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FBG-Based Monitoring and Hailstone Impact Assessment of an SLM Lattice Leading Edge for Aircraft De-Icing Applications

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Abstract—Hailstone and soft-body impacts represent a critical threat to the structural integrity of aircraft leading edges, potentially compromising anti-icing system functionality and flight safety. This paper addresses the combined challenge of impact resilience and in-service monitoring for a novel Selective Laser Melting (SLM) lattice-core leading edge designed for subsonic aircraft de-icing applications. Three alloys—AlSi10Mg, AISI 316L, and Ti-6Al-4V—were manufactured and subjected to an explicit Finite Element Method (FEM) impact analysis using Altair Radioss with Smooth Particle Hydrodynamics (SPH) ice discretisation, covering hailstone diameters of 15–35 mm and velocities of 100–200 m/s. A complementary gas-gun experimental campaign, designed according to a Face-Centered Central Composite Design of Experiments, provided ground-truth damage data classified on a 0–3 scale and validated the numerical predictions. Fiber Bragg Grating (FBG) sensors, bonded on the external skin, were deployed as a dual-function sensing network: thermal cycling tests between -40°C and $+50^{\circ}\text{C}$ yielded temperature-wavelength-shift correlation coefficients above 99% for both AlSi10Mg and AISI 316L, while the same sensors captured deformation onset, post-impact damping, and residual strain during ballistic events with sub-millisecond resolution. AISI 316L exhibited no perforation across the full test envelope; AlSi10Mg reached skin breakage above ~ 170 m/s for diameters ≥ 25 mm.

Index Terms—FBG sensors, SLM, lattice structure, hailstone impact, de-icing, structural health monitoring.

I. INTRODUCTION

The accumulation of ice on the leading edges of wings, empennages, and engine inlets is a persistent safety and efficiency challenge in aviation [1]. Ice formation degrades aerodynamic performance, increases drag, and can compromise structural integrity under combined aerodynamic and thermal loads [2]. Conventional anti-icing strategies—hot-air bleed systems, pneumatic de-icers, electrothermal heaters—address the thermal problem but introduce additional weight, energy penalties, and maintenance complexity [3]. An emerging paradigm exploits additive manufacturing (AM) to realise multifunctional lattice-core leading edges that simultaneously carry structural loads, distribute de-icing hot air through the internal trabecular network, and host embedded sensing systems [4], [5].

Among the threats to operational effectiveness of such systems, hailstone and soft-body impacts are particularly critical [6]. A single impact event can locally deform or perforate the thin external skin, interrupting hot-air flow and ultimately

compromising anti-icing performance in safety-critical flight phases [7]. The problem is compounded by the mechanical response of AM alloys at high strain rates [8], making material selection a key design decision alongside lattice topology optimisation [9].

Robust monitoring of both thermal performance and structural integrity is therefore essential for next-generation integrated anti-icing systems. Fiber Bragg Grating (FBG) sensors are particularly attractive for this role: lightweight (< 1 g/m), immune to electromagnetic interference, and capable of wavelength-division multiplexing along a single fibre [10], [11]. These properties make them well suited for integration into complex lattice-core structures [12], [13], and they have been demonstrated in aerospace SHM applications including composite-wing strain monitoring [14], impact detection in fuselage panels [15], and temperature measurement in turbine sections [16].

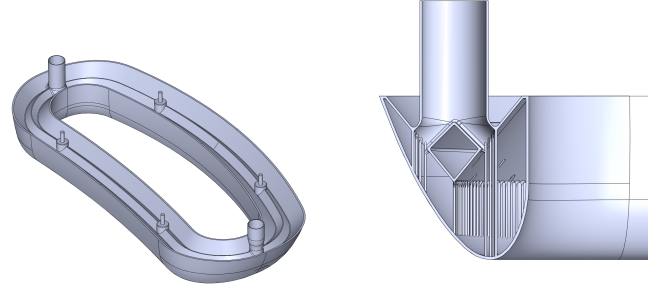
The present study follows a structured workflow: first, an explicit FEM model of the leading edge is developed to predict structural response under hailstone impact across the full parametric space; second, the FEM predictions are cross-validated against a gas-gun experimental campaign providing ground-truth damage data; third, FBG sensors—active throughout both campaigns—deliver real-time thermal and strain information that serve simultaneously as independent validation evidence and as a demonstration of embedded monitoring capability on the actual test hardware.

