

Notch Sensitivity of Vat-Printed Thermosets: Root Radius, Orientation, Cure State and Fracture-Controlled Design

A state-resolved framework from realised notch geometry to validated component transfer

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Abstract

Notch sensitivity in a vat-printed thermoset is not determined by a CAD radius or elastic stress-concentration factor alone. The realised root geometry, notch depth, edge condition, layer arrangement, wash and cure state, conditioning, material strength, fracture resistance, component scale and loading mode jointly determine whether failure is governed by a finite stress gradient, crack-like fracture or another local mechanism. A printed V-notch, printed U-notch, machined notch, razor precrack, central hole and natural process defect are not interchangeable.

This review defines a non-compensatory qualification framework for fracture-controlled notch design in printed photopolymers. It begins with as-built geometry and a frozen process state, separates nominal strength from local elastic concentration and crack-driving quantities, and requires the selected model to be checked against its mechanical assumptions. Theory-of-critical-distances, finite-fracture, cohesive and mixed-mode approaches may organize evidence, but any fitted material length or fracture envelope remains state- and method-specific until validated at another radius or scale. Direct studies of scaled DLP notches, sharp manufactured cracks, mixed-mode specimens, orientation- and cure-dependent toughness, and printed dental resins support the workflow. They do not establish a universal safe radius, critical distance, knock-down factor, stress-concentration factor or transferable acceptance threshold.

Keywords: vat photopolymerization; thermoset; notch sensitivity; root radius; build orientation; cure state; fracture mechanics; critical distance

1. Significance and scope

Geometric discontinuities are unavoidable in functional printed parts. Holes, grooves, internal corners, channels, attachment features and support-removal scars create local stress gradients. In a brittle or weakly yielding printed network, a small change in realised root radius or local cure can shift the failure locus and invalidate a nominal-stress comparison. Design therefore requires a declared notch class, local material state and failure model.

ER-232 addresses monotonic failure caused by a specified notch in a vat-printed thermoset. Its central decision is whether a model calibrated for one geometry and process state can predict another root radius or scale without changing the controlling mechanism.

1.1 Corpus boundary

ER-010 retains dimensional and geometric metrology. ER-031 retains cure-shrinkage stress and warpage. ER-039 retains cyclic notch fatigue and time-dependent failure. ER-069 retains crack-growth kinetics and thresholds. ER-070 retains general fracture-toughness methods and damage tolerance. ER-073 retains general anisotropy and interlayer cohesion. ER-088 retains surface topography, roughness and finishing. ER-171 retains design values and allowables. ER-184 retains generic defect-mechanism inference. ER-206 retains micro-CT defect detection. ER-207 retains residual-stress measurement. ER-231 retains Weibull models, gauge-volume scaling and statistical lower-tail evidence. ER-233 retains impact and high-rate response. ER-235 retains general multiaxial failure criteria. ER-232 uses inputs from those domains only to resolve the declared notch problem; it does not establish a design value or allowable.

2. Classify the discontinuity before choosing a model

A finite-radius V- or U-notch has a bounded elastic root stress for an ideal continuum. A sharp fatigue or razor precrack is intended to generate a crack-like field. A printed slit retains a process-defined tip shape and may contain partially cured material. A drilled or printed hole has two interacting roots and a distinct stress field. A natural pore, layer flaw or support scar has uncertain geometry and material state. These cases cannot share one label or one acceptance value.

The scaled DLP study directly compared sharp V-shaped and rounded U-shaped notches across several component sizes [1]. The SLA mixed-mode study used central holes with radial cracks that were printed and then sharpened [2]. The DLP semicircular-bend study used cracks introduced during manufacture [4]. Together they show that notch and crack preparation must remain explicit. They do not establish equivalence among those geometries.

3. Measure the as-built notch

Record designed depth, included angle, root radius, ligament, thickness and edge location. Then measure the realised geometry after printing, washing, support removal and post-cure. Include root rounding, stair-stepping, overcure, trapped resin, surface damage and any asymmetry. The measurement method must resolve the root at the scale relevant to the model, with uncertainty reported.

