

Compression, Local Buckling and Crushing of Printed Photopolymer Structures: Material State, Architecture and Boundary Conditions

A mechanism-resolved framework from bulk compression to progressive architectural collapse

Juan Seguro

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

ER-234 · Engineering Review · Version 0.3 · 20 September 2026

Abstract

The compressive response of a printed photopolymer structure is not a single material property. A solid coupon may exhibit elastic deformation, yielding, cracking, barreling or confinement, while a lattice can respond through strut bending, node rotation, local cell buckling, global instability, brittle fracture, progressive crushing and densification. The measured curve also depends on as-built relative density, wall and strut fidelity, skins, platen alignment, friction, aspect ratio, contact, loading rate and the definitions used for stress, strain, plateau and densification.

This review defines a non-compensatory qualification framework for monotonic compression, local buckling and crushing of solid and architected vat-printed photopolymer structures. It separates base-material constitutive response from architecture-driven response, requires the tested geometry rather than the CAD model to control interpretation, and treats boundary conditions and contact as part of the experiment. Energy absorption must retain its integration limit and mass or volume normalization. Numerical models require measured geometry, appropriate material and contact laws, imperfection treatment and independent validation at another scale, cell count, relative density or topology. The primary corpus supports mechanism-resolved evaluation across rigid, tough and elastomeric systems, but not universal plateau stresses, densification strains, topology rankings, buckling coefficients or crashworthiness claims.

Keywords: printed photopolymer; compression; local buckling; crushing; lattice; relative density; densification; energy absorption

1. Significance and scope

Compression is often selected because it is easy to apply and because architected structures can absorb large deformation. Yet a force–displacement curve can mix material response, geometry, contact and instability. Two specimens with the same CAD relative density can have different cured wall thicknesses, trapped resin, node dimensions and surface skins, leading to different collapse paths.

ER-234 addresses monotonic, quasi-static or explicitly low-rate compression of solid and architected printed photopolymer structures. Its central decision is whether observed strength, plateau and energy absorption can be attributed and transferred without confusing the resin state with the architecture.

1.1 Corpus boundary

ER-026 retains relative density, topology and general mechanical qualification of cellular and TPMS photopolymer architectures. ER-010 retains dimensional metrology and geometric fidelity across scales. ER-031 retains cure shrinkage and warpage. ER-039 retains cyclic compression, fatigue, creep and recovery. ER-073 retains general anisotropy. ER-090 retains dynamic-mechanical damping and viscoelastic frequency-temperature response. ER-101 retains elastomeric creep, compression set and cyclic durability. ER-170 retains ageing design. ER-184 retains diagnostic discrimination between competing defect mechanisms under uncertainty; it does not own constitutive inverse inference in general. ER-206 retains micro-CT acquisition and segmentation. ER-231 is a forward reference to the planned statistical-size review. ER-233 retains impact and genuine high-rate response. ER-235 retains general multiaxial criteria. No existing incumbent is assigned generic topology optimization. ER-234 is restricted to compression-specific collapse mechanisms, boundary conditions, densification rules and energy-integration limits.

2. Separate bulk compression from structural crushing

Bulk compression seeks a constitutive response for a material specimen whose geometry is intended to remain continuous. Structural crushing concerns a component whose architecture deliberately bends, buckles, fractures or contacts itself. A lattice curve cannot be reported as the compressive strength of the resin unless an independently validated inverse method separates architecture and material.

Reinforced photopolymer compression work demonstrates formulation- and filler-dependent bulk response [5]. Elastomeric cellular structures exhibit topology-dependent global buckling, bending or local cell buckling [2]. These results require separate material and architecture descriptions.

3. Freeze the printed material state

Report resin and batch, printer and exposure, build location and orientation, layer thickness, supports, wash, drying, post-cure, storage and conditioning. For elastomers, include viscoelastic history, preconditioning and recovery time. For rigid networks, record brittle damage or microcracking introduced during support removal and post-processing.

The elastomeric vat-photopolymer study changed the post-processing route relative to earlier work and treated the material through hyperelastic and viscoelastic laws [2]. Its observations are state-specific, not generic material categories.

4. Measure as-built architecture

Record unit-cell family, nominal dimensions, cell count, strut or wall thickness, node and junction geometry, skins, grading, designed solid fraction and orientation. Measure actual external dimensions, mass, volume or density, representative struts and walls, node overgrowth, closed channels, trapped resin and damaged features. Report the method and uncertainty.

