

Impact-Energy-Absorbing Photopolymer Lattices: Crushing Modes, Rate Effects, Recovery and Repeatability

Separating architecture-controlled collapse from polymer rate sensitivity, damage and rebound in protective lattice qualification

Juan Seguro

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Correspondence: info@3Dresyns.com · www.3Dresyns.com

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Abstract

Impact-energy absorption in photopolymer lattices depends on the sequence of cell collapse, strain-rate sensitivity and the extent to which the architecture recovers after unloading. ER-365 treats energy absorption as a history-dependent structural response rather than a single peak-load metric. High-rate force and displacement data, collapse imaging and post-impact geometry are used together to identify progressive crushing, localisation and permanent set. Impact-velocity, relative-density and repeat-loading perturbations separate rate effects from topology and accumulated damage. The resulting qualification framework defines a usable impact envelope, the conditions for repeatable absorption, and the point at which recovery or residual deformation invalidates reuse claims.

Keywords: energy absorption; lattice; impact; strain rate; crushing; recovery

1. Qualification problem: impact lattices

The review frames impact lattices around what an engineer must decide after measurement. Those decisions are acceptable peak force, absorbed energy and residual function as a joint envelope, single-use versus reusable protection architecture, and minimum safety margin to densification; normalised strain rate, relative density, and inertial number provide the regime labels needed to interpret them. [1]

1.1 Scope boundary.

ER-365 owns impact-absorption response, including crushing, rate dependence, recovery and repeatability. ER-361 owns general metamaterial qualification, ER-363 graded lattices, ER-364 snap-through stability, and ER-370 folding structures; they enter only where architecture changes the impact collapse mode.

2. Governing balances for impact lattices

Impact response is organised around the following relations for rate, density, and inertia so that crushing mode changes remain explicit.

absorbed energy is the integral of force-displacement up to a defined displacement, densification or failure criterion

specific energy absorption normalizes energy by mass but does not capture peak-force constraints

dynamic response combines architecture inertia, constituent rate dependence and stress-wave effects [1]

These descriptors locate the transition from useful plateau crushing to premature localisation or densification.

3. Regime boundaries for impact lattices

The impact map assigns evidence according to whether peak force, recoverability, or densification margin is the limiting decision.

Table 1. Regime indicators for impact-absorption response.

Indicator	Engineering meaning	Use
normalised strain rate	loading rate scaled by the characteristic relaxation time	Attach normalised strain rate to 'acceptable peak force, absorbed energy and residual function as a joint envelope' as a regime descriptor. It connects that decision to loading rate scaled by the characteristic relaxation time and marks when a new validation case is needed.
relative density	solid fraction governing plateau stress and densification strain	Attach relative density to 'single-use versus reusable protection architecture' as a regime descriptor. It connects that decision to solid fraction governing plateau stress and densification strain and marks when a new validation case is needed.
inertial number	local collapse time relative to wave-transit time	Attach inertial number to 'minimum safety margin to densification' as a regime descriptor. It connects that decision to local collapse time relative to wave-transit time and marks when a new validation case is needed.

Impact qualification does not cross an untested rate, density, or inertia regime without fresh crushing evidence.

4. Couplings that move the impact lattices

Brittle fracture can increase apparent dissipation while destroying reusability.

Graded lattices can sequence collapse and reduce peak force. [2,3]

Viscoelastic resin damping changes with temperature and rate.

5. Failure signatures and false diagnoses

The observable fault space comprises catastrophic shear banding instead of progressive collapse, early densification and fragment ejection and loss of recoverability. Diagnosis uses instrumented drop tower or SHPB where rates require, force-displacement/velocity histories and high-speed imaging of collapse mode to test those branches individually rather than assuming that one visible defect identifies the mechanism. The four Table 2 rows create the contrasts needed to separate competing mechanisms before any model is calibrated.

Table 2. Failure-mode discrimination for impact-absorption response.

Failure mode	Observable signature	Discriminating evidence
catastrophic shear banding instead of progressive collapse	instrumented drop tower or SHPB where rates require	matched quasi-static and dynamic tests
early densification	force-displacement/velocity histories	vary impact energy at constant mass or velocity separately
fragment ejection and loss of recoverability	high-speed imaging of collapse mode	repeat impacts with recovery dwell
cycle-to-cycle loss of plateau stress	post-impact CT and residual geometry	compare uniform and graded architectures at equal mass

6. Measuring impact lattices with traceable uncertainty

The metrology architecture maps the three Table 2 channels onto separate uncertainty terms and preserves that partition through model validation. Rather than reduce impact lattices to one surrogate, the analysis combines separate monitoring of densification with independent resolution of force-displacement energy and specific energy absorption; during metrology of impact lattices, stress-wave effects is resolved against densification. A separate an uncertainty-controlled perturbation of stress-wave effects is used to challenge that interpretation, making disagreement between the two routes visible instead of averaging it away; the uncertainty record for impact lattices keeps densification separate from force-displacement energy.