The CAD radius is an input to manufacturing, not proof of the final stress field. Voxel or pixel exposure, orientation and compensation can alter local geometry. A machined sharpening step can change the surface and residual state. If the notch cannot be measured adequately, the design claim should be framed around a bounded geometry range rather than a nominal point value. Dimensional and geometric metrology

remains under ER-010; surface topography, roughness and finishing remain under ER-088. ER-232 requires only the measurements necessary to define the notch problem.

4. Freeze the printed material and cure state

Notch response depends on the local network that surrounds the root. Report resin and batch, printer, exposure settings, build position and orientation, layer thickness, supports, wash medium and duration, drying, post-cure spectrum, time and temperature, storage and environmental conditioning. If post-cure penetration or oxygen inhibition can vary through thickness, the state near the root deserves particular attention.

DLP research shows that exposure, layer thickness, orientation and post-processing affect tensile and fracture-related properties [3]. Printed denture-resin studies likewise bind notched-beam response to material formulation, orientation and water conditioning [5,6]. These results demonstrate state dependence. They do not provide generic corrections for another resin or cure schedule.

5. Resolve notch plane, layers and load path

Three orientations should be declared separately: build direction relative to the component, notch plane or root line relative to the layers, and applied load relative to both. A nominal orientation label can conceal whether the prospective fracture plane crosses layers, follows an interface or intersects a free surface. Local support attachment and platform position can add further asymmetry.

Unnotched flexural evidence shows that print angle and load direction can change measured strength in provisional dental resins [8]. Notched DLP evidence shows orientation and post-treatment effects in fracture-toughness specimens [3]. Those studies require orientation-matched inputs; they do not prove isotropy when one comparison shows a small directional difference. ER-073 retains the general anisotropy framework, while ER-232 preserves orientation only as a state variable in notch prediction.

6. Separate nominal strength, local stress and fracture response

Nominal notch strength is the applied failure load divided by a declared nominal section. A stress-concentration factor relates an ideal elastic root stress to nominal stress for a specified geometry. Notch sensitivity compares the observed loss of strength with an elastic or unnotched reference. Fracture toughness or energy-based parameters characterize crack-like resistance under validated conditions. These quantities answer different questions.

An elastic peak stress can be mesh-sensitive for a sharp corner and physically misleading when yielding, damage or a finite fracture process zone controls failure. Conversely, using a crack intensity factor for a blunt root may violate the crack-like field assumption. Whole-component fracture loads and notched-coupon toughness are complementary, not interchangeable. The endocrown study paired structural fracture load with an experimental notched-beam parameter and failure morphology [7], illustrating the need to retain both geometry levels.

7. Check fracture-mechanics applicability

Before using a linear-elastic fracture parameter, verify specimen geometry, crack or notch sharpness, ligament, thickness, loading, material linearity and the relevant standard or analytical validity conditions. Printed polymers may show limited macroscopic yielding while still possessing a non-negligible process zone. Cure state and conditioning can change that relation.

The denture-base studies used notched three-point-bend configurations and declared conditioning protocols to compare materials [5,6]. Their reported values remain specific to those methods and specimen states. They do not automatically become component design toughness. ER-070 owns general toughness qualification; ER-232 requires only that the input used in a notch model be valid and matched to the component state.

8. Use stress concentration as a diagnostic, not an acceptance rule

Elastic analysis is useful for mapping the root gradient, identifying hot spots and normalizing geometry. Report the realised geometry, constitutive assumptions, boundary conditions, contact, mesh convergence and the stress component used. A tabulated factor for an ideal notch is insufficient when the printed root departs from that geometry or when local layers produce directional response.

No universal stress-concentration factor or knock-down factor follows from the corpus. Even for geometrically similar parts, scale can change the relationship between root gradient and material length. The direct DLP evidence shows that nominal strength depends on both size and notch geometry [1]. ER-231 retains the separate question of statistical defect opportunity with changing stressed volume.

9. Calibrate fracture-controlled models cautiously

Theory-of-critical-distances approaches evaluate stress over or at a distance related to material strength and fracture resistance. Finite-fracture models consider a finite crack advance or coupled stress and energy conditions. Cohesive models represent a traction-separation law and process zone. Each can be useful, but each adds fitted or measured inputs whose state identity matters.