II. MATERIALS AND METHODS

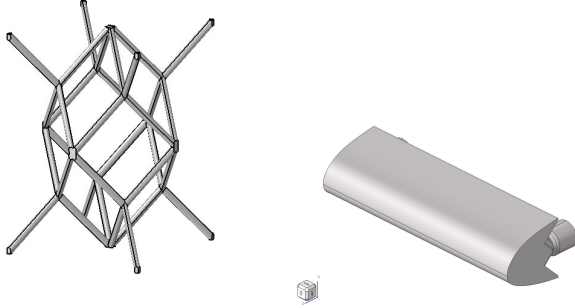
A. Test Article Geometry and SLM Manufacturing

The test article is a representative spanwise section of a wing leading edge featuring an internal orthorhombic trabecular core and a thin external skin, designed by Ellena S.p.A. The geometry was originally supplied as an STL file and subsequently rebuilt as a parametric solid CAD model to support FEM meshing and manufacturing process control.

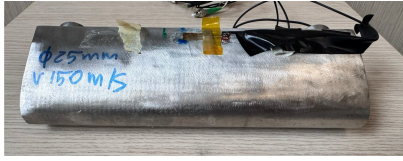
The external geometry and internal architecture are illustrated in Fig. 1. The full leading-edge lip features a curved aerodynamic profile with four rear attachment connectors; the cross-sectional view reveals the lattice foam filling the internal volume. The repeating elementary cell has dimensions $15 \times 15 \times 22$ mm with circular member diameter 0.7 mm: these



(a) Isometric view of the full leading-edge lip. (b) Cross-section exposing the internal lattice foam.



(c) Elementary orthorhombic cell (d) 3D view of the assembled test article. (15×15×22 mm, d=0.7 mm members).



(e) Manufactured SLM specimen with FBG sensor bonded on the external skin.

Figure 1: Test article: CAD geometry (a–d) and manufactured specimen (e). The curved outer skin and rear connectors enclose an orthorhombic lattice core; photo (e) shows the as-built SLM test article with the FBG sensor installed on the external skin.

parameters govern simultaneously the mechanical stiffness of the core and the hydraulic resistance to hot-air flow. The assembled test article (Fig. 1d) integrates skin, lattice, and vertical pillars in a single SLM-manufactured piece.

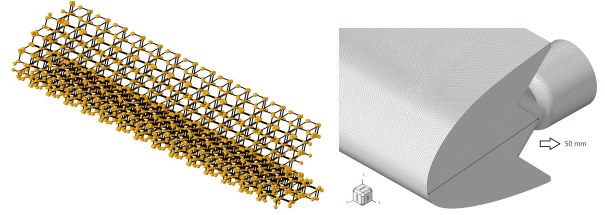
Specimens were produced by Selective Laser Melting (SLM) in three alloys spanning a wide range of strength, ductility, and thermal conductivity (Table I).

B. FEM Numerical Model

Explicit FEM simulations were carried out in Altair Radioss [20] to predict structural response under hailstone impact prior to the experimental campaign, and to provide a validated numerical companion to the sensing dataset. The structural model (Fig. 2) combines ~ 1.09 M first-order Tetra4 solid

Table I: Key material properties of the SLM alloys (tonne–mm–s system).

Property	AISI 316L	Ti-6Al-4V	AlSi10Mg
E [MPa]	193 000	110 000	72 000
σ_y [MPa]	465	800	200
UTS [MPa]	620	1 000	350
ρ [t/mm ³]	7.95×10^{-9}	4.43×10^{-9}	2.65×10^{-9}
k [W/(mm·K)]	16.2	6.7	160
α_T [10^{-5} K ⁻¹]	1.60	0.86	2.15



(a) 1D beam mesh of the internal lattice (2661 elements). (b) 3D tetrahedral mesh of the external shell (~ 1.09 M elements).

Figure 2: FEM discretisation of the test article. Beam elements model the slender lattice members; Tetra4 elements discretise the outer skin and connectors.

elements (average size 0.8 mm) for the external shell with 2661 Euler–Bernoulli beam elements for the internal lattice.

Ice hailstones ($\rho_{ice} = 916.7$ kg/m³) were discretised with Smooth Particle Hydrodynamics (SPH) [18] using a face-centred cubic particle layout (~ 1000 particles per projectile), governed by a hydrodynamic Johnson–Cook constitutive law. The SPH smoothing length h was set slightly below the particle pitch (ratio ≈ 0.8) to correctly reproduce brittle fracture dynamics of the ice [19]. Target failure was handled by a BIQUAD ductile damage criterion calibrated on database data for each alloy; contact between projectile and structure was enforced via a TYPE7 penalty interface with friction coefficient 0.15 [20]. Three impact velocities (100, 150, 200 m/s) and three hailstone diameters (15, 25, 35 mm) were simulated for each alloy.

