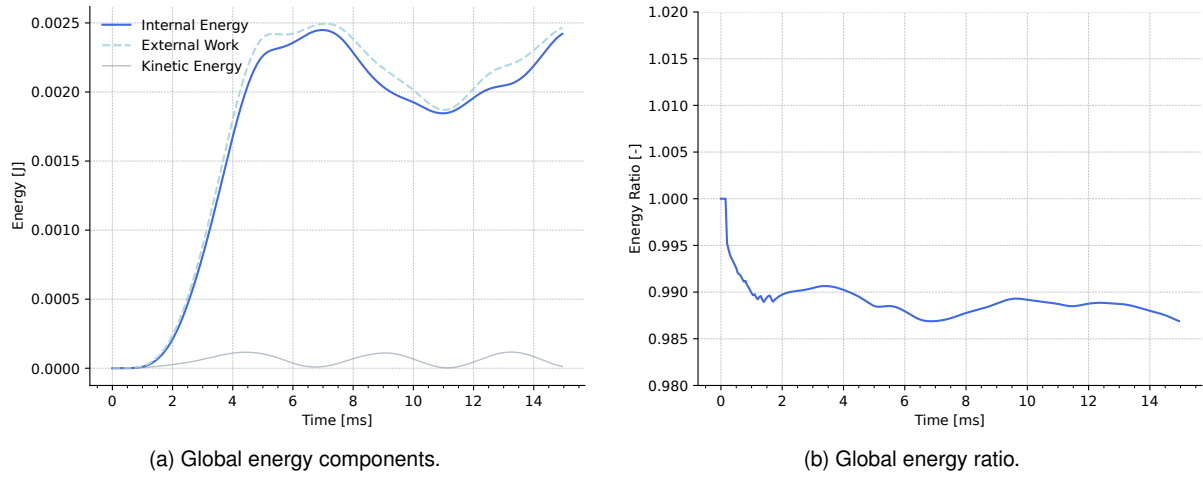


Figure 4.1: Global energy components and energy ratio for the aerodynamically loaded trailing-edge flap. Transient regime.

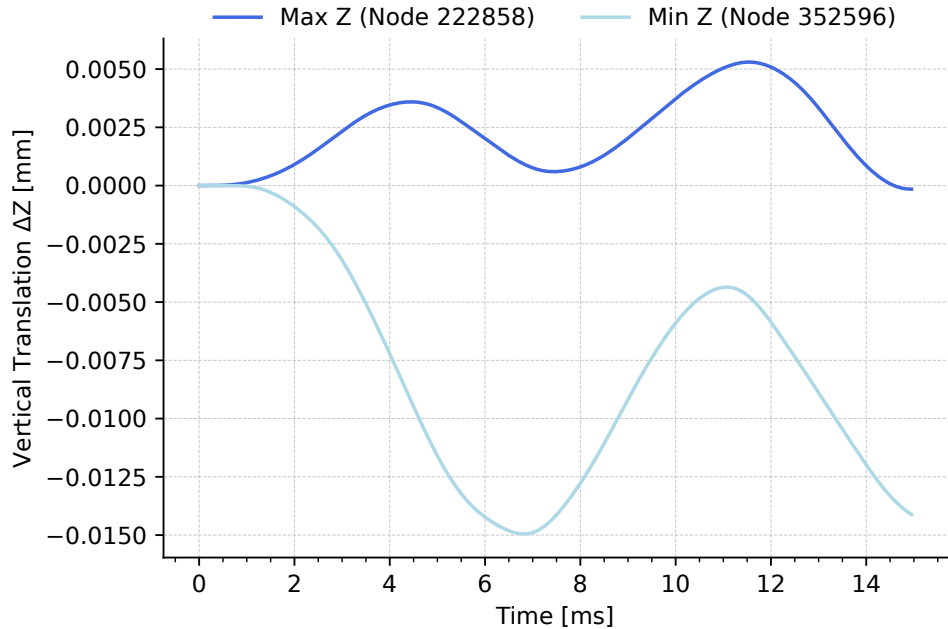


Figure 4.2: Aerodynamic deformation history of the nodes with the maximum positive and negative resultant deformation.

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 Finite Element (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 4.3 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 proportion to the applied aerodynamic pressure envelope.

