

Research Article

Deterministic Post-Processing of Low-Velocity Impact Force–Time Data with ASTM D7136-Guided Automated Feature Extraction

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DOI : 10.31202/ecjse.1938364

Received: 27.04.2026 Accepted: 09.07.2026

How to cite this article:

Uyaner M., "Deterministic Post-Processing of Low-Velocity Impact Force–Time Data with ASTM D7136-Guided Automated Feature Extraction", El-Cezeri Journal of Science and Engineering, Vol: 13, Iss: 3, (2026), pp.(417-428).

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Abstract Low-velocity impact (LVI) experiments generate high-frequency force–time signals that require careful post-processing to reliably extract key response parameters. Spreadsheet-based workflows are widely used in laboratory environments; however, they are highly sensitive to regional numeric formats, inconsistent data imports, and manual interventions, which can compromise reproducibility. This study presents a deterministic post-processing methodology guided by the ASTM D7136 definitions for the automated analysis of LVI force–time histories starting exclusively from raw experimental signals. The proposed workflow performs locale-independent TXT import, centralized numeric parsing, and synchronized force–energy–time reconstruction, enabling the batch extraction of impact metrics across multiple tests. Both impact velocity–driven and impact energy–driven analysis modes are supported, with automatic conversion between velocity and energy using kinetic relations. In this study, ASTM D7136 is used solely to define post-processing metrics and kinetic relationships; the experimental impact conditions themselves are not constrained by the standard. Key impact parameters, including the maximum contact force (F_{max}), first force discontinuity ($F1$), absorbed energies (E_{max} and $E1$), contact duration, impulse, and dent depth, are identified algorithmically without operator intervention and summarized in consolidated tables. The methodology further provides experiment-level force–time, force–displacement, and dual force–energy–time visualizations to facilitate rapid experimental interpretation. Validation using experimental data acquired from a custom low-velocity impact rig demonstrates physically consistent trends across different impact conditions. By eliminating locale-dependent spreadsheet behavior and legacy import mechanisms, the proposed methodology provides a practical and reproducible experimental workflow for extracting the impact response parameters from raw LVI force–time measurements.

Keywords: ASTM D7136, Automated feature extraction, Force–time post-processing, Impact testing, Low-velocity impact, Reproducible experimental workflows.

1. INTRODUCTION

Low-velocity impact testing is widely employed to characterize the damage tolerance and energy absorption behavior of composites and lightweight structures. Typical experiments generate high-frequency force–time signals, which must be transformed into derived quantities, such as absorbed energy, impulse, contact duration, and peak forces.

Despite the availability of specialized commercial software, many laboratories rely on spreadsheet-based workflows because of their accessibility and flexibility. However, spreadsheet-based processing introduces several challenges, including sensitivity to regional decimal formats, inconsistent data import behavior, manual extraction of key parameters, and limited reproducibility across different systems. To address these limitations, we developed an Excel-based automated framework that transforms raw TXT impact data into standardized analytical outputs, including synchronized force–energy–time visualizations, ASTM-style F1/E1 detection, experiment-wise summary metrics, and batch processing capabilities.

Similar automated post-processing frameworks have been reported across various experimental domains; however, many existing approaches rely on proprietary software or lack deterministic handling of raw signals and regional numeric dependencies [1–7]. This study describes the architecture, algorithms, and validation of the proposed framework.

The proposed workflow accepts generic force–time histories and is therefore directly compatible with outputs from commercial finite-element solvers such as LS-DYNA, allowing identical feature extraction procedures to be applied to both experimental and simulated LVI data.

Beyond software implementation, this study contributes a deterministic and reproducible framework for extracting physically meaningful low-velocity impact metrics directly from raw force–time histories. The proposed pipeline enables the

automated identification of $F_{\max}$, F_1 , absorbed energy, impulse, contact duration, rebound velocity, and displacement histories in accordance with the ASTM D7136 definitions, eliminating manual cursor-based interpretation.

By enforcing locale-independent numeric handling and standardized feature extraction, the framework reduces operator-dependent variability in experimental LVI postprocessing. This approach facilitates a systematic comparison across impact velocities and supports both experimental and simulation-derived force–time inputs, providing a transparent alternative to proprietary post-processing tools for the rapid assessment of impact response.

The proposed framework was validated using experimental force–time histories obtained from a custom-developed low-velocity impact test rig. The experimental setup, specimen characteristics, data acquisition procedure, and dataset organization are described in the following sections.

2. METHODS

The experimental campaigns in this study were performed using a custom-developed low-velocity impact (LVI) setup. Although the experimental configuration was not strictly constrained by all procedural requirements of ASTM D7136, the standard was adopted as a reference framework for defining key impact response parameters and establishing deterministic post-processing relations applied to raw force–time histories. Accordingly, quantities such as the absorbed energy, contact duration, and characteristic forces ($F_{\max}$ and F_1) were derived algorithmically following the ASTM D7136 formulations. The proposed framework is compatible with both ASTM D7136-compliant experimental setups and non-standard LVI rigs, provided that time-resolved force–time histories are available as input, whether they are obtained experimentally or numerically.