The scaled DLP study evaluated a critical-distance framework for its two resins and tested more than one geometry and scale [1]. This is direct evidence that a length-based method can be examined in printed photopolymers. Its fitted distances and errors remain specific to the reported materials, cure, orientation, geometry and loading. A critical distance derived from tensile strength and toughness is not process-invariant when either input changes.

Calibration and validation must be separated. Do not fit a model to every tested radius and then call agreement validation. Reserve at least one root radius, scale or orientation for prediction. Report uncertainty in geometry and material inputs, and show whether the predicted failure locus matches observation.

10. Treat mixed mode as a separate loading problem

Notches near holes, inclined features and asymmetric loads can combine opening and sliding. State how mode mixity was determined and whether the stress analysis accounts for nonsingular terms or geometry effects. A mixed-mode envelope depends on specimen geometry, crack or notch preparation, material state and chosen criterion.

SLA hole-crack experiments varied crack angle to obtain a range of mode mixities and combined finite-element intensity factors with observed fracture [2]. DLP semicircular-bend experiments compared several fracture criteria under mode-I, mixed and mode-II conditions [4]. These studies support explicit mixed-mode analysis and crack-path reporting. They do not establish a universal envelope for finite-radius notches or other printed networks.

11. Couple strength and toughness without erasing state identity

Many fracture-controlled notch models require an unnotched strength and a fracture-resistance input. Both must come from material produced, washed, cured, oriented and conditioned compatibly with the notched component. Values from supplier data sheets or differently oriented coupons can create an apparently precise but physically inconsistent prediction.

Process-parameter work directly links exposure and post-processing to tensile and fracture properties [3]. Orientation-sensitive flexural evidence reinforces the need for load-path matching [8]. Dental notched-beam comparisons show substantial material and protocol dependence [5,6]. A model should propagate the uncertainty of those inputs and should be recalibrated or revalidated when the state changes.

12. Preserve component scale and statistical boundaries

Increasing scale can change stress gradient, constraint, surface-to-volume ratio, cure uniformity, print distortion and the opportunity to sample defects. A fracture-controlled model addresses some gradient and material-length effects. A Weibull or weakest-link treatment addresses a distinct statistical hypothesis under ER-231. Combining the two is possible only when each part is stated and independently supported.

The scaled DLP dataset contains both notch and size variation [1], but it does not allow every mechanism to be assigned uniquely. Report whether scaling is geometric, which process parameters remained constant and whether the failure origin changed. A prediction validated at one additional radius may still fail at a much larger component if the process state or defect population changes.

13. Verify failure locus and damage sequence

Inspect the root and fracture surfaces to determine whether failure initiated at the intended notch, a layer boundary, a pore, a support scar, an edge or a grip-related location. Record crack direction, branching, stable damage if visible and the relation to build layers. Digital image correlation or full-field methods can help test whether the local deformation pattern agrees with the model.

The SLA mixed-mode study used digital image correlation and observed crack propagation alongside numerical analysis [2]. Endocrown work included visible failure morphology in addition to load and notched-beam data [7]. These methods support model checking, but visible correlation does not by itself identify the microscopic mechanism. Defect-detection limits remain explicit, and micro-CT method development remains under ER-206.

14. Validate another radius, scale or state

A defensible design transfer requires a prospective test outside the calibration set. Select an additional root radius or geometrically scaled specimen that probes the intended use range. Preserve process and orientation where the purpose is model validation. If a process or cure state also changes, treat that as a second validation dimension rather than a silent substitution.

Compare predicted and observed load, nominal stress, failure locus and, where available, deformation or crack path. Define acceptance bands before seeing the results. If the model succeeds only after refitting its material length or cohesive law, it has described the new state but has not demonstrated transfer.

15. Include conditioning and requalification

Water, temperature, chemical exposure, sterilization or ageing can change stiffness, strength, fracture resistance and interface quality. The relevant condition must be applied to both the notched test and the input coupons. Denture-base research demonstrates state-specific comparison after prescribed water storage [5,6], while restoration studies combine conditioning with component fracture [7]. Those protocols are application evidence, not generic service simulations.