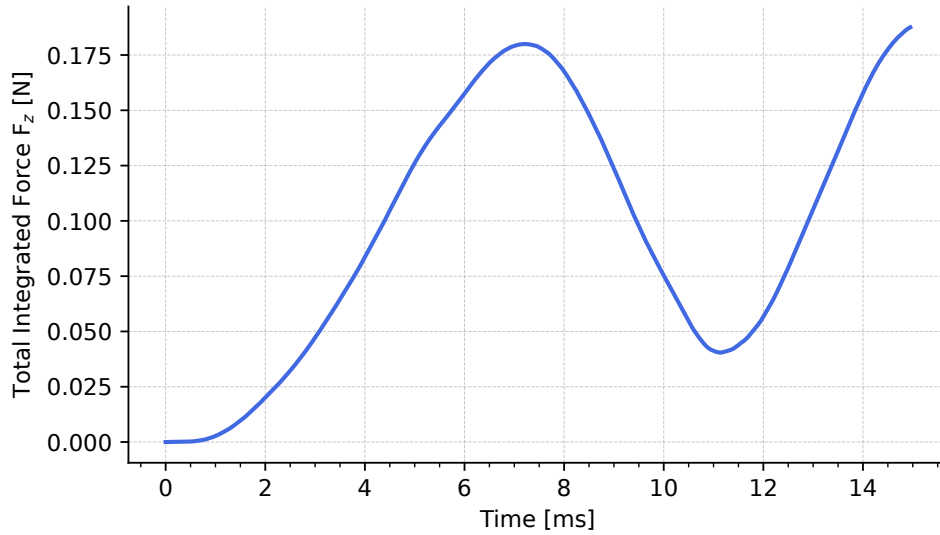


Figure 4.3: Combined vertical boundary resultant reaction force history showing the cumulative load transfer to the support mounts during the aerodynamic pressure ramp.

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 presence of high-frequency micro-oscillations on the reaction curve mirrors the kinematic flutter observed in the displacement histories. This confirms that the transient inertial forces generated by the structural flexing are being transmitted through the localized load paths of the internal spar caps into the hard mounting constraints, verifying the structural load path integrity of the assembly model.

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.

This numerical discrepancy points directly to an upstream unit-system scaling mismatch during the fluid-structure interface mapping sequence. This suggests possible formatting discrepancies, most notably applying pressure arrays in Pa rather than MPa, which introduces downscaling factors of 10^6 .

While this scaling anomaly invalidates the absolute load magnitudes of this case, the simulation retains value as a qualitative framework verification. The fact that the energy curves remain perfectly conserved and the reaction force wave shape precisely follows the loading profile proves that the structural load paths, element formulations, and boundary constraints are functioning correctly. The framework is computationally viable; resolving the magnitude issue simply requires modifying a single scalar multiplier in the loading input deck prior to deployment.

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 4.4 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.

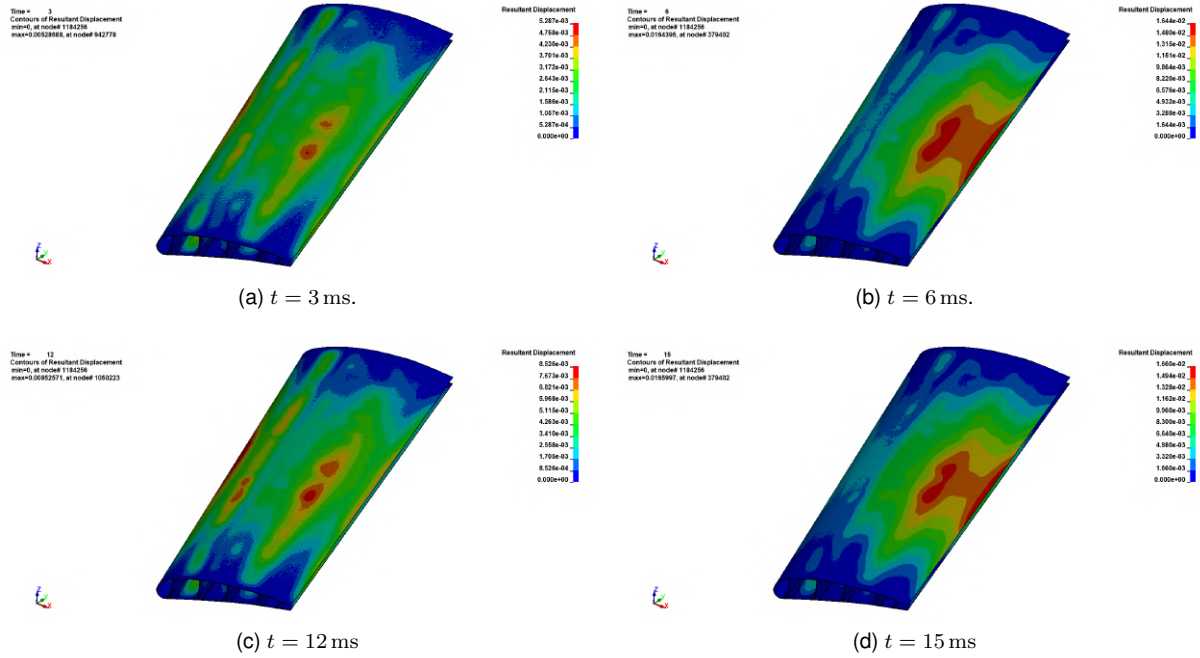


Figure 4.4: Visualization of the deformation history during the transient aerodynamic loading.