C. CFD Thermofluid Analysis

To characterise the thermal performance of the lattice leading edge under operative de-icing conditions, a computational fluid dynamics (CFD) study was conducted in STAR-CCM+ using a coupled flow–energy solver. The computational domain was split into two sequential spanwise sections to keep the ~ 70 M-cell mesh within available high-performance computing resources. Hot air entered at 373.15 K (100 °C) and 10 m/s, representing the bleed-air supply of a typical de-icing system. The external skin was exposed to a convective boundary condition ($h = 3.5$ W/m²K, $T_\infty = 273.15$ K) simulating cruise in icing conditions. Turbulence was modelled with the Realizable k – ϵ two-layer formulation.

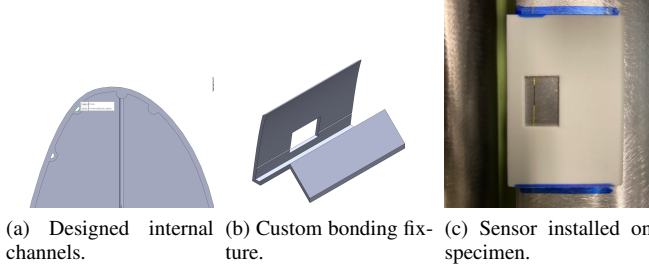


Figure 3: FBG integration: designed internal routing (a), external bonding fixture (b), and final installed configuration on the leading-edge skin (c).

D. FBG Sensor Network: Design and Integration

An FBG reflects a Bragg wavelength $\lambda_B = 2n_{\text{eff}}\Lambda$ that shifts with both mechanical strain ε and temperature ΔT [10]:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - p_e)\varepsilon + (\alpha_\Lambda + \alpha_n)\Delta T, \quad (1)$$

where p_e is the photo-elastic constant, α_Λ the fibre thermal expansion coefficient, and α_n the thermo-optic coefficient. This dual sensitivity is exploited as an asset: since thermal and impact campaigns were conducted separately, the same sensor array delivers independent, cross-talk-free measurements in both regimes.

Dedicated 0.7 mm-radius longitudinal channels were designed within the lattice core for internal FBG routing (Fig. 3a). However, the as-built SLM parts presented excessive internal roughness and trapped powder [17], making direct insertion impractical. For the current campaign, sensors were bonded on the external skin using a high-temperature epoxy-ceramic adhesive (rated to 400 °C). A custom fixture (Fig. 3b) enforced repeatable placement and uniform bond-line thickness.

E. Thermal Cycling Protocol

Two sets of three leading-edge specimens (AlSi10Mg and AISI 316L), each instrumented with three FBG channels, were placed simultaneously inside a climatic chamber. Temperature was cycled between -40°C and $+50^\circ\text{C}$ in discrete 10°C steps with a 30-minute dwell at each level. Three complete up-down cycles were executed to assess measurement repeatability and to confirm the absence of sensor drift under repeated thermal loading.

F. Gas-Gun Impact Campaign

The ballistic facility consists of a pressurised reservoir, a rifled launch barrel, and an electrically triggered firing assembly; projectile velocity is measured by a three-point laser-photodiode timing system. Hailstone specimens (diameters 15, 25, 35 mm; density 916.7 kg/m^3) were manufactured following an established protocol [7] and housed in a custom sabot.

A Face-Centered Central Composite Design of Experiments (CCD) [21] was adopted to maximise information content with a minimum number of tests, including three replicates per case

Table II: Impact test matrix (Face-Centered CCD). Ti-6Al-4V specimens under manufacturing at time of writing.

