Inferring spatial impulse from Digital Image Correlation of near field blast loaded plates

R. Curry[1a], G. Langdon[1] and A. Tyas[2,1]

[1] School of Mechanical, Aerospace and Civil Engineering, University of Sheffield, Sheffield, UK, [2]Blastech Ltd., Sheffield, UK

[a] corresponding/presenting author: r.curry@sheffield.ac.uk

Abstract.
This research validates ultra-high-speed 3D Digital Image Correlation (DIC) as a robust, non-contact methodology for capturing full-field transient kinematics under extreme near-field blast loading [1]. By overcoming the destruction and spatial limitations of traditional contact sensors, this approach reliably infers localized specific impulse distributions within 5% agreement of Hopkinson pressure bar array measurements. Achieving displacement precision near 0.01 mm, the study establishes crucial experimental guidelines while demonstrating DIC's unique capability to capture fluid-structure interactions, wave reflections, and high-velocity fragment ejections during dynamic target failure.

Introduction

Measuring spatially and temporally varying pressure distributions during extreme near-field high-explosive detonations remains a formidable experimental challenge [2]. Traditional contact sensors and pressure transducers often suffer destruction or severe signal distortion when subjected to high-pressure detonation fireballs. While rigid-target Hopkinson pressure bar arrays (such as the Characterisation of Blast Loading, or CoBL, facility) provide baseline pressure histories, they are inherently limited by spatial bar resolution and cannot capture fluid-structure interactions on deforming targets. This study presents an experimental methodology validating the use of ultra-high-speed stereo Digital Image Correlation (DIC) to extract full-field, transient out-of-plane velocity and displacement fields from blast-loaded steel target plates. By converting full-field transient velocity measurements into localized specific impulse distributions, this non-contact optical approach is cross-validated against direct Hopkinson pressure bar measurements, establishing quantitative accuracy limits and key experimental design guidelines for extreme blast environments.

Experimental Methodology

Measurements were performed on fully clamped deformable target plates and a rigid measurement rig called the Characterisation of Blast Loading (CoBL) facility [3] enabling the measurements from the two systems to be directly compared. The deformable plates were fabricated from 3mm thick high-strength Strenx 700 structural steel, featuring an exposed region of 300 mm × 300 mm (outer dimension 400 mm × 400 mm) secured by 20 peripheral M15 bolts in similar manner to previous work [4]. PE10 plastic explosive was used in 16 tests utilizing 38 mm diameter cylindrical charges (10–40 g mass, Stand-Off Distances [SOD] of 0–50 mm) and 6 tests utilizing spherical charges (30–60 g mass, SOD of 20–50 mm).

Dual Ultra-High-Speed Optical Systems were used to assess hardware-dependent biases and measurement uncertainties, two ultra-high-speed 3D-DIC camera systems equipped with Samyang 135 mm fixed focal lenses were operated at 100,000 frames per second.

- Shimadzu HPV-X2 10-bit sensor (400 x 250px resolution and 32 µm pixel size), illuminated using a 30k Luminys arc flash bulb with a 20 µs exposure time. A 5 mm ink-rolled speckle pattern was applied to match the resolution magnification of 1.18 px/mm.
- Photron SA-Z: 12-bit sensor (640 x 280px resolution and 20 µm pixel size), illuminated with GsVitec LED arrays providing an 8 µs exposure time. A 2.5 mm speckle pattern matched the resolution magnification of 1.72 px/mm.

Baseline pressure measurements were collected using the CoBL facility. The setup comprised 17 maraging steel Hopkinson pressure bars (10 mm diameter, 3.25 m length) flush-mounted in a cross array across a 1400 mm diameter near-rigid steel plate. Discrete pressure-time histories recorded at radial intervals of 0, 25, 50, 75, and 100 mm were integrated over time to derive comparative specific impulse maps.

Error Analysis and Method Validation for DIC

DIC Uncertainty & System Noise Floor Characterization was evaluated via rigorous static and dynamic uncertainty evaluations that were performed in alignment with iDICS best practice standards [5,6]. The out-of-plane displacement noise floor Sigma_Z was computed via least-squares error minimization of stationary pre-test imagery:

Transient displacement errors across both systems remained strictly below 0.14 mm in worst-case scenarios and consistently near 0.01 mm for standard frames. The Photron SA-Z demonstrated lower noise floors due to higher sensor resolution, lower bit-noise, and shorter exposure times. However, both systems yielded virtually identical transient deformation profiles, proving that carefully configured DIC results are independent of the high-speed camera platform.

Cross-Validation of the Inferred Specific Impulse vs. CoBL Pressure Bars Specific impulse distributions i(x) were taken directly from early-stage out-of-plane transient velocity profiles v(x) using a momentum equivalence formulation [7]:

$$i(x) = \rho t . v(x)$$

Where *i(x)* is the specific impulse, ρ is the density (assumed to be 7850 kg/m^3) and *t* is the plate thickness (nominally 3mm, but the measured value is used for each test). Inferred central specific impulses from 30 g cylindrical charges at 50 mm SOD exhibited less than 5% deviation from CoBL records (epicentral DIC values were only ~0.35 MPa·ms lower than CoBL). For 20 g charges, the difference was ~0.15 MPa·ms. Cumulative Impulse Integration: Spatial integration of specific impulse across radial coordinates demonstrated excellent total impulse agreement ~27Ns for 30 g charges and ~21Ns for 20 g charges).

The slight reduction in epicentral DIC momentum relative to CoBL is attributed to early-stage structural membrane stretching and shear resistance, which redistributes momentum to adjacent radial zones prior to full load duration completion.

Key Experimental Findings

The influence of Charge Geometry can be seen in full-field DIC measurements which successfully captured distinct transient deformation mechanisms governed by charge shape. Cylindrical Charges showed highly localized, high-velocity deformation caps (v_{max} > 330m/s), producing sharp conical profiles. Peak displacements were 50%–80% larger than spherical counterparts. Spherical Charges produced broader, dome-shaped deformation modes characterized by lower initial velocities (v_{max} < 100m/s) and more distributed loading profiles across the central 100 mm region.

Wave Propagation and Boundary Reflections affect transient velocity maps which revealed the propagation of an initial elastic disturbance followed by a slower plastic shear wave moving radially toward the clamp frame. Upon reaching the boundaries (~ 60-80μs), a reflected strain wave propagated back toward the plate centre. To avoid artificial momentum addition when inferring impulse via DIC, velocity data must be temporally cropped prior to the arrival of boundary reflection waves. Increasing the physical plate span extends this valid measurement window.

Conclusions

Ultra-high-speed 3D DIC provides a validated, non-contact technique for measuring full-field transient kinematics and spatial impulse distributions in extreme near-field blast environments. Experimental uncertainties as low as 0.01 mm are achievable with appropriate speckle patterning, short exposure times (~20 μs), and high-intensity illumination. Specific impulses inferred from plate kinematics correlate within 5% of direct Hopkinson pressure bar measurements. Structural boundary reflections and plate thickness effects dominate measurement limits far more than camera sensor noise.

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