Complementing the displacement global tracking, Fig. 4.5 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 internal 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.

4.2.1 Pre-Stress Characterization and Internal Force Mapping

Following the framework verification, a new simulation was executed to capture the complete structural force mapping profile. This simulation successfully computed the full 14.95 ms aerodynamic loading sequence across 300 continuous time frames, matching the temporal scale of the baseline calibration.

The primary objective of this run was to map the full three-dimensional internal nodal force fields across all 307 614 discrete elements of the internal CFRP assembly. This established the complete pre-stressed equilibrium state required immediately prior to the transient bird strike event.

The cumulative boundary reaction forces were resolved across the X , Y , and Z local coordinate

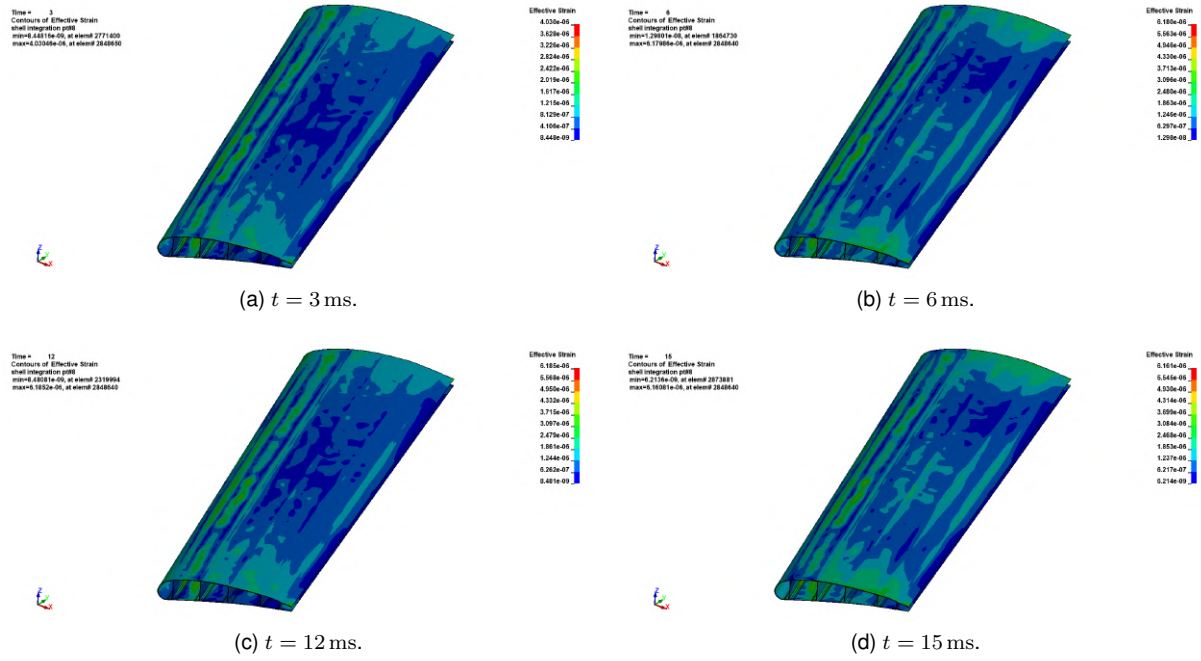


Figure 4.5: Visualization of the effective von Mises strain history during the transient aerodynamic loading.

axes via the single-point constraint repository (`spcforc`). Figure 4.6 maps the evolution of these global load components throughout the loading sequence.