2.1 Data Import and Preprocessing

The recorded data are stored in TXT format via NI SignalExpress. Each recording file contains two columns: the first column represents time in seconds, while the second column corresponds to the voltage output (V) from the force sensor. Figure 1 illustrates the raw voltage–time signal recorded during an impact test conducted at 3.0 m/s. This signal represents the unprocessed sensor output prior to calibration and automated post-processing. The total recording duration is 2 s. Only the portion of this raw data corresponding to the impact event is plotted in the 0.66–0.71 s interval.

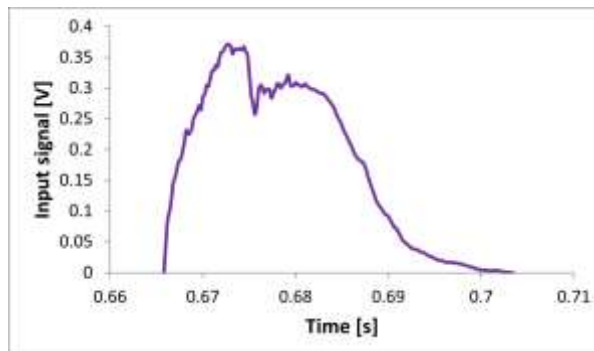


Figure 1. Raw voltage–time signal acquired from the quartz force ring during a low-velocity impact test conducted at 3.0 m/s.

Raw impact data were imported from TXT files using a custom VBA-based manual parsing engine, replacing Excel's native QueryTable mechanism. Each file was read line-by-line and deterministically mapped into two numeric columns representing time and force signals. To prevent locale-induced numeric corruption, all imported values were processed using centralized locale-independent parsing routines capable of handling both comma and dot decimal separators.

A fixed two-column layout was enforced prior to analysis to maintain compatibility with the computational template and prevent structural misalignment during batch processing. Post-import normalization was applied to guarantee a consistent numeric representation across all datasets.

Time shifting was performed by subtracting the initial timestamp from all subsequent values. The force signals were calibrated using a user-defined conversion factor.

Input data are not restricted to experimental measurements. Any time-resolved force signal formatted as two-column text input (time–force) can be processed, including histories exported from numerical impact solvers such as LS-DYNA, thereby extending the framework to both experimental and simulation-based LVI workflows.

Following deterministic data ingestion, the framework requires definition of the impact condition, which can be specified either in terms of impact velocity or impact energy.

2.2 Impact Input Modes

To accommodate common experimental practices, the framework supports two complementary input modes: velocity-driven and energy-driven analysis. In the velocity-driven mode, the user specifies the initial impact velocity. The impact energy

is computed automatically by $E = 0.5mv^2$. Alternatively, the user provides the impact energy, and the corresponding velocity is reconstructed by $v = \sqrt{2E/m}$. The striker mass was entered once and reused for all tests. Default velocity or energy values are automatically extracted from the file names when available, allowing rapid batch processing.

2.3 Feature Extraction

For each experiment, the automated framework deterministically computed the maximum contact force (Fmax), contact duration, impulse, absorbed energy, dent depth, and rebound velocity from the processed force–time data.

The first force discontinuity (F1) was identified using a sliding window slope analysis of the force–time curve. In cases where the discontinuity detection is ambiguous, a fallback criterion based on a fixed fraction of Fmax is applied to ensure robustness. The corresponding times and energies (t(F1), E1) were extracted synchronously.

The peak force (Fmax), its occurrence time t(Fmax), and the associated energy Emax were determined directly from the calibrated force and energy vectors.

2.4 Visualization and Summary Reporting

For each dataset, the framework generated force–time, force–displacement, and dual-axis force–energy–time plots. The key points (Fmax, F1, Emax, and E1) were automatically annotated.

A consolidated ‘Summary’ worksheet was created, aggregating all the extracted parameters across the experiments. All values were written using locale-safe numeric handlers to ensure reproducibility.

2.5 Robustness Measures

To eliminate platform dependency, the framework removes the reliance on Excel regional formatting and legacy import routines. All numeric operations employed centralized parsing functions, and template alignment was enforced programmatically. These measures guarantee consistent results across different Windows localization settings.

3. SOFTWARE ARCHITECTURE AND WORKFLOW

The proposed framework was implemented entirely in Microsoft Excel using Visual Basic for Applications (VBA). The architecture follows a modular design consisting of five primary layers: data ingestion, template-based computation, feature extraction, visualization, and summary reporting.

3.1 Overall Workflow

The processing pipeline operates as follows:

1. The user selects the analysis mode (impact velocity–driven or impact energy–driven) and enters the striker mass.
2. A target workbook is generated from the predefined template sheets.
3. Raw TXT files are imported sequentially using a custom manual parsing routine.
4. The imported signals are normalized and aligned with the computational template.
5. Time shifting and force calibration are applied.
6. Impact features (Fmax, F1, energies, impulse, and contact duration) are extracted.
7. Experiment-level plots are generated automatically.
8. A consolidated summary table is populated across all tests.

This workflow enables the fully automated batch processing of multiple impact experiments with minimal user intervention.

3.2 Modular Design

The framework is organized into specialized functional blocks as follows:

3.2.1 Data Import Module

Handles deterministic TXT parsing and column normalization:

- ImportTxtToSheetManual2Cols
- NormalizeImportedAB
- EnsureTwoLeadingColsOnce

These routines guarantee consistent data placement, independent of Excel localization.