As-built relative density should control compression-specific normalization when it can be measured defensibly. CAD relative density is insufficient when exposure broadening, drainage and resolution alter small features. The general ownership of relative density, topology and mechanical qualification of cellular architectures remains with ER-026, while dimensional metrology and geometric fidelity remain with ER-010. Here those quantities are used only to interpret compression and collapse. Double-gradation research comparing manufacturing processes shows that the fabrication route affects realised structures and compressive response [4]. Recent SLA elastomeric lattice work explicitly links dimensional accuracy and buckling topology [8].

5. Classify the collapse mechanism

Distinguish at least elastic compression, material yielding, strut bending, node rotation, local wall or cell buckling, global Euler-type instability, brittle strut fracture, progressive layer collapse, contact-driven plateau and densification. Several mechanisms may occur sequentially. Record the onset and spatial progression with synchronized images when practical.

In elastomeric structures, simple cubic cells showed global structural buckling, body-centered cells accommodated deformation through bending, and gyroid cells showed local cell buckling in the examined system [2]. These mechanism labels cannot be assigned solely from the shape of the stress–strain curve.

6. Define boundary conditions and contact

Report platen material, alignment, parallelism, lubrication or dry contact, estimated friction, end preparation, specimen aspect ratio, centering and load-train compliance. For architected specimens, state whether boundary cells are complete, truncated, skinned or directly contacting the platen. End constraints can suppress or trigger buckling and create a response different from an interior periodic cell.

The vat-printed elastomer study used direct steel-platen contact and included contact and friction in nonlinear simulations [2]. Such details are part of the test definition. A topology ranking obtained under one platen condition cannot be assumed under another.

7. Use consistent stress and strain definitions

Define whether stress uses initial envelope area, current area, solid material area or another reference. Define engineering, logarithmic or machine displacement-based strain and any compliance correction. For irregular or graded structures, explain the reference dimensions and gauge region.

Report force–displacement data as the primary structural record when stress normalization is ambiguous. Do not mix true and engineering measures within a comparison. In large collapse, current area and specimen height change substantially, so the chosen convention can affect apparent plateau and densification behavior.

8. Identify plateau and densification without circular rules

A plateau may contain repeated peaks from buckling and fracture rather than a constant stress. State the interval and averaging method. Define densification using a reproducible criterion, such as efficiency, slope or geometry-based contact, and show its sensitivity. Avoid choosing the endpoint after observing which design gives the preferred energy ranking.

Elastomeric structures showed topology-specific transitions and size-related shifts in densification for one body-centered architecture [2]. No universal densification strain follows.

9. Report energy absorption with its integration limit

Absorbed energy is the area under a declared force–displacement or stress–strain curve to a specified endpoint. Specific energy absorption requires a stated mass basis. Volumetric energy absorption requires a stated envelope volume. Efficiency measures require exact equations and the same endpoint for comparison.

Static energy-absorption research illustrates the importance of collapse sequence and normalization [6]. A design can have higher total energy because it contains more material, without having higher mass-specific efficiency. Report both when the decision requires them.

10. Control scale and cell count

A specimen with few cells can be dominated by boundaries and may not represent a periodic continuum. Increasing cell count can change global stability, defect opportunity, load distribution and densification sequence. Geometric scaling can also encounter printer resolution and wash limitations.

The elastomeric study directly compared several part sizes and found limited scale effects for some topologies but a distinct densification shift for another [2]. That result is topology- and material-specific. Validate at another cell count or size before claiming scale independence. Statistical defect scaling remains under ER-231.

11. Treat displacement rate within the correct regime

Even nominally quasi-static compression of a viscoelastic structure can depend on rate. Report crosshead speed, normalized strain rate and whether the entire specimen remained near equilibrium. Preconditioning cycles and recovery intervals can change elastomeric curves.

The vat-printed elastomer study found stiffer response at its highest displacement rate for selected topologies while explicitly noting that the tested rates remained within a quasi-static range [2]. This evidence belongs in ER-234 as low-rate dependence. Genuine impact or dynamic crushing, with inertia and stress-wave questions, belongs to ER-233.

12. Match constitutive law to the base material

Rigid, tough and elastomeric networks require different constitutive descriptions. A linear elastic model cannot reproduce large rotation, contact, viscoelasticity, yielding and damage. Report how base-material parameters were measured in the same print, cure, orientation and conditioning state as the architecture.

Elastomeric structures were modeled with calibrated hyperelastic and viscoelastic laws [2]. Brittle lattices may require damage or element failure to reproduce progressive fracture. Reinforced systems require their own inputs [5]. Supplier data are not a substitute for state-matched characterization.

