

Statistical Size Effects and Weibull Analysis in Printed Photopolymers: Defect Populations, Gauge Volume and Design Interpretation

A population-resolved framework for strength distributions, weakest-link transfer and lower-tail decisions

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Abstract

Strength scatter in a printed photopolymer is not a single material constant. It reflects the population sampled: resin and batch, printer and build, orientation and position, wash and post-cure, conditioning, specimen geometry, stressed area or volume, loading and failure mode. A Weibull fit can organize a declared population, but it does not by itself prove a weakest-link mechanism, identify the controlling defect, establish a safe threshold or justify transfer to a larger component.

This review defines a non-compensatory framework for statistical size effects and Weibull analysis in vat-printed thermosets. It separates central strength, distribution shape and lower-tail reliability; requires the estimator, censoring, confidence intervals and model checks to be reported; and distinguishes a change in sampled defect opportunity from geometric, energetic, surface and process-state effects. Effective stressed area or volume is treated as a model quantity tied to the stress field and flaw population, not as nominal specimen volume. Statistical evidence must be paired with fracture-surface or defect observations, while preserving their detection limits. Direct evidence from geometrically scaled DLP specimens, printed dental resins and process-sensitive strength studies supports a state-resolved workflow, but not universal Weibull parameters, specimen counts, allowables or size-scaling laws.

Keywords: printed photopolymer; Weibull analysis; statistical size effect; defect population; gauge volume; weakest link; probability of failure; lower-tail design

1. Significance and scope

A mean strength can remain similar while the lower tail changes, and a narrow observed distribution can arise from a small or selectively prepared sample. Conversely, wider scatter can reflect several mixed process states rather than an intrinsically unreliable material. Design interpretation therefore starts by defining what population was sampled and what decision the statistical model is expected to support.

ER-231 addresses monotonic strength populations in printed photopolymers and the defensibility of transferring a probability-of-failure statement between stressed areas, volumes or geometrically related specimens. It does not treat a fitted distribution as a substitute for process control, fracture mechanics or physical inspection.

1.1 Corpus boundary

ER-039 retains fatigue, creep and time-dependent deformation. ER-069 retains subcritical and fatigue-crack growth. ER-070 retains fracture-toughness testing and damage tolerance. ER-073 retains general mechanical anisotropy and interlayer cohesion. ER-171 retains design values and allowables. ER-184 retains generic diagnostic inference under uncertainty. ER-206 retains micro-CT acquisition, segmentation and defect-detection limits. ER-207 retains residual-stress measurement. ER-209 retains interlaboratory reproducibility. ER-232 retains notch-root geometry and fracture-controlled notch assessment. ER-233 retains impact and high-rate response. ER-235 retains general multiaxial failure criteria. ER-231 uses those domains only where necessary to preserve the identity of a strength population or to test a statistical transfer claim; it supplies statistical evidence but does not establish design values or allowables.

2. Freeze the population before fitting a distribution

Each observation must retain resin identity and batch, printer and relevant settings, build identifier, platform position, orientation, layer thickness, support history, wash, drying, post-cure, storage, conditioning, specimen manufacture, inspection status, geometry, test method, loading direction and failure mode. Replicates taken from one build are not automatically independent production replicates. Several coupons cut from one region can estimate within-build variation while providing little evidence about between-build or between-batch variation.

Manufacturing studies show that build orientation, layer thickness and post-curing time can affect printed photopolymer response [4]. Dental-resin studies likewise demonstrate that resin, build orientation, load direction and water ageing define different mechanical states [5,6]. A fracture-load study of printed restorations also shows that orientation and post-cure must remain attached to component-level results [8]. These sources prohibit indiscriminate pooling. They do not establish that every observed difference is large or that one factor dominates every formulation.

Pooling is defensible only after the equivalence question is stated and tested at the resolution relevant to the decision. Failure mode, fracture origin and distributional shape should be compared as well as means. If populations are intentionally combined for a conservative decision, the mixture and its weighting must be declared rather than hidden inside one fitted modulus.

3. Separate strength level, scatter and reliability

Mean or median strength describes location. Standard deviation or coefficient of variation describes spread in a chosen scale. Weibull characteristic strength identifies a distributional scale at a defined cumulative probability. The Weibull modulus describes shape under that model. A lower-tail quantile or probability of failure at a declared stress is a further derived quantity. None is interchangeable with toughness, service life or defect tolerance.

Endocrown research illustrates why fracture load, Weibull parameters, an experimental fracture-toughness measure and failure morphology provide complementary information [2]. A material can exhibit a relatively narrow fracture-load distribution without having the highest central strength, and the ranking depends on the endpoint. Biofilm-conditioned appliance resins further show that reliability-related parameters may change without an equivalent change in characteristic strength [3]. Design reports should therefore state the decision metric and show the full observations, not replace them with a single fitted number.