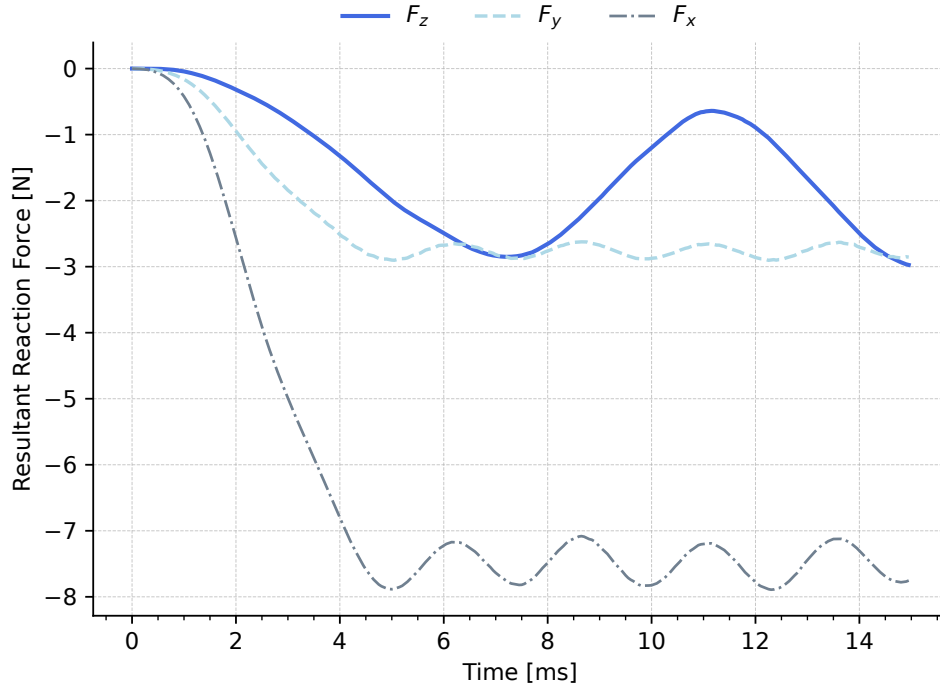


Figure 4.6: Completed global boundary mounting reaction force history over the full 14.95 ms aerodynamic loading period.

The numerical sign convention of the resulting curves provides immediate physical validation of the boundary constraint environment. All three primary force vectors resolve into negative regimes. Be-

cause the transient aerodynamic pressure field exerts positive out-of-plane forces (pushing the flap skin structurally upward (+ Z) and downstream (+ X)) the mounting constraints must respond with equal and opposite reaction vectors, pulling the assembly downward ($-Z$) and forward ($-X$) to preserve structural equilibrium.

Additionally, both the F_y and F_x reaction tracks exhibit synchronized, low-frequency macro-oscillations. This confirms that the global load-cell mounts are successfully registering and transferring the structural inertial flexing of the cantilevered design, establishing a complete, dynamically active pre-stress state prior to the high-velocity projectile collision.

However, from an absolute quantitative standpoint, the terminal magnitudes achieved at peak pre-stress exhibit particularities that demand an engineering evaluation. Similar to the trends observed in the original calibration baseline, the total reaction loads scale significantly below operational flight thresholds. This pattern suggests that while the directional orientation, coordinate systems, and load paths are functioning correctly, an underlying unit scaling artifact persists within the external data pipeline interface.

Simplified Aerodynamic Load Modelling

The full-detail fluid-structure interface mapping generated a massive array of individual localized pressure definitions, with significant costs in terms of the input deck's file size and parsing time. A simplified load model was developed by strategically aggregating the local spatial pressure fields into a consolidated configuration with a much smaller number of *LOAD cards, as described earlier in 3.2.2.

The structural validity of this optimization framework is explicitly verified by the boundary reaction signatures. As seen in Fig. 4.7, the simplified loading model produces a near-identical structural response compared to the high-fidelity baseline deck.

4.2.2 Static Pre-load Verification via Dynamic Relaxation

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 4.2.1. Acceptable agreement was observed in the overall displacement distribution, peak displacement magnitude, and stress levels within the flap structure. The comparison demonstrates that the transient initialization procedure produces a similar global structural response to that predicted by the DR analysis. As detailed