3.2.2 Numeric Parsing Layer

All numeric values pass through locale-independent parsers:

- ParseDoubleSmart
- ReadDoubleSmart

These functions accept both comma and dot decimal formats and prevent silent truncation or magnitude-scaling errors.

3.2.3 Input Management

User inputs (mass, velocity, or energy) are unified through a single Double-standard interface. The conversion between velocity and energy is handled automatically using kinetic relations.

Default values were extracted directly from the file names when available.

3.2.4 Feature Extraction Engine

The core impact parameters, including the peak contact force (F_{max}), first force discontinuity (F_1), associated times and energies, impulse, absorbed energy, dent depth, and rebound velocity, are programmatically derived from the processed force–time histories.

Discontinuity detection employs a sliding-window slope algorithm with a fallback mechanism for atypical signals.

3.2.5 Visualization Subsystem

For each experiment, the framework automatically generates force–time, force–displacement, and dual-axis force–energy–time visualizations.

The critical points (F_{max} , F_1 , E_{max} , and E_1) are marked automatically. Aggregated “all-in-one” plots were also produced across the experiments.

3.2.6 Summary Reporting

A dedicated ‘Summary’ worksheet compiles all the extracted parameters into a single table, enabling rapid comparison between the tests.

The values were written exclusively using locale-safe numeric handlers to ensure reproducibility.

3.3 Robustness-Oriented Design Philosophy

Version 3 adopts a robustness-first design by removing legacy QueryTable imports, eliminating Excel regional dependencies, enforcing template alignment programmatically, and centralizing all numerical parsing operations.

These measures ensure identical analytical results across different operating systems and regional settings.

4. EXPERIMENTAL SETUP, DATASET, AND VALIDATION

4.1. Experimental Setup and Dataset Description

All experimental impact data used in this study were obtained using a custom-developed low-velocity impact (LVI) test rig designed and operated by the author. The setup consisted of a guided striker system equipped with a PCB M202B quartz force ring, which enabled the direct measurement of the contact force history during impact events (Figure 2). Detailed information about the first prototype of the LVI test setup is available in a thesis supervised by the author [8].

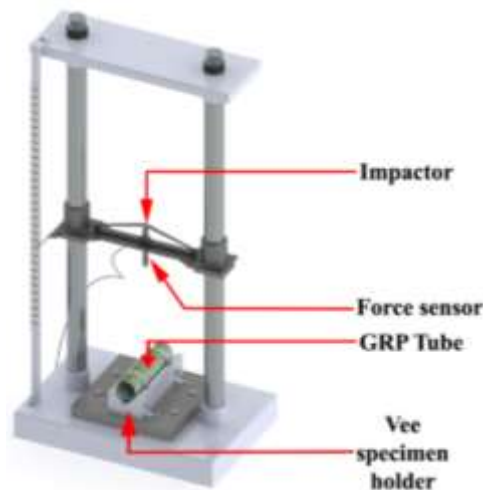


Figure 2. Custom low-velocity impact (LVI) test rig with guided striker and quartz force ring used for force–time measurements.

Impact tests were conducted by releasing a striker of mass 15.5 kg from predefined heights corresponding to target impact velocities ranging from 2.0 to 3.0 m/s. The striker’s mass was maintained constant throughout all experiments. The force–time signals were acquired at a sampling interval of 0.0002 s, corresponding to an effective sampling frequency of 5 kHz.

For impact tests, filament wound ($\pm 55^\circ$)₆ glass-reinforced plastic (GRP) tubes were used. The composite tube samples laid onto Vee-holder. The tubes were then subjected to LVI tests. Each specimen was subjected to a single impact event, after

which no further loading was applied to the specimen. The experiments were conducted solely for this study, and the experimental data have not been used in any other research.

Only the raw force–time histories recorded by the quartz force ring were measured directly during the tests.

The dataset accompanying this study, published via Mendeley Data [9], exclusively contains unprocessed force–time signals for all the impact tests. These raw measurements constitute the sole input to the analysis pipeline, enabling the full traceability of all extracted parameters back to the original experimental records and the fully reproducible validation of the proposed post-processing framework.

4.2. Kinetic Analysis

Displacement, velocity, and energy-related quantities were not experimentally acquired but were deterministically derived from the force–time data using the automated framework proposed in this study, in accordance with the ASTM D7136 definitions [10]. All detailed information regarding the kinetic analysis implemented in the “Template” sheet of the Excel workbook is as follows:

4.2.1 Acceleration, Velocity and Displacements

During the low-velocity impact test, force data is recorded every 0.0002 s. The acceleration values for each moment are calculated using (1).

$$a_i = \frac{F_i}{m} \quad (1)$$

Here, F_i is the force value obtained from the force sensor at time t_i . The change in acceleration over time is similar to that of the force–time graph. Assuming that the change in acceleration between successive times t_{i-1} and t_i is linear, the acceleration relationship in the interval between (a_{i-1}, t_{i-1}) and (a_i, t_i) can be given by (2),

$$a(t) = kt + c \quad (2)$$

Here, the k and c parameters are determined using (3) and (4), respectively.