Define requalification triggers for resin change, printer or exposure change, orientation change, wash or post-cure change, geometry compensation, support strategy, machining, environmental conditioning and failure-mode shift. No universal safe notch radius survives an uncontrolled change in state.

16. Build a non-compensatory qualification matrix

Gate	Required evidence	Unsupported shortcut prevented
Geometry	As-built depth, root radius, angle, ligament, edge and uncertainty	Treating the CAD notch as the tested notch
Material state	Resin, print, orientation, wash, post-cure and conditioning	Using state-invariant strength or toughness
Model validity	Stress field, constitutive assumptions and crack/notch applicability	Applying a familiar equation outside its regime
Calibration	Declared inputs and fitting set	Hiding refitting inside prediction
Validation	Additional radius or scale, prediction band and failure locus	Accepting one-resin, one-radius agreement
Transfer	Component geometry, loading, environment and defect-population check	Moving coupon results directly into service

The gates are independent. Accurate geometry cannot compensate for a mismatched cure state; valid toughness cannot compensate for the wrong notch class; and agreement at one radius cannot establish a universal material length.

17. Minimum reporting set

Report resin and batch; printer and exposure state; build location and orientation; layer thickness and supports; wash, drying, post-cure, storage and conditioning; designed and measured notch depth, angle, root radius, ligament, thickness and edge state; measurement uncertainty; notch or crack creation route; unnotched reference; loading mode, rate, fixture and environment; nominal stress definition; elastic or numerical stress field and convergence; tensile strength and fracture-resistance inputs with matched state and uncertainty; selected fracture-controlled model and assumptions; calibration data; reserved validation radius or scale; predicted and observed failure load or stress; failure locus and crack path; deviations and exclusions; and limits of transfer.

Every numerical input must retain geometry, process, orientation, cure, conditioning and method identity. No radius, critical distance, stress-concentration factor, toughness value, knock-down factor or acceptance load becomes universal when those qualifiers change.

18. Knowledge boundary

The corpus directly supports scaled finite-radius and sharp-notch testing in two DLP resins [1], sharp manufactured cracks and mixed-mode analysis in SLA and DLP specimens [2,4], process- and orientation-sensitive tensile or fracture inputs [3,8], and notched-beam or component fracture evidence for printed dental resins [5–7]. It does not provide a common validated model across those materials and geometries. ER-010 remains authoritative for dimensional and geometric metrology, ER-031 for cure-shrinkage stress, ER-069 for crack growth, ER-070 for general toughness, ER-073 for anisotropy, ER-088 for surface topography, roughness and finishing, ER-171 for design values and allowables, ER-207 for residual stress, ER-231 for statistical scaling and ER-235 for general multiaxial criteria. ER-232 supplies notch-specific evidence and qualification logic only; it does not set a design value or allowable.

19. Limitations

The strongest direct radius-and-scale evidence comes from one research group, two commercial resins and one general loading family [1]. Mixed-mode studies use manufactured sharp cracks rather than finite-radius service notches [2,4]. Dental studies expand the material and conditioning envelope but employ application-specific notched beams or restorations [5–7]. Reference depth was classified as **full-text**, **abstract** or **record**: references [1–8] were checked at full-text depth, and no claim relies only on an abstract or record. No shared printer, cure, orientation, notch preparation, conditioning or validation protocol spans the corpus. The review therefore supplies no universal notch design value or qualification threshold.

20. Conclusions

Notch sensitivity in a vat-printed thermoset is a coupled geometry, material-state and fracture problem. The discontinuity must first be classified as a finite-radius notch, sharp crack, hole or natural defect, then measured in its as-built state. Orientation, wash, post-cure and conditioning must remain attached to strength and fracture inputs. Elastic concentration is informative but not sufficient. Fracture-controlled models require explicit applicability checks, separate calibration and validation, and confirmation of failure locus. Transfer demands prediction at another radius or scale and requalification when the process state changes. The defensible output is a bounded, state-specific design relation, not a universal safe radius or knock-down factor.

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