

Mechanical Metamaterials Made by Photopolymerisation: Unit Cells, Boundary Effects, Nonlinearity and Qualification

From nominal unit-cell mechanics to finite printed specimens whose response depends on architecture, scale, defects and polymer state

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Abstract

Mechanical metamaterials derive performance from architecture, but photopolymerisation introduces dimensional error, boundary truncation and nonlinear constituent behaviour that can shift the apparent unit-cell response. ER-361 establishes a qualification route from as-built geometry to specimen-scale mechanics. Relative density, cell count and slenderness are linked to stiffness, instability and failure, while CT or optical metrology is paired with full-field deformation and force-displacement data. Cell-count and specimen-size sweeps expose boundary effects; geometric perturbations test sensitivity to manufacturing variation. The review therefore separates a transferable architectural response from behaviour that exists only for one specimen size, boundary condition or as-printed defect population.

Keywords: mechanical metamaterial; vat photopolymerisation; unit cell; boundary effect; nonlinearity; qualification

1. Qualification problem: mechanical metamaterials

For mechanical metamaterials, qualification fails if a result is transferred across an unmeasured regime change. The review therefore separates minimum cell count for representative behaviour from whether a topology is robust to VPP feature error and which performance metric should govern acceptance for the intended service, and records relative density, slenderness ratio, and cell-count-to-specimen-size ratio for every relevant comparison. [1,2]

1.1 Scope boundary.

ER-361 owns qualification of mechanical metamaterial behaviour at the unit-cell-to-specimen scale. ER-362 owns auxetic architectures, ER-363 graded lattices, ER-364 snap-through/negative-stiffness designs, and ER-365 impact-energy absorption; those siblings supply specialised subclasses without replacing this general qualification framework.

2. Governing balances for mechanical metamaterials

Architected mechanical response is reduced to relations for density, member stability, and finite-specimen boundary effects.

effective stiffness and strength emerge from architecture, relative density and deformation mode rather than resin modulus alone

Maxwell-type connectivity and stretch- versus bending-dominated behaviour provide first-order topology classification

geometric nonlinearity and instability become dominant at strains far below constituent failure in slender architectures

This separation prevents a density effect from being misread as buckling or as a boundary-cell artefact.

3. Regime boundaries for mechanical metamaterials

The metamaterial regime map identifies whether specimen size, member stability, or density controls the acceptance test.

Table 1. Regime indicators for mechanical-metamaterial response.

Indicator	Engineering meaning	Use
relative density	solid fraction used as the primary structural normalisation variable	The scale limit for 'minimum cell count for representative behaviour' is expressed by relative density; use it to detect changes in solid fraction used as the primary structural normalisation variable before reusing prior evidence.
slenderness ratio	member geometry governing buckling susceptibility	The scale limit for 'whether a topology is robust to VPP feature error' is expressed by slenderness ratio; use it to detect changes in member geometry governing buckling susceptibility before reusing prior evidence.
cell-count-to-specimen-size ratio	number of cells relative to specimen size, governing boundary effects	The scale limit for 'which performance metric should govern acceptance for the intended service' is expressed by cell-count-to-specimen-size ratio; use it to detect changes in number of cells relative to specimen size, governing boundary effects before reusing prior evidence.

Mechanical performance is transferred only after the tested density, stability, and finite-size regime has been matched.

4. Couplings that move the mechanical metamaterials

Cure resolution changes strut thickness and therefore relative density.

Surface inhibition/overcure alters nodes disproportionately.

Base-resin viscoelasticity couples with architecture to set rate dependence and hysteresis.

5. Failure signatures and false diagnoses

The engineering diagnosis partitions failure into boundary-layer deformation that invalidates periodic-cell predictions, node stress concentration and strut buckling and fracture triggered by print defects before designed instability. Evidence from CT-based as-built geometry, full-field DIC under monotonic and cyclic loading and resin coupon tests across strain rate and orientation is kept branch-specific because the same final response can arise through different routes. The four Table 2 contrasts are evaluated together so that boundary, geometry and material effects cannot all be absorbed into one empirical label.

Table 2. Failure-mode discrimination for mechanical-metamaterial response.

Failure mode	Observable signature	Discriminating evidence
boundary-layer deformation that invalidates periodic-cell predictions	CT-based as-built geometry	vary unit-cell count at constant cell geometry
node stress concentration and strut buckling	full-field DIC under monotonic and cyclic loading	fabricate same topology over several relative densities
fracture triggered by print defects before designed instability	resin coupon tests across strain rate and orientation	compare as-designed and as-built FE models
size effects when only a few unit cells span the gauge section	energy absorption and recoverability in addition to stiffness/strength	test multiple build orientations and strain rates

6. Measuring mechanical metamaterials with traceable uncertainty

Measurement confidence comes from agreement among the three Table 2 channels after calibration, not from repeated acquisition of only one channel. Evidence for mechanical metamaterials is not accepted from a single nominal condition; during metrology of mechanical metamaterials, bending-versus-stretching response is resolved against geometric instability. The analysis requires independent resolution of relative density and topological connectivity, follows it with separate monitoring of geometric instability, and uses an uncertainty-controlled perturbation of bending-versus-stretching response as a targeted challenge wherever the two indicate different mechanism or margin; the uncertainty record for mechanical metamaterials keeps geometric instability separate from relative density.