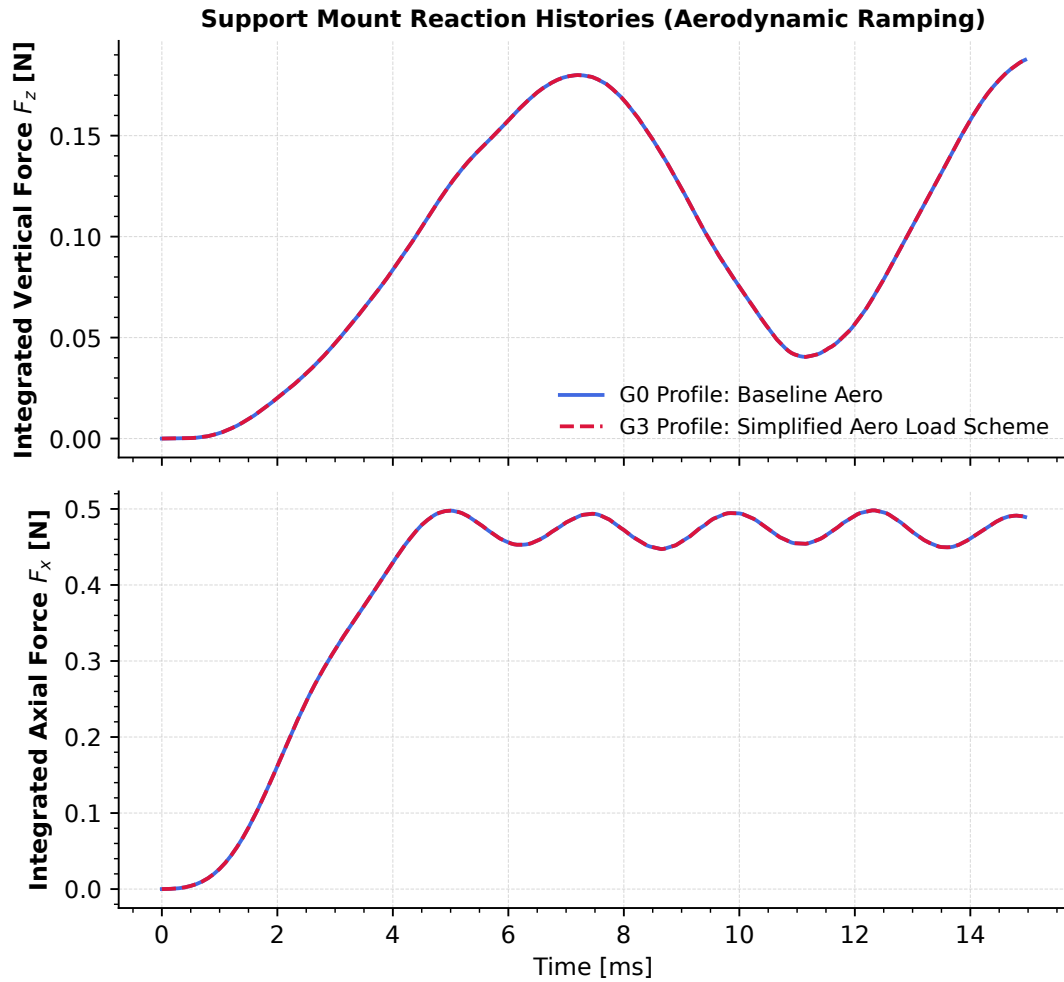


Figure 4.7: Comparison of integrated boundary reaction force histories between the full-detail pressure mapping deck and the optimized, simplified aerodynamic loading model. Agreement is observed.

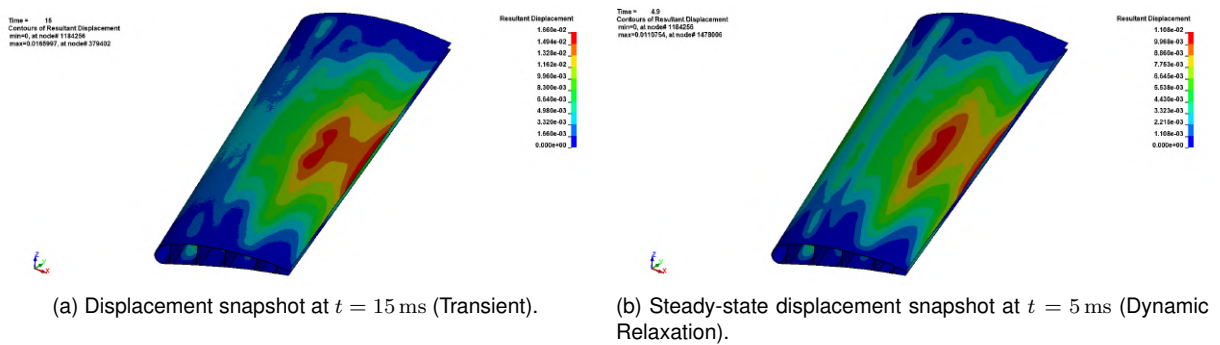


Figure 4.8: Static displacement field achieved via dynamic relaxation, confirming architectural alignment with the transient quasi-static snapshots.

in Table 4.3, the relative errors for peak structural deflection and peak von Mises stress are 47.82 % and 30.80 %, respectively. While these percentage values appear high, they appear as consequence of comparing values near zero; the absolute variances are restricted to a negligible 5.37×10^{-3} mm in displacement and 1.91 Pa in stress. Consequently, the transient preload methodology is adequate e for the purposes of the present study.

Table 4.3: Quantitative correlation metrics between static dynamic relaxation (DR) initialization and explicit transient baseline end-state.

Structural Parameter	Static (DR)	Transient	Absolute difference (Δ)	Rel. Error
Peak Deflection	1.123×10^{-2} mm	1.66×10^{-2} mm	5.37×10^{-3} mm	47.82 %
Peak von Mises Stress	6.185 Pa	8.09 Pa	1.91 Pa	30.80 %

4.3 Bird Strike Impact Response

This section transitions to the transient impact phase. The results are evaluated based on the damage quantification metrics.

4.3.1 Response with Aerodynamic Loading

This section evaluates the primary research question of this study: *"How does aerodynamic loading influence the impact response of a wing flap?"*

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.