Diam. [mm]	Speed [m/s]	Material
15	100	AlSi10Mg / Ti-6Al-4V
15	200	AlSi10Mg / Ti-6Al-4V
35	100	AlSi10Mg / Ti-6Al-4V
35	200	AlSi10Mg / Ti-6Al-4V
15	150	AISI 316L
35	150	AISI 316L
25	100	AISI 316L
25	200	AISI 316L
25	150	All three

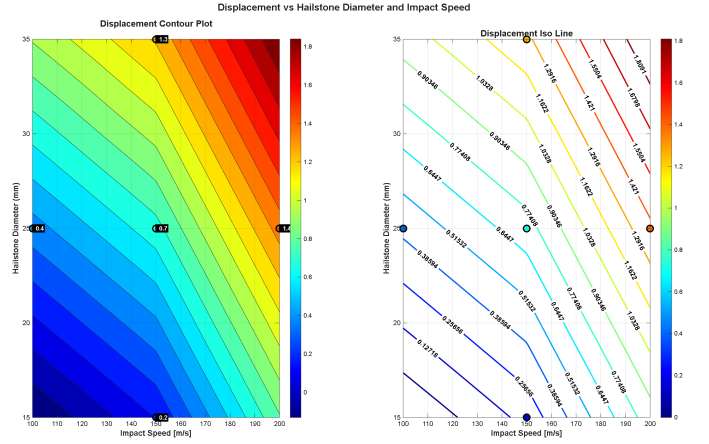


Figure 4: FEM contour maps of maximum skin displacement (AISI 316L case). The transition from minor deformation ($<0.5\text{ mm}$) to severe structural response ($>1.5\text{ mm}$) defines the critical threshold used to validate experimental observations and FBG residual data.

for statistical robustness. The 15 test cases (Table II) span the full parameter space. FBG sensors remained active throughout every shot. Post-impact specimens were classified on a 0–3 damage scale (0 = no damage; 1 = surface deformation; 2 = cracking without perforation; 3 = full skin perforation).

III. RESULTS

A. FEM Impact Simulations

The FEM displacement contour maps (Fig. 4) show a clear and physically consistent monotonic increase of maximum skin displacement with both hailstone diameter and impact velocity. At low energy (small diameter, $\sim 100\text{ m/s}$) skin deformation remains below 0.5 mm for all materials; as either parameter increases, displacement escalates, reaching values above 1.5 mm for 35 mm projectiles at 200 m/s.

B. CFD Thermofluid Results

Heat transfer initiates at the discrete contact points between the internal lattice cells and the outer skin, initially forming a characteristic dot pattern on the external surface. As the simulation progresses these localised hot spots merge into

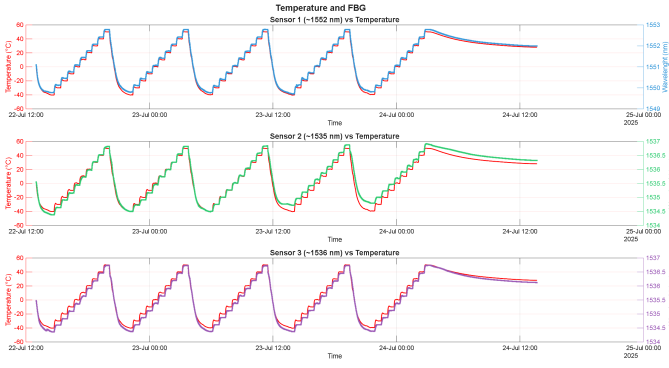


Figure 5: Temperature vs. wavelength shift — AISI 316L specimens, three complete thermal cycles, channels 1–3. Excellent linearity and cycle-to-cycle repeatability confirm sensor stability.

Table III: FBG thermal cycling results — AISI 316L specimens.

Channel	R^2	T range [°C]	$\Delta T/\Delta \lambda$ [°C/nm]
Fiber 1	0.9995	−40.4 to +50.3	29.44
Fiber 2	0.9897	−40.4 to +50.3	35.68
Fiber 3	0.9979	−40.4 to +50.3	38.00

Table IV: FBG thermal cycling results — AlSi10Mg specimens.

Channel	R^2	T range [°C]	$\Delta T/\Delta \lambda$ [°C/nm]
CH1	0.9982	−40.4 to +50.2	29.31
CH2	0.9978	−40.4 to +50.2	28.74
CH3	0.9993	−40.4 to +50.2	29.62

a continuous thermal field covering the full leading-edge surface.

After 10 s of physical time the external surface reaches a maximum temperature of 291 K—18 K above the ambient freezing level—confirming the anti-icing effectiveness of the lattice configuration under the imposed boundary conditions. The average heat flux delivered to the trabecular structure is **1256 W/m²**, directly linking the CFD and structural simulation chains.

