

Multiaxial Strength and Failure Criteria for Printed Photopolymers: Combined Loading, Anisotropy and Model Validation

A state-resolved framework for calibrating and testing failure surfaces

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Abstract

The strength of a printed photopolymer under combined loading cannot be reconstructed safely from one tensile strength and one elastic modulus. Tension, compression and shear can activate different deformation and fracture processes, while print orientation, cure, conditioning, temperature, rate, specimen geometry and local stress gradients alter the observed failure state. Familiar criteria such as maximum stress, von Mises, Drucker-Prager, Mohr-Coulomb, Tsai-Hill and Tsai-Wu encode different assumptions. Selecting one by convenience does not establish its applicability, and fitting an interaction coefficient to the same data used for evaluation does not validate prediction.

This review defines a non-compensatory qualification framework for multiaxial strength of printed photopolymers. It separates the material coordinate system from the specimen and loading axes, requires proportional and non-proportional paths to be declared, and distinguishes material failure from grip, fixture, free-edge, notch and instability failures. Uniaxial data may anchor directional limits but cannot identify combined-load interaction terms. Calibration must therefore use independently measured loading paths, preserve tension-compression asymmetry where observed, report parameter identifiability and uncertainty, and reserve additional paths for prospective validation. The direct printed-photopolymer corpus supports orientation- and state-dependent strength and distinct failure morphologies, but direct multiaxial evidence remains limited. Accordingly, this article supplies a bounded test and validation architecture rather than universal coefficients or a preferred failure criterion.

Keywords: printed photopolymer; multiaxial strength; combined loading; anisotropy; failure criterion; interaction parameter; calibration; validation

1. Significance and scope

Components rarely experience pure coupon tension. Bending produces tension and compression, torsion produces shear, pressure creates biaxial or triaxial states, and assembly loads can rotate the principal directions relative to printed layers. A safe model must therefore address both the stress state and the printed material state.

ER-235 addresses monotonic failure under proportional and non-proportional combinations of tension, compression and shear. It asks which experiments are needed to select, calibrate and validate a failure surface without treating a convenient equation as a material law.

1.1 Corpus boundary

ER-010 retains dimensional and geometric metrology. ER-039 retains fatigue, creep and repeated loading. ER-070 retains general fracture toughness and damage tolerance. ER-073 retains the general anisotropy framework. ER-088 retains surface topography, roughness and finishing. ER-171 retains design values and allowables; ER-235 provides no transferable allowable. ER-184 retains generic uncertainty inference. ER-207 retains residual-stress measurement. ER-231 retains statistical size effects. ER-232 retains notch sensitivity. ER-233 retains impact and high-rate response. ER-234 retains compression, buckling and structural crushing. ER-236 retains stress-environment coupling. ER-235 uses those domains only to define the state and failure event of a multiaxial qualification.

2. Define the claim before choosing a criterion

Separate at least four claims: interpolation inside a measured envelope, prediction of an untested proportional path, prediction of a non-proportional path, and transfer to another printed state or geometry. Each requires progressively stronger evidence. Agreement with the points used for fitting establishes only calibration performance.

The quantity to be predicted must also be explicit: first nonlinearity, yield, maximum load, crack initiation, loss of stiffness, specified strain or complete separation. Brittle and ductile UV-curable resins can show different tensile failure mechanisms [5]. A criterion fitted to maximum load must not silently become a crack-initiation criterion.

3. Freeze the printed material state

Record resin and batch, printer, wavelength and exposure, build location, orientation, layer thickness, supports, wash, drying, post-cure spectrum and thermal history, storage, conditioning, temperature and test rate. State specimen age and whether surfaces are as-printed, polished or machined.

Orientation-dependent mSLA data show statistically significant build-direction dependence for compressive strength in the tested system [1]. SLA studies also demonstrate effects of post-cure, strain rate and processing state [2,4]. These observations require state-bound parameters. They do not authorise a correction factor that transfers one failure surface to another resin or cure schedule.

4. Establish coordinate systems

Define the build axes, layer normal, scan or pixel axes where relevant, specimen axes and principal-stress directions. Report the transformation used to express stress in the material coordinates. Terms such as horizontal, vertical and 45 degrees are ambiguous unless tied to a drawing and to the load direction.

An isotropic invariant criterion ignores material axes. An orthotropic or more general anisotropic criterion requires them. Process-induced anisotropy can affect strength differently from stiffness, as recognised in anisotropy-aware structural optimisation [8]. Consequently, an elastic symmetry assumption does not automatically establish the same symmetry for strength.