$$k = \frac{a_i - a_{i-1}}{t_i - t_{i-1}} \quad (3)$$

$$c = \frac{t_i a_{i-1} - t_{i-1} a_i}{t_i - t_{i-1}} \quad (4)$$

$$dv = a(t)dt \quad (5)$$

With the help of (5), the expression for velocity is

$$v = v_0 + \frac{1}{2}k(t^2 - t_0^2) + c(t - t_0) \quad (6)$$

If we rearrange (6) for the time intervals t_{i-1} and t_i ,

$$v_i = v_{i-1} + \frac{1}{2}k_i(t_i^2 - t_{i-1}^2) + c_i(t_i - t_{i-1}) \quad (7)$$

The velocity expression for the successive moments t_{i-1} and t_i is obtained. Now, let's find the displacements,

$$ds = vdt \quad (8)$$

When the expression for v from (6) is substituted into (8) and the integral of the expression is taken

$$s = s_0 + \frac{1}{6}k(t^3 - t_0^3) + \frac{1}{2}c(t^2 - t_0^2) - (v_0 + ct_0 + \frac{1}{2}kt_0^2)(t - t_0) \quad (9)$$

If we arrange (9) for the displacement in the interval between t_{i-1} and t_i ,

$$s_i = s_{i-1} + \frac{1}{6}k_i(t_i^3 - t_{i-1}^3) + \frac{1}{2}c_i(t_i^2 - t_{i-1}^2) - (v_{i-1} + c_i t_{i-1} + \frac{1}{2}k_i t_{i-1}^2)(t_i - t_{i-1}) \quad (10)$$

Equation (10) is obtained. Thus, from N pairs of (F_i, t_i) force–time data, N pairs of (F_i, s_i) force–displacement values are obtained.

4.2.1 Absorbed Energy and Energy History

If the mass changes during motion, Newton's second law is expressed as

$$F = \frac{d(mv)}{dt} \quad (11)$$

Here, the term $m.v$ refers to the linear momentum p . If the mass is constant, (11) takes the following form.

$$Fdt = d(mv) = mdv \quad (12)$$

If the integral of both sides of (12) is taken,

$$\int_{t_1}^{t_2} Fdt = \int_{v_1}^{v_2} mdv \quad (13)$$

The integral on the left side of (13) gives the area under the force–time curve and is called impulse force. Impulse force is denoted by J .

$$J = \int_{t_1}^{t_2} \left(\frac{dp}{dt}\right) dt = p_{t_2} - p_{t_1} = p_{final} - p_{initial} = \Delta p = m \quad (14)$$

It can be seen, with the help of (14), that the impulse force J is equal to the change in linear momentum.

$$W = \int_{t_0}^t Fvdt = \int_v^v vdp = \frac{1}{2}m(v_2^2 - v_1^2) \quad (15)$$

It can be seen that the right side of (15) is equal to the change in kinetic energy. This represents the energy absorbed by the specimen. In a low-velocity impact event, the absorbed energy can also be determined by the area under the force-displacement curve.

$$W = \int_1^2 F ds \quad (16)$$

In the current Excel workbook in Mendeley Data [9], the absorbed energies are calculated using both (15) and (16). Thus, the accuracy of the procedures was validated internally using three different calculations.

The energy value E_i at time $t=t_i$ is obtained by adding the value $(Fvdt)@t_i$ to the energy value E_{i-1} at the previous time, t_{i-1} . Thus, the energy history from $t=0$, the initial moment of the pulse, to $t=t_i$, the end of the impact duration, is obtained.

4.3 Dataset Description

The experimental dataset associated with this study is publicly available via Mendeley Data [9] and consists exclusively of raw force–time signals acquired from the PCB M202B quartz force ring for each of the impact tests. No displacement or energy measurements were included in the shared files; all derived quantities reported in this study were computed downstream using the proposed automated framework.

Each test was stored as an individual ASCII text file containing two columns corresponding to the time and contact force. The file names encode the nominal impact condition (e.g., “2.00mps”, “2.50mps”, “31J”), allowing the automated extraction of default impact parameters during batch processing.

To support both velocity- and energy-driven experimental workflows, the dataset is provided in two complementary formats:

- i. impact velocity–based datasets, where the file names specify the nominal striker velocity in m/s;
- ii. impact energy–based datasets, where the file names specify the nominal impact energy in joules.

In both cases, only the raw force–time histories were distributed. The automated analysis framework resolves internal consistency by computing the complementary quantity (velocity or energy) using kinetic relations with the user-specified striker mass.

All files share an identical column structure and sampling characteristics, enabling deterministic parsing independent of regional numeric formatting. The dataset is intentionally minimalistic, containing only primary experimental measurements, thereby allowing the transparent verification of every derived parameter produced by the framework.

This design ensures that all reported metrics, including peak force, contact duration, impulse, absorbed energy, F_1 , F_{max} , and associated timing and energy values, can be reproducibly regenerated starting from the original unprocessed signals.

4.4 Validation Strategy

The proposed framework was validated through a direct comparison between the automated outputs and manual inspection of representative impact datasets. For each test case, the force–time, force–displacement, and dual force–energy–time responses were visually examined to confirm physical consistency and correct temporal alignment.