13. Model geometry, imperfections and contact

Numerical models should use measured or bounded wall and strut dimensions, node geometry, skins and initial imperfections where they control buckling. State element type, mesh convergence, contact, friction, boundary conditions and stabilization. Ideal periodic geometry may overpredict stability and suppress asymmetric collapse.

Model validation must compare the full curve, collapse sequence and observed mechanism, not only initial stiffness or peak load. A calibrated contact coefficient or imperfection amplitude is a model parameter, not a universal material property.

14. Validate transfer prospectively

Reserve at least one scale, cell count, relative density or topology outside calibration. Predict its initial stiffness, peak or plateau response, collapse mode, densification and energy measure with uncertainty. Define acceptance criteria before examining the validation result.

If the model requires new constitutive or imperfection parameters for each geometry, it can describe the tests but has not demonstrated transfer. Graded lattices [4], variable-section cores [3] and distinct topology families [2,8] provide useful challenges, but no single source validates a universal model.

15. Include ageing and damage-state controls

Storage, temperature, humidity, additional light exposure and repeated preconditioning can change the base network and recovery. Record whether a specimen is virgin, precycled or retested. The elastomeric study found little change over its bounded ageing interval and protocol [2], but explicitly limited that conclusion. It does not establish long-term durability.

ER-039 retains cyclic crushing and recovery, while ER-170 retains accelerated-ageing design. ER-234 requires these histories only to identify the monotonic state being tested.

16. Build a non-compensatory qualification matrix

Gate	Required evidence	Unsupported shortcut prevented
Material state	Resin, print, cure, conditioning and base-material law	Calling a lattice curve a resin property
As-built geometry	Struts, walls, nodes, skins, mass and relative density	Using CAD density as tested density
Boundary conditions	Platens, alignment, friction, aspect ratio and contact	Treating fixtures as irrelevant
Mechanism	Images and curve evidence for bending, buckling, fracture and densification	Ranking designs from one peak
Energy metric	Integration limit and mass or volume normalization	Reporting an endpoint-free energy value
Transfer	Holdout scale, cell count, density or topology	Declaring universal topology superiority

The gates are independent. Detailed geometry cannot compensate for an unmatched material state, and a good force prediction cannot compensate for the wrong collapse mechanism.

17. Minimum reporting set

Report resin, batch, printer, exposure, orientation, layer, support, wash, post-cure, storage and conditioning; architecture and unit cell; designed and measured struts, walls, nodes, skins, dimensions, mass and relative density; specimen cell count and aspect ratio; platen, alignment, lubrication, friction and compliance; loading and preconditioning history; force–displacement data; stress and strain conventions; stiffness, peak, plateau and densification definitions; absorbed and specific energy equations and endpoints; images and failure sequence; base-material characterization; constitutive and damage laws; mesh, imperfections and contact; calibration data; holdout validation; replicates, exclusions and uncertainty.

No plateau stress, densification strain, energy value, buckling coefficient or topology ranking becomes universal when the material, architecture or boundary conditions change.

18. Knowledge boundary

The technical claims in this review are supported by full-text sources [2–6] and publisher-abstract source [8]. References [1] and [7] are retained only to identify additional corpus records and do not support technical claims. The technical sources do not share one resin, geometry, rate, contact or endpoint. ER-026 retains general relative-density, topology and cellular-architecture qualification; ER-010 retains dimensional metrology; ER-101 retains elastomeric compression set and cyclic durability; ER-090 retains frequency-temperature viscoelastic response; ER-206 retains CT methods; ER-231 remains a forward reference; and ER-233 retains dynamic crushing.

19. Limitations

The evidence spans markedly different material classes, architectures and normalization rules. References [1] and [7] were limited to bibliographic-record depth and are retained for corpus identity only; no technical claim rests on them. References [2], [3], [4], [5] and [6] were read at full-text depth; reference [8] was used at publisher-abstract depth. Several studies use small cell counts or application-specific designs. The recent abstract-level source [8] has limited independent replication. Static and low-rate compression cannot establish impact crashworthiness. The review therefore supplies a qualification architecture, not universal design values.

20. Conclusions

Compression and crushing of printed photopolymer structures must separate the base-material state from architecture, contact and instability. The as-built structure, not the CAD model, controls relative density and collapse. Boundary conditions, stress and strain conventions, plateau rules and densification criteria must be explicit. Energy absorption retains its integration endpoint and normalization. Models require state-matched constitutive laws, measured geometry, imperfections, contact and holdout validation. A defensible claim is bounded to the resin, print state, architecture, scale and boundary conditions tested.

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