C. FBG Thermal Monitoring

All FBG channels exhibited a highly linear and repeatable temperature–wavelength-shift correlation across the three thermal cycles (Figs. 5–6). Correlation coefficients exceeded 99% for both materials (Tables III and IV), confirming the accuracy of the external bonding approach over the full de-icing operational range.

D. FBG Structural Monitoring During Impact

For each shot, the FBG wavelength-shift history reveals three physically distinct phases (Fig. 7). The **onset** phase: a sharp, high-amplitude shift marks the instant of first contact. The **post-impact damping** phase: exponentially decaying

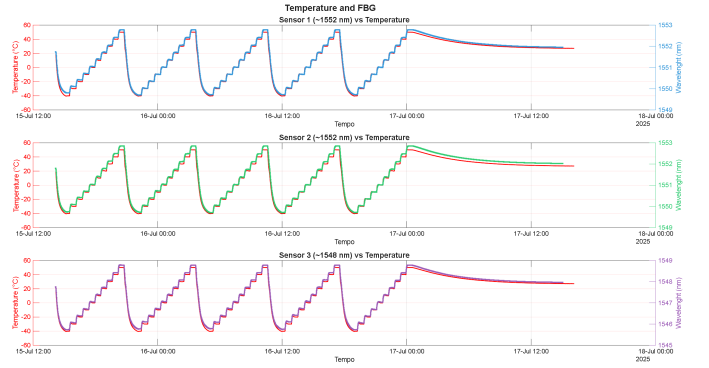


Figure 6: Temperature vs. wavelength shift — AlSi10Mg specimens, three thermal cycles. Correlation remains above 99% despite the higher thermal expansion of aluminium.

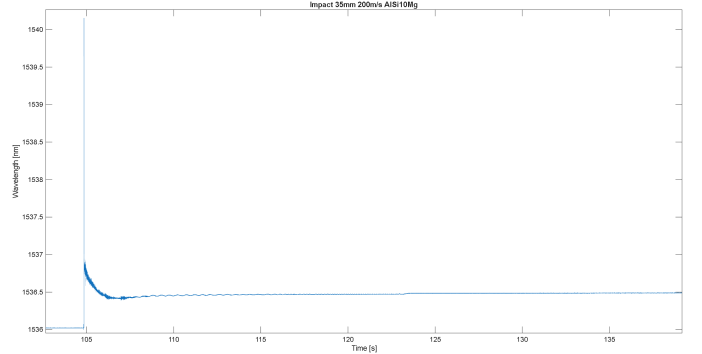


Figure 7: FBG wavelength-shift history — 35 mm projectile at 200 m/s, AlSi10Mg specimen. The three phases (onset, damped oscillation, residual deformation) are clearly distinguishable.

oscillations carry information on structural damping ratio and residual bending stiffness after impact. The **residual deformation** phase: the signal stabilises at a permanent offset directly proportional to the plastic strain imparted by the projectile, enabling quantification of permanent structural damage without disassembly or destructive inspection [23].

Sensors operated reliably across all shots, including cases of full skin perforation. The magnitude of the residual wavelength offset correlated monotonically with the visually assigned damage level, indicating its potential as a quantitative, non-invasive damage indicator for in-service inspection.

E. Experimental Impact Damage and FEM Validation

The discrete damage-level measurements were interpolated over the diameter–velocity plane using a radial basis function to generate continuous contour maps (Figs. 9 and 10).

AlSi10Mg (Fig. 9) exhibited steep sensitivity to both parameters: damage level 3 (perforation) was reached for diameters ≥ 25 mm at velocities above ~ 170 m/s, consistent with the limited fracture toughness and reduced strain-rate sensitivity of SLM-processed aluminium [8]. **AISI 316L** (Fig. 10) demonstrated markedly superior resistance—damage level 3 was *never* reached—confirming the high toughness

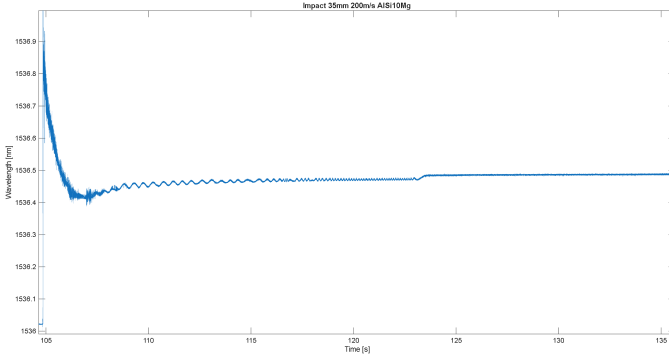


Figure 8: Zoom on the impact onset and early damping phase. Sub-millisecond temporal resolution confirms the suitability of FBG sensors for ballistic-rate structural events.