Key scalar metrics, including peak force (F_{max}), contact duration, impulse, impact energy, absorbed energy, and dent depth, were cross-checked against independently calculated spreadsheet values to verify their numerical accuracy. In addition, the automatically detected F_1 discontinuity points were reviewed across multiple impact conditions to ensure the reliable identification of the first force or slope discontinuity.

Batch processing capabilities were validated by simultaneously analyzing multiple impact files with varying sampling formats and naming conventions. Particular attention was paid to robustness under different regional numeric settings (decimal separators and thousands of delimiters), which frequently cause silent corruption in conventional spreadsheet workflows.

The framework was further tested under both impact velocity–driven and impact energy–driven modes to confirm the internal consistency between the kinetic relations and derived quantities. Summary tables aggregating the results across all experiments were inspected to verify the correct propagation of per-test metrics into comparative analyses.

Together, these validation steps demonstrate that the proposed framework produces deterministic and physically meaningful results across heterogeneous experimental inputs while eliminating manual intervention and region-dependent behavior.

4.5 Robustness to Regional Settings

A critical design objective of the proposed framework was to eliminate failures arising from regional numeric formatting, which is a common source of silent errors in spreadsheet-based experimental workflows. Differences in decimal and thousands of separators (e.g., comma versus period) frequently cause misinterpretation of imported numerical data, leading to corrupted force magnitudes, incorrect timing, and physically implausible results in the analysis.

To address this issue, all native Excel import mechanisms that rely on the system locale (including QueryTable-based parsing) were removed. Instead, raw text files were ingested through a deterministic manual import routine, followed by centralized numeric normalization. A custom parsing layer converts all imported values into canonical floating-point representations that are independent of the operating system settings.

Additional safeguards were implemented to detect and correct malformed numeric fields immediately after import, ensuring that the time and force columns were interpreted consistently across different regional environments. This approach

prevents common failure modes, such as unintended scaling by factors of 10–1000, loss of decimal precision, or conversion of decimal separators into thousands of delimiters.

The robustness of this design was verified by executing identical batch analyses under different Windows regional configurations, which confirmed the invariant numerical results. By enforcing locale-independent parsing at the earliest stage of data ingestion, the framework guarantees reproducible outcomes, regardless of the user environment.

4.6 Automation Efficiency

The proposed framework was designed to minimize manual intervention while preserving the full analytical transparency. Conventional spreadsheet-based post-processing of low-velocity impact data typically requires repeated manual steps, including data import, unit correction, curve inspection, feature identification, and result transcription. These operations are time-consuming and prone to user-dependent variability.

In contrast, the proposed framework enables fully automated batch processing of multiple impact tests starting from raw force–time files. Once the experimental folder is selected and the global parameters are defined, all subsequent steps, including data import, signal normalization, feature extraction, visualization, and summary reporting, are executed without further user input.

Automation efficiency was assessed qualitatively by comparing the time required to process representative datasets manually and using the proposed workflow. Tasks that previously required several minutes per test, including curve alignment, peak identification, and summary table preparation, were reduced to a single batch execution that covered all experiments. This reduction in operator workload also minimizes the risk of transcription errors and inconsistent analysis choices.

Importantly, automation was achieved without compromising interpretability. All intermediate calculations and extracted parameters remain visible within the spreadsheet environment, allowing users to inspect, verify, and override the results if necessary. This balance between automation and transparency distinguishes the framework from black-box post-processing tools and supports reliable, large-scale experimental studies.

5. RESULTS

This section presents the representative impact responses and automatically extracted parameters obtained using the proposed VBA-based framework.

5.1 Force–Time Response

Figure 3 illustrates a representative force–time history recorded at an impact velocity of 3 m/s, highlighting the characteristic loading–unloading behavior and the onset of damage prior to the peak force. It illustrates the peak force (F_{max}) and subsequent unloading phase observed during low-velocity impact. A distinct force discontinuity corresponding to F_1 was observed before the maximum force, consistent with the damage initiation. This force–time response serves as the basis for the automated extraction of F_1 , F_{max} , contact duration, impulse, and absorbed energy using the proposed VBA framework.

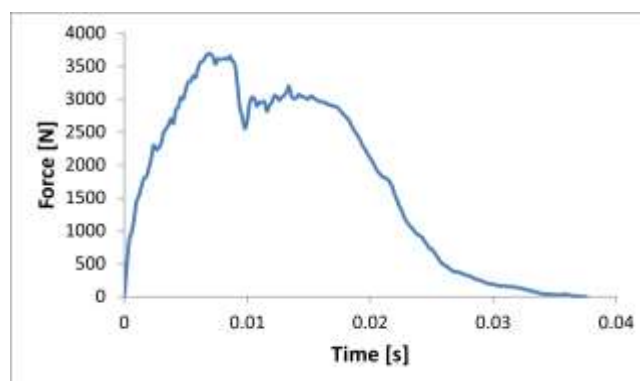


Figure 3. The representative processed force–time history obtained at an impact velocity of 3.0 m/s after calibration and automated post-processing.

5.2 Force–Displacement Response

Figure 4 shows the force–displacement response obtained at an impact velocity of 3 m/s. The curve illustrates the nonlinear contact behavior during the loading and unloading phases, including stiffness evolution, peak force development, and residual deformation after impact.