7. Experiments that discriminate competing mechanisms

The four Table 2 challenges provide independent evidence of causality. A candidate mechanism must predict the response of rows not used to motivate it. A boundary challenge involving topological connectivity is the first stress test for mechanical metamaterials; only after that result is bounded is a causal contrast between relative density and bending-versus-stretching response interpreted; during the causal challenge for mechanical metamaterials, geometric instability is tested against relative density. The record keeps a replicate test of geometric instability outside that inference and reports it as an independent line of evidence; the experiment for mechanical metamaterials separates relative density from topological connectivity.

8. Model identification and validation for mechanical metamaterials

[1,2] [6] [3,4] Uncertainty is transferred from the model to the three Table 3 decisions individually, keeping parameter and measurement contributions traceable. Qualification of mechanical metamaterials treats parameter estimation for relative density and topological connectivity as one axis and an uncertainty-bounded check on geometric instability as another; within model identification for mechanical metamaterials, relative density is not fitted through topological connectivity. Between them, prediction against bending-versus-stretching response supplies the deliberate challenge that determines whether the apparent transfer is mechanistic or merely coincidental; prediction for mechanical metamaterials keeps topological connectivity independent of bending-versus-stretching response. [5]

9. Qualification envelope and technology decisions

Table 3. Technology-decision matrix for mechanical-metamaterial response.

Decision	Minimum evidence	Acceptance logic
minimum cell count for representative behaviour	Quantify minimum cell count for representative behaviour with CT-based as-built geometry at multiple states, including the boundary condition where the response first becomes decision-relevant.	Accept the transfer when repeated 'vary unit-cell count at constant cell geometry' tests keep CT-based as-built geometry on the qualified trend and boundary-layer deformation that invalidates periodic-cell predictions is absent from the boundary state.
whether a topology is robust to VPP feature error	For whether a topology is robust to VPP feature error, require a replicated full-field DIC under monotonic and cyclic loading dataset that covers the proposed envelope and reports the uncertainty attached to the limiting state.	Passing requires full-field DIC under monotonic and cyclic loading to remain consistent across repeated 'fabricate same topology over several relative densities' challenges while node stress concentration and strut buckling stays below the diagnostic threshold.
which performance metric should govern acceptance for the intended service	Demonstration of which performance metric should govern acceptance for the intended service needs traceable resin coupon tests across strain rate and orientation measurements in the qualified state and at least two candidate states spanning the transfer interval.	Support the decision only when the resin coupon tests across strain rate and orientation response to 'compare as-designed and as-built FE models' is stable within uncertainty and the evidence does not indicate fracture triggered by print defects before designed instability.

The mechanical metamaterials workflow deliberately separates a separate boundary for bending-versus-stretching response from tested ranges in relative density and topological connectivity; this avoids fitting the challenge into the quantity being qualified; inside the mechanical metamaterials envelope, topological connectivity and bending-versus-stretching response define different transfer limits. An explicit transfer limit on geometric instability is then examined on its own terms before any transfer statement is retained; qualification of mechanical metamaterials bounds bending-versus-stretching response separately from geometric instability.

10. Design consequences for mechanical metamaterials

A design change is evaluated through a design change governed by relative density, while minimum cell count for representative behaviour is controlled independently; an implementation check on bending-versus-stretching response then determines whether the implementation remains inside the qualified mechanism; during design implementation for mechanical metamaterials, bending-versus-stretching response is constrained by geometric instability. This prevents a nominally unchanged machine setting from masking a different mechanical metamaterials regime; the mechanical metamaterials design record separates geometric instability from relative density.

11. Evidence gaps for mechanical metamaterials

The first and third branches should be sampled there to determine whether the observed limit is mechanistic or metrological. The working sequence for mechanical metamaterials has three parts: scale transfer of relative density; uncertainty in topological connectivity versus bending-versus-stretching response; and independent replication of geometric instability; for unresolved mechanical metamaterials transfer, geometric instability is studied separately from relative density. Each part answers a different engineering question, so uncertainty or failure in one part is not repaired by a favourable result in another; the evidence gap in mechanical metamaterials distinguishes relative density from topological connectivity.

12. Qualification outcome for mechanical metamaterials

The review closes with three traceable Table 3 limits rather than a single universal pass/fail designation. Three independent checks structure the mechanical metamaterials assessment; at final qualification of mechanical metamaterials, relative density is reconciled with topological connectivity. Agreement between measurement and prediction for relative density establishes the primary state, a renewed-evidence trigger when geometric instability changes tests whether that state survives transfer, and causal evidence that separates topological connectivity from bending-versus-stretching response is the perturbation used when the two disagree; the closing mechanical metamaterials claim keeps topological connectivity distinct from bending-versus-stretching response.

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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.