5. Separate stress state from stress gradient and geometry

A combined nominal load does not guarantee a uniform multiaxial stress state. Holes, fillets, grips, thin walls, bonded inserts and load introduction regions create gradients and may control failure. Report the full specimen geometry, as-built dimensions, fixture, alignment, load introduction and the validated region from which the stress state is inferred.

Experiments on printed specimens with holes demonstrate that hole geometry, material and raster orientation influence failure prediction [7]. That study provides useful validation logic but uses thermoplastic additive processes. Its fitted quantities cannot be transferred to neat vat-printed photopolymers.

6. Design an informative loading-path matrix

A minimum matrix normally includes positive and negative normal stress where feasible, positive and negative shear, and several combined ratios. Tubular tension-torsion, cruciform biaxial loading, Arcan-type fixtures, off-axis coupons and bending-torsion can provide different parts of the envelope. No fixture is automatically valid for every material.

For each path, document whether the ratio of stress components is constant. A proportional path preserves direction in stress space while magnitude increases. A non-proportional path changes direction and can reveal path dependence, damage accumulation or rotating failure planes. Do not merge the two populations.

7. Use uniaxial tests as anchors, not as an envelope

Directional tensile, compressive and shear tests can estimate axial and transverse limits and identify asymmetry. A full experimental framework for SLA materials shows why tension, compression, orientation, cure and rate must remain explicit [4]. These data constrain intercepts of a failure surface.

They do not determine curvature between intercepts. In a polynomial interaction criterion, an interaction coefficient governs combined states and is not identifiable from pure axial tests alone. Setting it to zero is a modelling assumption, not a measurement. Using a textbook relation for composites is also an assumption unless validated for the printed network.

8. Select candidate criteria by mechanism and symmetry

Maximum-stress and maximum-strain rules are transparent but omit interaction. Von Mises and Tresca represent pressure-insensitive isotropic yielding and are poor default choices when tension-compression asymmetry, brittle fracture or hydrostatic sensitivity matters. Drucker-Prager and Mohr-Coulomb introduce pressure or normal-stress sensitivity but require appropriate calibration. Tsai-Hill and Tsai-Wu provide anisotropic interaction forms, yet their composite origins do not make them automatically valid for printed photopolymers.

Candidate selection should follow observed symmetry, tension-compression asymmetry, pressure sensitivity, failure morphology and the intended domain. Multiple criteria should be compared when the corpus cannot discriminate a priori. The result can legitimately be that no tested form predicts the holdout paths adequately.

9. Distinguish yield, damage and final failure

A single surface may be insufficient when the material first yields or damages and then fails after evolving anisotropy. Define the event detected by load, strain, acoustic emission, digital image correlation, microscopy or stiffness change. If an initiation surface and an ultimate surface are both used, calibrate and validate them separately.

Fractographic work on brittle and ductile UV-cured resins identifies different sequences involving interfaces, building blocks, crack deflection and local damage [5]. Adjacent material-extrusion evidence likewise shows that specimen geometry and raster arrangement influence measured failure [6]. Morphology must therefore confirm that apparently comparable endpoints represent comparable mechanisms.

10. Control hydrostatic stress and confinement

Pressure sensitivity cannot be inferred from tension and unconfined compression alone when friction, barreling or fixture constraint changes the stress state. If hydrostatic or triaxial effects matter, use a method that quantifies confinement and reports the corresponding principal stresses. Separate true material pressure sensitivity from end friction and structural constraint.

Compression-derived coefficients must also exclude local buckling and crushing. Those structural mechanisms remain under ER-234. A specimen that loses load through geometric instability has not supplied a material failure point for ER-235.

11. Treat anisotropy as measured, not assumed

Test enough orientations to detect whether orthotropy is adequate. Three nominal directions may miss within-plane or off-axis variation. Report directional strength and failure-plane observations, not only modulus. The mSLA orientation study [1] and SLA processing studies [2,4] support material-state and orientation dependence, but none supplies a universal multiaxial surface.

If an isotropic fit is retained because observed anisotropy is small relative to uncertainty, state the equivalence margin and the tested orientations. Failure to reject anisotropy is not proof of isotropy.

12. Estimate parameters with identifiability checks

Report the objective function, weighting, parameter bounds, optimiser, starting values and convergence checks. Examine parameter correlation and sensitivity. A low residual can coexist with non-identifiable coefficients when loading paths provide redundant information.