4. Preserve raw observations, censoring and failure identity

Record every valid result, pre-test failure, runout, grip failure, invalid fracture origin and excluded observation. Define exclusion rules before examining group rankings. A broken specimen is not automatically a low-strength datum from the target failure mode, while deleting it without a rule can artificially narrow the distribution. Right, left or interval censoring must be represented by an estimator that supports that censoring scheme.

Component studies with complex failure paths provide useful evidence that specimen-level values and failure patterns should be reported together [7]. Whole-restoration fracture loads remain structural responses, not intrinsic coupon strengths. If multiple failure modes are present, a single unconditional distribution may obscure competing risks. The report should either separate physically distinct modes or justify a combined decision model and retain mode-specific evidence.

5. Choose the distribution and parameterization explicitly

The two-parameter Weibull model assumes zero failure probability at zero stress and contains shape and scale parameters. A three-parameter form introduces a fitted location or threshold. That extra parameter can improve apparent fit while becoming unstable, especially in small samples. It must not be interpreted as a physically safe stress unless independent evidence supports that mechanism and the uncertainty excludes operationally important alternatives.

Alternative lognormal, normal or other models may fit some datasets as well as or better than Weibull. Model selection should combine physical rationale, graphical diagnostics, likelihood or another declared criterion, and predictive performance in the decision-relevant tail. The biofilm study explicitly compared two- and three-parameter Weibull descriptions and used lower-tail reliability measures [3]. That supports comparison, not automatic preference for either parameterization.

State the stress convention, probability plotting positions if used, fitting method and software implementation. Do not mix maximum-likelihood and regression estimates without explanation. Parameter symbols must be tied to the exact distribution equation because conventions differ across disciplines and software.

6. Quantify estimation uncertainty

A point estimate conceals sampling uncertainty and parameter correlation. Report confidence intervals for distribution parameters and for the derived probability or quantile used in the decision. The method can be profile likelihood, bootstrap or another validated approach, but its assumptions and treatment of censoring must be stated. When several specimens share a build, resampling and hierarchical models should preserve that dependence.

No universal minimum sample count is defensible. Required information depends on the expected distribution, censoring, clustering, tail probability, tolerated uncertainty and consequence of error. Small groups may support exploratory comparison but generally provide weak lower-tail resolution. The studies in this corpus use diverse group sizes and geometries [1–8]; their sample counts cannot be converted into a general adequacy rule.

7. Evaluate fit without overclaiming the tail

Probability plots should show data, fitted relation and uncertainty rather than only a reported correlation coefficient. Examine residual patterns, influential observations and sensitivity to model choice or exclusion rules. A goodness-of-fit test with low power does not confirm the model. Conversely, a formal rejection can reflect a mixed population that needs physical resolution rather than a more flexible curve.

Tail extrapolation is usually farther from the data than the plotted central region suggests. Report the range directly populated by observations and mark any design quantile that lies beyond it. Compare plausible models at that quantile. If the design decision changes materially with model family, the correct output is model uncertainty or a need for more evidence, not a preferred curve selected after seeing the outcome.

8. Interpret Weibull parameters within the tested state

A higher fitted modulus indicates a steeper distribution under the selected model and dataset. It does not prove higher mean strength, greater fracture toughness, longer life or superior damage tolerance. Characteristic strength and modulus should be reported with their joint uncertainty and only for the frozen population.

Orientation and loading studies show that changes in build and load direction can change flexural response [6]. Water ageing, resin class and production route can also change the tested state [5]. Post-cure and orientation influence component fracture loads [8]. These are reasons to requalify a population, not correction factors that can be applied generically.

9. Distinguish statistical size effects from other size effects

A statistical size effect arises when a larger effectively stressed region samples more opportunities for a critical flaw under a weakest-link model. Geometric scaling can also alter stress gradients, constraint, heat history, surface-to-volume ratio, support strategy, cure uniformity and dimensional fidelity. Notches introduce energetic and gradient effects addressed in ER-232. These mechanisms can coexist but must not be collapsed into one volume exponent.

The direct DLP study tested geometrically related notched specimens at several scales and found size-dependent nominal response in two resins [1]. It provides direct evidence that scale matters and that notch geometry interacts with it. The small replicate sets and limited material range do not validate a universal Weibull scaling law. A fixed-geometry Weibull fit, such as those in dental-component studies [2,3], does not independently demonstrate geometric size transfer.

10. Define effective stressed area or volume

Nominal gauge volume is adequate only when the assumed flaw population is volumetric and the stress is sufficiently uniform. For nonuniform stress, an effective measure weights local volume or area by the failure-driving stress relative to a declared reference. Surface-controlled flaws require an area formulation; edge-controlled failures may require a distinct line or local treatment. The integration domain, stress component and exponent must be stated.