7. Experiments that discriminate competing mechanisms

The four Table 2 experiments are interpreted jointly, with failure to reproduce the expected response in any row triggering reconsideration of the mechanism. An acceptable record for impact lattices must show a replicate test of densification without inferring it from a causal contrast between force-displacement energy and stress-wave effects; during the causal challenge for impact lattices, densification is tested against force-displacement energy. In parallel, a boundary challenge involving specific energy absorption probes the boundary condition most likely to change the interpretation, and the resulting uncertainty is carried forward explicitly; the experiment for impact lattices separates force-displacement energy from specific energy absorption.

8. Model identification and validation for impact lattices

The model is fitted to one diagnostic branch and then challenged by the other two without refitting. This makes a failed prediction distinguishable from a poorly conditioned fit. [6] [4,5] The acceptance margins in Table 3 are widened only by the uncertainty sources relevant to that row, not by an undifferentiated global factor. Evidence for impact lattices is not accepted from a single nominal condition; within model identification for impact lattices, force-displacement energy is not fitted through specific energy absorption. The analysis requires parameter estimation for force-displacement energy and specific energy absorption, follows it with an uncertainty-bounded check on densification, and uses prediction against stress-wave effects as a targeted challenge wherever the two indicate different mechanism or margin; prediction for impact lattices keeps specific energy absorption independent of stress-wave effects.

9. Qualification envelope and technology decisions

Table 3. Technology-decision matrix for impact-absorption response.

Decision	Minimum evidence	Acceptance logic
acceptable peak force, absorbed energy and residual function as a joint envelope	The minimum evidence for acceptable peak force, absorbed energy and residual function as a joint envelope is a calibrated instrumented drop tower or SHPB where rates require dataset broad enough to separate baseline variability from a genuine regime shift.	Support the decision only when the instrumented drop tower or SHPB where rates require response to 'matched quasi-static and dynamic tests' is stable within uncertainty and the evidence does not indicate catastrophic shear banding instead of progressive collapse.
single-use versus reusable protection architecture	Justify single-use versus reusable protection architecture using repeated force-displacement/velocity histories measurements across the claimed range and a documented decision uncertainty at the limiting condition.	The candidate passes if repeated 'vary impact energy at constant mass or velocity separately' perturbations produce a consistent force-displacement/velocity histories response with no accompanying early densification.
minimum safety margin to densification	For minimum safety margin to densification, collect high-speed imaging of collapse mode in matched reference/candidate tests and repeat the condition nearest the acceptance boundary.	Accept only where the response of high-speed imaging of collapse mode to 'repeat impacts with recovery dwell' remains reproducible across the transfer states and fragment ejection and loss of recoverability is absent.

A separate boundary for stress-wave effects is the first stress test for impact lattices; only after that result is bounded is tested ranges in force-displacement energy and specific energy absorption interpreted; inside the impact lattices envelope, specific energy absorption and

stress-wave effects define different transfer limits. The record keeps an explicit transfer limit on densification outside that inference and reports it as an independent line of evidence; qualification of impact lattices bounds stress-wave effects separately from densification.

10. Design consequences for impact lattices

A releaseable design exists only inside the overlap of the three Table 3 limits. Engineering action centres on a design change governed by force-displacement energy; during design implementation for impact lattices, stress-wave effects is constrained by densification. In the same test, while minimum safety margin to densification is controlled independently, an implementation check on stress-wave effects provides the implementation check and a requalification trigger tied to densification marks the stop condition; the impact lattices design record separates densification from force-displacement energy. The selected geometry or recipe is therefore tied to evidence for impact lattices, not to a single nominal set point; implementation of impact lattices treats force-displacement energy and specific energy absorption as different control axes.

11. Evidence gaps for impact lattices

The impact lattices workflow deliberately separates uncertainty in specific energy absorption versus stress-wave effects from scale transfer of force-displacement energy; this avoids fitting the challenge into the quantity being qualified; for unresolved impact lattices transfer, densification is studied separately from force-displacement energy. Independent replication of densification is then examined on its own terms before any transfer statement is retained; the evidence gap in impact lattices distinguishes force-displacement energy from specific energy absorption.

12. Qualification outcome for impact lattices

The accepted operating space is the overlap of the three Table 3 conditions; the present review does not justify transfer outside that overlap. For impact lattices, the evidence chain starts with agreement between measurement and prediction for force-displacement energy; at final qualification of impact lattices, force-displacement energy is reconciled with specific energy absorption. It then adds causal evidence that separates specific energy absorption from stress-wave effects, while a renewed-evidence trigger when densification changes is retained as a separate control so the three sources of information cannot compensate silently; the closing impact lattices claim keeps specific energy absorption distinct from stress-wave effects.

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Competing interests

The author is Founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L. No comparative product recommendation is made.

Data availability

No new experimental dataset was generated for this review.