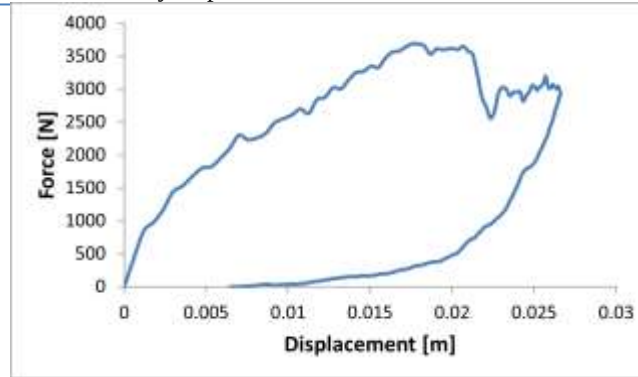


Figure 4. Force–displacement response obtained at an impact velocity of 3 m/s.

The loading branch exhibited a progressive decrease in contact stiffness as the displacement increased, whereas the unloading path revealed pronounced hysteresis associated with irreversible deformation and energy dissipation. The enclosed loop area reflects the absorbed impact energy, whereas the residual displacement corresponds to the permanent indentation of the specimen.

These characteristics are typical of low-velocity impact events, where elastic and plastic deformation mechanisms coexist during contact. The automated processing framework reconstructs the displacement history directly from time-domain measurements and force integration, enabling the consistent extraction of the maximum force, peak displacement, and absorbed energy across multiple test cases without manual intervention.

5.3 Dual Force–Energy–Time Response

Figure 5 presents the synchronized force–energy–time history obtained using the proposed dual-axis visualization framework. The force response exhibits a rapid increase during the initial contact, followed by peak force development (F_{max}) and subsequent unloading, whereas the absorbed energy increases monotonically throughout the contact duration.

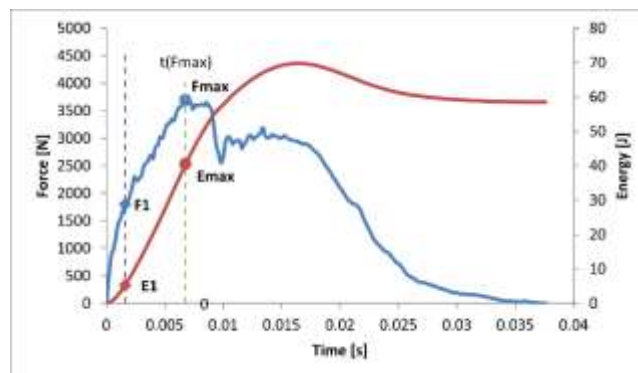


Figure 5. Dual-axis force–energy–time response obtained at an impact velocity of 3 m/s.

The automated extraction of F_{max} and its corresponding time enables the direct identification of the maximum contact load and its occurrence within the impact event. In parallel, the algorithm detects the first force discontinuity ($F1$), which is associated with the onset of damage or the degradation of stiffness. The corresponding energy values at these characteristic points (E_{max} and $E1$) provide quantitative measures of the impact severity and material response.

Superimposing the force and energy on a common time axis facilitates the direct interpretation of the load transfer and energy absorption mechanisms. This representation highlights the temporal separation between the peak force and peak absorbed energy, emphasizing that the maximum structural loading precedes full energy dissipation. This behavior is consistent with typical low-velocity impact dynamics, where damage initiation occurs before complete energy transfer.

5.4. All-in-One Comparative Responses Across Impact Velocities

To facilitate a direct comparison between multiple impact conditions, the framework automatically generates consolidated “All-in-One” plots for the force–time, force–displacement, and energy–time responses. These visualizations overlay individual test curves corresponding to different impact velocities, enabling the rapid assessment of peak force evolution, contact duration, displacement progression, and energy absorption behavior within a unified graphical context.

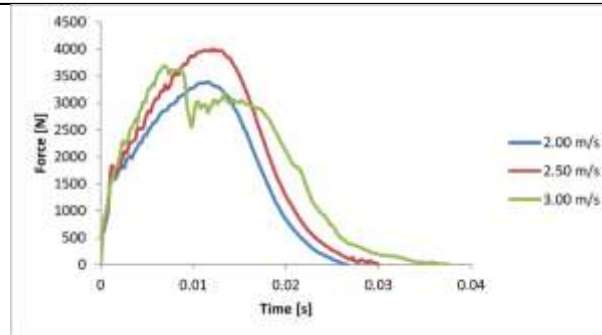


Figure 6. Overlaid force–time responses for multiple impact velocities (All-in-One visualization)

Figure 6 shows the overlaid force–time histories for impact velocities of 2.00, 2.50, and 3.00 m/s. An increase in the impact velocity resulted in higher peak forces and prolonged contact durations, whereas subtle deviations along the loading branches reflected specimen-dependent stiffness variations and experimental signal noise.