Evaluating this coupled timeline allows the investigation to look past isolated baseline approximations and capture the complex interaction between static pre-stress fields and severe, high-rate transient impact dynamics.

The global system energy tracks were captured via the explicit solver's global statistical repository (glstat). Figure 4.9 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.

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.

The numerical check line for hourglass energy (E_{hg}) remains completely flat and close to zero throughout the high-velocity impact event. In soft-body impact simulations using smoothed particle hydrodynamics (SPH) or highly compressed shell elements, localized high-pressure gradients can trigger severe hourglassing failures. The strict stability of E_{hg} documented in Fig. 4.9 proves that the element

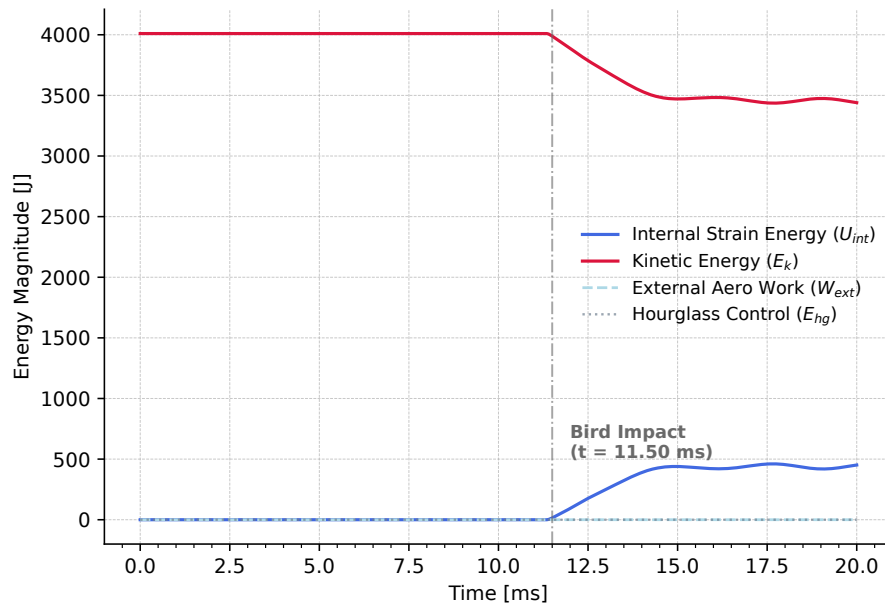


Figure 4.9: Global energy conservation and transformation history, documenting the transition from aerodynamic preloading to projectile impact at $t = 11.50$ ms.

formulations maintain structural and numerical validity under extreme localized crushing loads, validating the framework's capability to predict bird strike events.

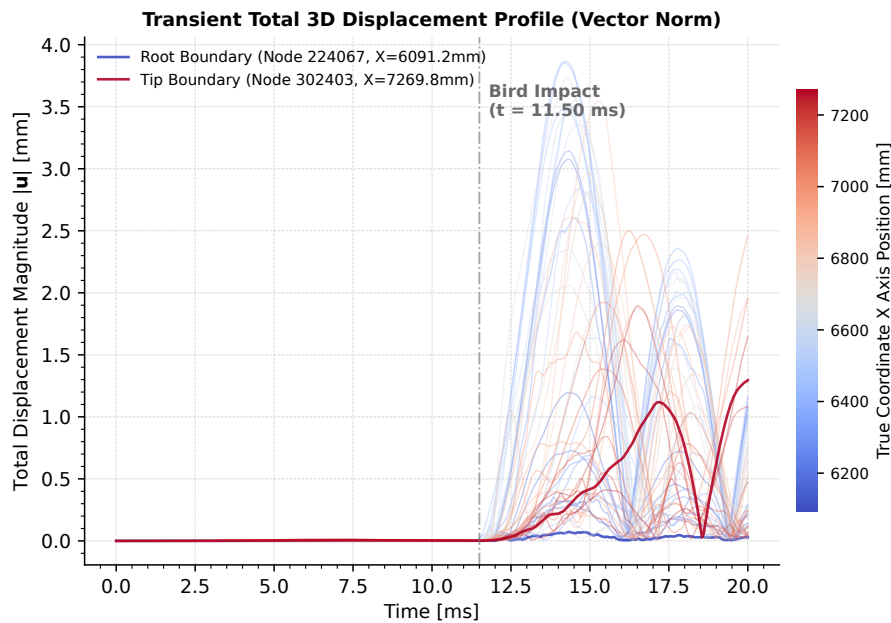


Figure 4.10: Total displacement of selected control nodes on the flap surface upon bird strike.