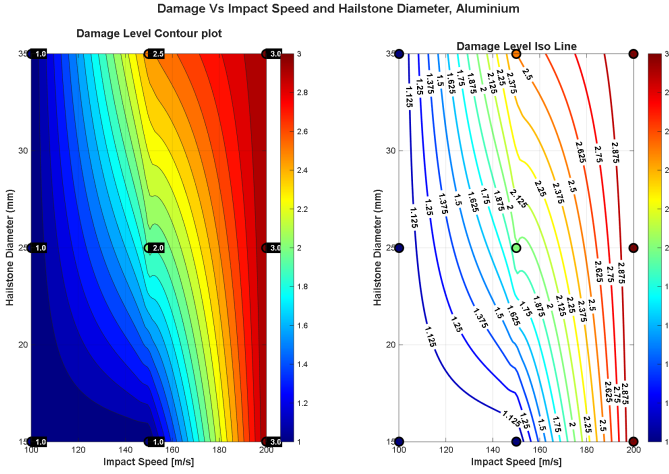


Figure 9: Experimental damage contour map — AlSi10Mg. Steep gradients above 170 m/s indicate rapid damage escalation.

and pronounced positive strain-rate hardening of austenitic stainless steel [22]. Both experimental contour maps show critical transition regions in the same diameter–velocity zones predicted by the FEM displacement results, confirming the three-way consistency between numerical predictions, visual damage classification, and FBG residual-offset data.

IV. CONCLUSIONS

An integrated experimental, numerical, and sensing investigation of an SLM lattice leading edge for aircraft de-icing has been presented, combining a gas-gun impact campaign, explicit FEM/SPH simulations, and a dual-function FBG sensing network. The thermal cycling campaign confirmed the reliability of FBG sensors as thermal probes on SLM surfaces, achieving correlation coefficients above 99% for both AlSi10Mg and AISI 316L across the full de-icing operational range of -40°C to $+50^{\circ}\text{C}$. The impact campaign demonstrated a strong material dependency in structural resilience: AISI 316L sustained no perforation across the full parametric envelope of 15–35 mm diameters and 100–200 m/s velocities, while

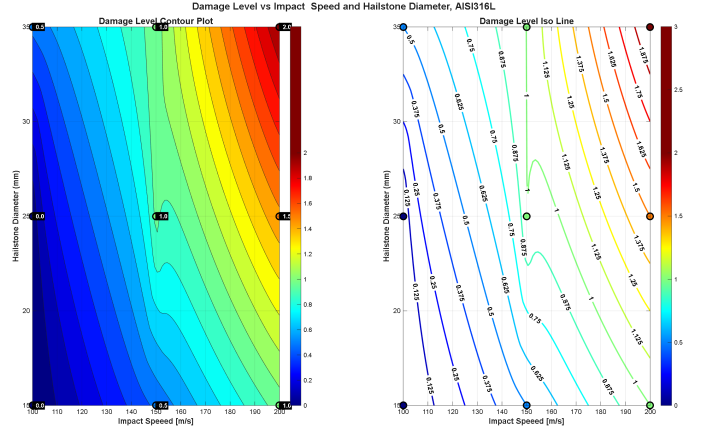


Figure 10: Experimental damage contour map — AISI 316L. The absence of level-3 iso-lines confirms no perforation throughout the tested envelope.

AlSi10Mg was perforated above approximately 170 m/s for projectiles of 25 mm or larger. The FBG sensors provided real-time structural monitoring during every ballistic event with sub-millisecond temporal resolution, resolving the onset of deformation, post-impact damped oscillation, and permanent residual strain; the residual wavelength offset correlated monotonically with the visually assigned damage level, suggesting its use as a quantitative, non-destructive damage indicator applicable in operational maintenance. The explicit FEM/SPH simulations reproduced the experimental damage trends and contour boundaries with good fidelity, validating the numerical framework as a predictive tool and establishing a consistent three-way agreement with the experimental and FBG datasets.

Future work will focus on embedding FBG fibres inside the internal lattice channels through abrasive flow machining or liner-based encapsulation strategies, to achieve full decoupling of thermal and mechanical signals. The dataset will be extended to Ti-6Al-4V specimens currently under manufacturing, completing the material comparison.

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