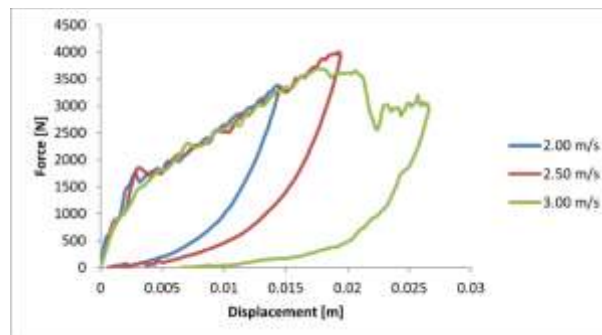


Figure 7. Force–displacement histories at multiple impact velocities.

The combined force–displacement curves illustrate the loading–unloading behavior under different impact conditions (Figure 7). The curves reveal a nonlinear stiffness evolution and expanding hysteresis loops with increasing velocity, highlighting the transition from a predominantly elastic response to progressive damage and plastic deformation.

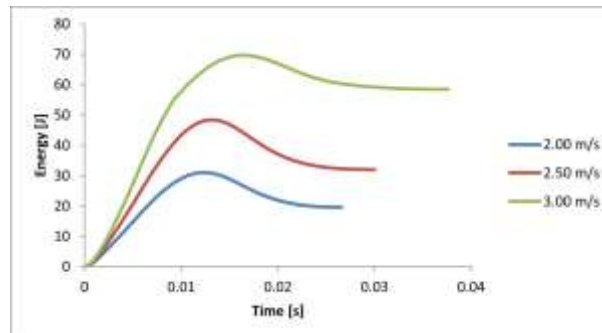


Figure 8. Consolidated energy–time histories for impacts at multiple velocities.

Higher impact velocities resulted in larger maximum energies and increased residual energy levels, indicating progressively greater damage accumulation and irreversible deformation (Figure 8).

While the All-in-One plots provide qualitative insight into the impact behavior, a quantitative comparison is achieved through the automatically generated summary metrics table, which consolidates the key parameters extracted from each experiment.

5.5. Summary Metrics Table

Table 1 summarizes the key impact metrics automatically extracted by the proposed framework for each of the test conditions. The reported parameters include the initial and residual velocities, contact duration, impulse, impact and absorbed energies, maximum contact force (F_{max}) and its occurrence time, characteristic discontinuity force (F_1) with corresponding time and energy, and final dent depth. These quantities provide a compact quantitative representation of the force–time, force–

displacement, and energy–time responses, enabling direct comparisons across impact velocities and facilitating downstream statistical or mechanistic analyses.

Table 1. Automatically Extracted Impact Parameters for Each Experimental Condition

Parameter	2.00 m/s	2.50 m/s	3.00 m/s
Initial velocity, v_i (m/s)	2.00	2.50	3.00
Rebound velocity, v_f (m/s)	−1.22	−1.46	−1.21
Contact duration, t_T (s)	0.0266	0.0300	0.0376
Impulse, J (N·s)	49.9	61.3	65.2
Impact energy (J)	31.00	48.44	69.75
Absorbed energy, E_a (J)	19.5	32.0	58.5
Maximum contact force, F_{max} (N)	3388	4001	3686
Time at maximum force, $t(F_{max})$ (s)	0.0116	0.0122	0.0068
Energy at maximum force, E_{max} (J)	30.8	48.0	41.0
First force discontinuity, F_1 (N)	1549	1512	1799
Time at F_1 , $t(F_1)$ (s)	0.0012	0.0010	0.0016
Energy at F_1 , E_1 (J)	2.00	1.97	5.29
Dent depth, d (m)	0.0016	0.0006	0.0065

The extracted parameters enable a systematic comparison across multiple impact conditions. Their physical implications and experimental relevance are discussed in the following section.

6. DISCUSSION

The force–time and energy-related metrics obtained using the proposed framework provide a quantitative basis for interpreting the impact mechanics under low-velocity impact conditions.

The force–time responses revealed the characteristic loading and unloading phases of low-velocity impact, with increasing impact velocity leading to higher peak forces, extended contact durations, and more pronounced post-peak decay behavior. Similarly, the force–displacement curves highlight the nonlinear contact behavior and energy dissipation mechanisms, including stiffness evolution and residual deformation. The energy–time histories further confirmed that higher impact velocities resulted in increased absorbed energy and delayed stabilization, reflecting enhanced damage accumulation during the impact.

An additional strength of the framework is its solver-agnostic design. Force–time histories originating from finite-element simulations (e.g., LS-DYNA) can be analyzed using the same pipeline applied to experimental data, enabling direct comparison between physical tests and numerical predictions. Beyond experimental datasets, the proposed framework has already been applied to raw force–time histories generated by LS-DYNA low-velocity impact simulations in several published studies, where the macro was used directly for post-processing and visualization of numerical impact responses [11–13]. This confirms its practical applicability to both experimental and computational LVI workflows.

Since its initial development, successive versions of the macro have been routinely employed by the authors and their students across multiple experimental impact studies, with generated plots and extracted parameters directly incorporated into peer-reviewed publications [14–23]. This sustained academic usage demonstrates the practical maturity of the framework and its reliability for real-world LVI data analysis.

Spreadsheet-based workflows are widely used in experimental impact mechanics because of their accessibility and flexibility. However, such workflows are often developed incrementally and rely heavily on implicit assumptions regarding numeric formatting, data import behavior and manual intervention. These factors significantly limit the reproducibility and can introduce subtle but severe analytical errors.