Upon impact contact, a massive influx of kinetic energy (E_k) enters the structural domain, reflecting the high momentum transfer of the disintegrating soft-body bird mass. Simultaneously, the internal strain energy (U) experiences a rapid, non-linear vertical acceleration. Because the aerodynamic pre-stress field has already used a portion of the material's elastic resilience capacity, the localized structural skin panels transition rapidly into plastic deformation regimes, absorbing the projectile's kinetic energy

through plastic shear straining, crushing of the internal rib webs, and local structural tearing. These deformations are visualized in Fig. 4.10 as the displacement values at multiple selected nodes.

4.3.2 Damage Assessment Summary

Within high-velocity impact logistics and soft-body aircraft component vulnerability analysis, a variety of advanced damage proxy parameters exist to quantify material degradation, including continuum damage mechanics tensors, delamination footprint metrics, and specialized failure index variables. The structural integrity evaluation in this work is explicitly driven by transient deformation fields and effective plastic strain histories. These two kinematic and constitutive metrics serve as reliable, direct indicators of localized energy absorption, yielding a clear representation of structural compliance and permanent material distortion.

To evaluate the macro-structural consequences of the foreign object damage (FOD) event, a comparative transient analysis was compiled between the standalone aerodynamic baseline and the fully coupled pre-load impact sequence (Figure 4.11).

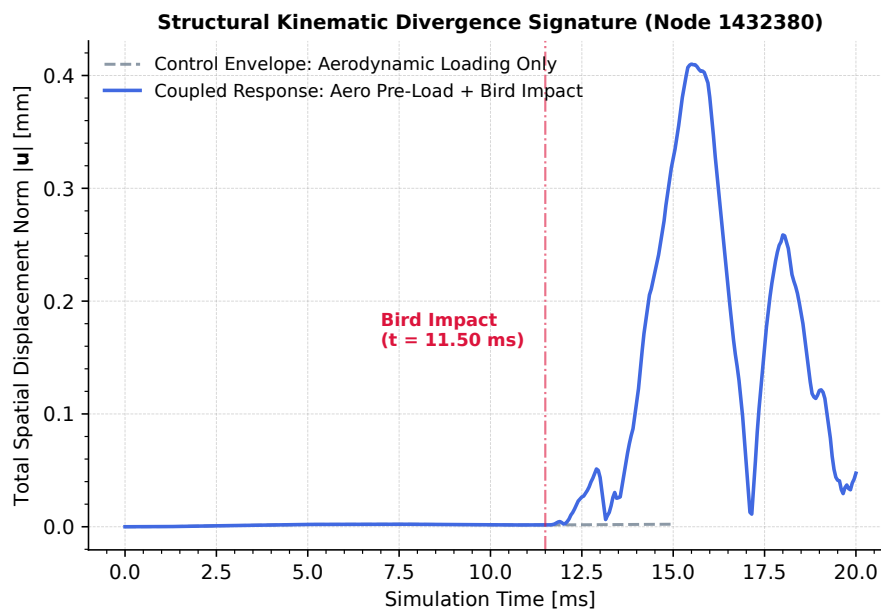


Figure 4.11: Transient displacement history comparison between the standalone aerodynamic pre-load calibration case and the coupled pre-load bird strike sequence.

To isolate the operational envelope thresholds and verify structural boundary stability across the trailing-edge assembly, a localized kinematic assessment was conducted. Figure 4.12 tracks the transient displacement magnitude histories for the absolute maximum and minimum deflecting node locations recorded during the coupled aerodynamic pre-load and soft-body impact event.

The physical coordinates of these tracking nodes are mapped directly onto the structural assembly mesh in Figure 4.13 to establish their spatial relationship with the structural architecture. The maximum-amplitude tracking node (Node 1587411) is located within the flexible skin panels near the mid-span impact region. This position successfully captures the localized structural indentation and localized