Use replicates to separate specimen variability from model discrepancy. Propagate uncertainty in measured dimensions, loads and stress reconstruction. Do not report more significant digits for an interaction coefficient than the evidence supports. If several parameter sets predict calibration data equally well but diverge elsewhere, the design needs additional loading paths.

13. Separate calibration from validation

Reserve at least one loading ratio and preferably one loading-path family outside calibration. Define acceptance limits before examining the holdout results. Compare predicted failure load, location, plane and mode, not only a global coefficient of determination.

The combined-load thermoplastic study [7] illustrates the value of comparing predicted and experimental failure loads, while anisotropic optimisation work [8] separates strength from stiffness constraints. These are adjacent methodological examples. A photopolymer claim still requires state-matched direct evidence.

14. Validate proportional and non-proportional loading separately

A surface calibrated under proportional loading may predict only the instantaneous stress combination. It may fail when the load path rotates, unloading occurs or damage accumulates before the final state. Include a non-proportional holdout if the service history contains sequential assembly, pressure and torsion or other rotating paths.

Report the complete load path in component space. Two tests reaching the same terminal stress point can have different histories and different outcomes. A path-independent model must earn that simplification experimentally.

15. Prevent fixture and free-edge failures

Inspect every specimen and classify failure location. Failures at grips, bonded tabs, load pins, free edges or abrupt thickness transitions should not be accepted automatically as material-envelope points. Document exclusion rules before testing and report all exclusions.

Digital image correlation can verify field uniformity and detect premature localisation. Finite-element analysis can support stress reconstruction, but it must use measured geometry and boundary conditions and must not be tuned solely to reproduce the final load.

16. Build a non-compensatory qualification matrix

Gate	Required evidence	Unsupported shortcut prevented
Material state	Resin, print, cure, conditioning, temperature and rate	Pooling unlike printed states
Coordinates	Build, specimen and principal axes with transformations	Calling an undefined angle anisotropy
Stress state	Validated field, path and fixture	Treating nominal load as uniform stress
Identifiability	Independent paths for every interaction term	Deriving a surface from uniaxial data
Mechanism	Failure location, plane and morphology	Mixing grip failure, buckling and material failure
Transfer	Prospective holdout path and acceptance limits	Calling calibration validation

The gates are independent. A close curve fit cannot compensate for fixture failure, and a detailed fractograph cannot identify an interaction term that was never excited.

17. Minimum reporting set

Report resin, batch, printer, exposure, orientation, layer, support, wash, post-cure, storage, conditioning, temperature and rate; coordinate definitions; specimen and fixture geometry; as-built dimensions; loading components and histories; field measurement and stress reconstruction; failure endpoint, location, plane and morphology; replicates and exclusions; candidate criteria and rationale; equations, units and sign convention; calibration and holdout allocation; parameter estimates, correlations and uncertainty; validation metrics and acceptance limits; and the exact transfer domain.

No coefficient, envelope or criterion becomes universal when chemistry, cure, orientation, temperature, rate, geometry or failure mechanism changes.

18. Knowledge boundary

The direct corpus establishes orientation-sensitive response in specific printed photopolymers [1,2,4], together with cure, rate, tension-compression and fracture-morphology evidence across the bounded systems in [2-5]. Adjacent additive-manufacturing studies contribute specimen, gradient, combined-load and anisotropic design logic [6-8]. Direct, replicated multiaxial datasets for neat vat-printed photopolymers remain sparse. The evidence therefore supports a qualification framework, not universal interaction parameters.

19. Limitations

Several direct studies use one commercial resin and a limited set of orientations or loading modes. Some adjacent sources concern material extrusion, nanocomposites, notched specimens or structural optimisation rather than neat vat-printed material. Published endpoints and post-processing states are heterogeneous. References [1], [2], [4], [5], [6], [7] and [8] were read at full-text depth; reference [3] was used at publisher-abstract depth. This review does not resolve which criterion is best for every formulation and does not provide design allowables.

20. Conclusions

Multiaxial strength of printed photopolymers must be treated as a state-resolved model-validation problem. Uniaxial tests anchor directional limits but cannot identify interaction. Coordinate systems, proportionality, stress gradients, fixtures and failure mechanisms must be explicit. Candidate criteria should reflect observed symmetry and pressure sensitivity, and parameters must pass identifiability and uncertainty checks. Prospective holdout paths, including non-proportional loading when relevant, are required before transfer. The defensible result is a bounded failure surface for a defined printed state, not a universal criterion.

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