The framework presented in this study addresses these limitations by enforcing deterministic data ingestion, centralized numeric parsing, and automated feature extraction. By removing Excel’s native QueryTable import and regional formatting dependencies, the proposed approach eliminates a major source of inconsistency observed in traditional spreadsheet-based analysis.

A notable strength of the framework lies in its dual-mode handling of the impact conditions. Allowing analyses to be driven by either impact velocity or impact energy reflects common experimental practice while maintaining internal consistency via kinetic relations. The automatic extraction of default input values from file names further streamlines batch processing and reduces the operator burden.

The automated detection of F_{max} and F_1 provides a systematic alternative to the manual cursor-based identification of key events in the force–time history. In particular, the inclusion of fallback logic for discontinuity detection enhances the robustness in the presence of noisy or atypical signals, a scenario frequently encountered in experimental datasets.

The consistency observed across the force–time, force–displacement, and energy–time representations further supports the robustness of the automated feature extraction and summary metrics generated by the framework.

Compared with commercial impact analysis software, the proposed framework prioritizes transparency and user control over black-box processing. All computations are visible in the spreadsheet environment, enabling traceability and ease of verification. Although not intended to replace dedicated finite element or proprietary post-processing tools, the framework offers a lightweight and reproducible solution for rapid experimental data analysis.

The results demonstrate that careful workflow design principles, including modularization, defensive programming, and locale-independent data handling, can substantially improve the reliability of spreadsheet-based experimental analyses. Therefore, the framework may serve not only as a practical tool for LVI analysis but also as a reference implementation for robust data processing in other experimental domains.

7. LIMITATIONS AND FUTURE WORK

Although the proposed framework significantly improves the robustness and reproducibility of spreadsheet-based LVI data analysis, several limitations remain.

First, the current implementation prioritizes numerical accuracy and workflow automation over computational performance. Although batch processing is substantially faster than manual analysis, further optimization is possible through memory pre-allocation, reduced recalculation calls, and accelerated plotting routines. These enhancements are planned for future studies.

Second, the detection of the first force discontinuity (F1) relies on a slope-based sliding window algorithm combined with a fallback criterion. Although this approach performs reliably for a wide range of experimental signals, highly irregular or extremely noisy datasets may require more advanced signal processing techniques, such as adaptive filtering or statistical change-point detection.

Third, the framework is currently implemented within Microsoft Excel using VBA, which limits scalability for very large datasets and constrains integration with external numerical libraries. Future development may explore the migration of core algorithms to standalone environments (e.g., Python or MATLAB) while preserving Excel as a front-end interface.

Finally, although the current version extracts key impact metrics, contact stiffness estimation and advanced damage indicators have not yet been implemented. These features are planned for subsequent releases, along with extended validation against standardized benchmark data sets.

Despite these limitations, the proposed framework establishes a robust baseline for automated LVI post-processing and provides a transparent foundation for future methodological extensions. While numerical force–time histories from finite-element solvers (e.g., LS-DYNA) can already be directly processed by the framework, validation in the present study is intentionally restricted to experimental datasets. Systematic benchmarking against simulation outputs is planned as part of future work.

8. CONCLUSION

This study presents a robust, fully automated Excel-based framework for post-processing low-velocity impact experimental data by integrating deterministic data ingestion, locale-independent numeric parsing, automated feature extraction, and standardized visualization. Starting exclusively from raw force–time measurements, the framework reproducibly derives the displacement and energy histories in accordance with the ASTM D7136 definitions, enabling consistent analysis across heterogeneous experimental conditions.

A key contribution of the proposed approach is its dual-mode handling of impact inputs, allowing experiments to be parameterized by either the impact velocity or impact energy while maintaining internal physical consistency. The automatic extraction of default parameters from file names further streamlines batch processing and minimizes the operator burden.

Through systematic validation using real experimental datasets obtained from a custom-developed LVI test rig, the framework demonstrated reliable detection of critical impact features, including F_{max} , F1, contact duration, impulse, absorbed energy, and associated timing and energy metrics. The removal of Excel's locale-dependent import mechanisms eliminates a major source of silent numerical corruption that is commonly encountered in spreadsheet-based workflows.

Beyond its immediate application to low-velocity impact studies, the framework illustrates how the principles of modular design, defensive programming, and transparency can substantially improve the reliability of spreadsheet-driven scientific analyses. By combining open experimental data with an openly documented processing pipeline, this study provides a reproducible and extensible baseline for experimental impact mechanics and related domains.

Future development will focus on performance optimization, advanced signal processing for discontinuity detection, and the integration of additional damage and stiffness metrics. The proposed framework and accompanying dataset provide a practical foundation for reproducible LVI post-processing and a reference implementation for robust experimental data workflows.

Statements and Declarations

Ethics Approval

This study did not involve human or animal subjects requiring ethics approval. The research was conducted using publicly available datasets, literature reviews, and theoretical analyses. In accordance with ethical standards, academic integrity and scientific ethics were fully observed throughout the research process. Therefore, ethics committee approval was not required.

Competing Interests

The author declares that he has no conflict of interest.

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