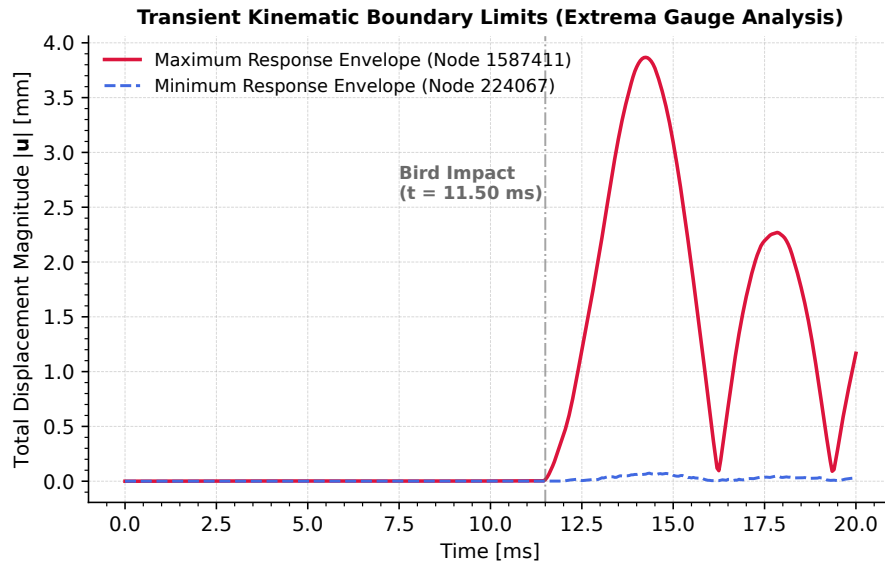


Figure 4.12: Transient displacement magnitude histories for the absolute maximum and minimum bounding nodes under coupled aerodynamic and bird strike loading.

compliance directly targeted by the hydrodynamic SPH projectile stream.

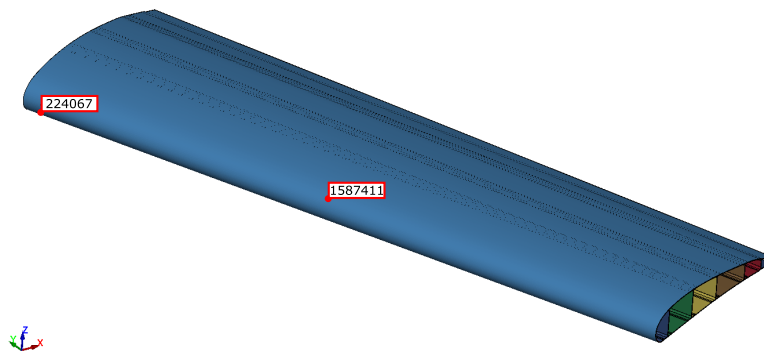


Figure 4.13: Spatial localization of the tracking nodes within the explicit finite element mesh, identifying the maximum amplitude bounds near the mid-span panel skin and the minimum amplitude bounds adjacent to the rigid support track.

Conversely, the highly attenuated kinematic history belonging to Node 224067 is situated immediately adjacent to the rigid structural support track. This sharp spatial differentiation confirms that the explicit numerical model correctly interprets the localized boundary stiffness transitions, capturing the high structural restraint imposed by the track attachments while simultaneously resolving the flexible transient response of the unreinforced skin panels.

Chapter 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 integration of high-fidelity tabulated material models and multi-physics projectile definitions has yielded physical insights into the mechanics of HVI.

5.1 Achievements

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 applies a quasi-static initialization phase that applies mapped load segments over time, achieving a stable, albeit unsteady, 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 XFR1 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.

5.2 Future Work

The successful establishment and verification of the core implicit–explicit numerical pipeline provides a solid foundation for subsequent research. While the pipeline itself proved structurally sound, some of the simulated cases encountered technical constraints that limit the range of cross-case comparability. Consequently, the immediate next phase of this work entails executing a highly structured, fully repeated simulation matrix, in order to allow a more comprehensive comparison. By subtly adjusting simulation parameters, this validated coupling framework can be used to generate a more aligned and comprehensive set of cross-case aero-structural impact visualizations (.d3plot) and complete time-history data streams.

Beyond finalizing the current parametric matrix, this research can be expanded and advanced across three primary technical fronts:

Integration of Advanced Composite Material Models:

- Transition from the current isotropic metallic baseline used for pipeline validation to high-fidelity Carbon Fibre Reinforced Polymer (CFRP) material cards, enabling the evaluation of orthotropic progressive damage mechanisms under pre-stressed flight configurations.
- Implementation of Cohesive Zone Modelling or specialized tie-break contact definitions at the internal interfaces to explicitly investigate interlaminar delamination and debonding characteristics between the outer skin and the multi-spar web cells.

Higher-Fidelity Fluid-Structure Interaction (FSI):

- Progress from the current one-way sequential pressure mapping to a fully coupled, two-way partitioned FSI architecture, where the severe structural deformations occurring during the sub-millisecond impact event actively feed back into and alter the localized aerodynamic flow field.
- Assess transient, unsteady aerodynamic effects and atmospheric gust loads using time-accurate Reynolds-Averaged Navier-Stokes (RANS) formulations to capture the influence of dynamic flow fluctuations on the target's structural vulnerability footprint.

Experimental Validation and Correlation:

- Conduct physical gas-gun impact tests on representative multi-spar flap segments to establish an experimental baseline for validating the numerical damage morphology, residual plastic strains, and transient strain-time histories obtained in LS-DYNA.
- Refine the Smooth Particle Hydrodynamics (SPH) projectile model through direct correlation with high-speed experimental imagery, ensuring that the critical Hugoniot stagnation pressure and subsequent hydrodynamic flow phases are captured with maximum empirical accuracy.

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