Weakest-link scaling assumes an applicable flaw population, local failure criterion and independence structure. Layer-correlated defects, cure gradients or build-wide process excursions can violate simple independence. A stress field from an unvalidated model cannot rescue a statistical fit. Report mesh, geometry, boundary conditions and convergence where a numerical field is used, and propagate uncertainty that materially affects the effective measure.

11. Validate transfer between sizes

Fit at one size and predict at another before treating the model as transferable. Validation should include at least one additional stressed area or volume not used to tune the transfer and should compare the entire observed distribution or decision-relevant quantiles, not only the mean. Geometric similarity, surface finish, print orientation and process state must be preserved or their changes separately studied.

If the scaled prediction fails, investigate whether the flaw population, stress field, surface-to-volume contribution, failure mode or manufacturing state changed. Re-fitting each size independently may describe the data but does not validate transfer. The direct size-and-notch study [1] is valuable precisely because it exposes scale and geometry together; it does not license extrapolation beyond its resins, print conditions and measured range.

12. Connect statistics to defects and fracture surfaces

Distribution fitting identifies patterns, not causes. Fractography should locate origins and classify whether failure initiated at a surface, edge, layer boundary, pore, inclusion, machining feature or another discontinuity. Defect metrology may estimate size and location distributions, but nondetection is bounded by resolution, contrast, segmentation and sampled volume. Those acquisition questions remain under ER-206.

Pair unusually low and high observations with fracture-surface evidence where practical. Look for changes in origin class across sizes or process states. A multimodal or curved probability plot can motivate physical examination, but scatter alone cannot establish a defect family. Similarly, a detected pore near a fracture surface does not prove it initiated failure without appropriate origin evidence.

13. Treat process drift and environment as population changes

Build drift, resin age, temperature, wash efficiency, post-cure dose and conditioning can shift both central strength and distribution shape. Biofilm exposure broadened or altered reliability behavior in printed appliance resins under its particular protocol [3]. Water ageing and orientation were explicit variables in provisional-restoration resins [5]. These studies support state-specific inference, not universal environmental penalties.

Trend data should retain time order and build hierarchy. A single pooled historical distribution can mask drift. Qualification should define when new data update an established population and when a process or material change creates a new population requiring re-baselining.

14. Build a non-compensatory qualification matrix

Gate	Required evidence	Unsupported shortcut prevented
Population identity	Resin, build, orientation, cure, conditioning, geometry and failure mode	Treating all printed specimens as exchangeable
Data integrity	Raw observations, censoring, exclusions and build hierarchy	Narrowing scatter by selective deletion
Model adequacy	Parameterization, estimator, diagnostics and alternatives	Assuming Weibull because it is conventional
Uncertainty	Parameter and decision-metric confidence intervals	Reporting a precise-looking tail from sparse data
Size transfer	Stress field, effective area or volume, weakest-link assumptions and holdout size	Scaling by nominal volume alone
Physical support	Fracture origins and defect evidence with detection limits	Assigning causation from statistical scatter

The gates do not compensate for one another. Good fit cannot repair a mixed population; a large sample cannot validate the wrong stress field; and detailed imaging cannot justify an untested size extrapolation.

15. Minimum reporting set

Report resin and batch; printer, settings and build identifier; location and orientation; layer and support state; wash, drying, post-cure, storage and conditioning; specimen design and as-built dimensions; loading and stress definition; failure mode and origin; number of builds and specimens per build; all observations and censoring; exclusion rules; selected and alternative distributions; equations and parameter conventions; estimator and software; goodness-of-fit and model-selection evidence; confidence intervals; decision probability or quantile; stress-field method; effective stressed area or volume and integration domain; weakest-link assumptions; validation sizes; fractography or defect observations and detection limits; and limits of transfer.

Every reported parameter must remain attached to its population and model. No Weibull modulus, characteristic strength, threshold, lower-tail allowable, minimum sample count or size factor becomes transferable when the resin, process, geometry, environment or failure mechanism changes.

16. Knowledge boundary

The corpus directly supports one controlled size-and-notch comparison in DLP resins [1], two implementations of Weibull analysis in printed-resin components or specimens [2,3], and several demonstrations that manufacturing state, orientation, ageing and geometry change strength populations [4–8]. It does not provide a multi-laboratory validation of one distribution family or a broad set of matched sizes across resin families. ER-070 remains the authority for fracture toughness, ER-073 for general anisotropy, ER-171 for design values and allowables, ER-206 for micro-CT, ER-209 for interlaboratory reproducibility and ER-232 for notch-root design. ER-231 supplies statistical evidence and a transfer framework only; it does not set a design value or allowable.

17. Limitations

The strongest scale evidence is concentrated in two commercial resins and small replicate sets [1]. Much of the remaining evidence comes from dental coupons or restorations with fixed geometry and application-specific conditioning [2,3,5–8]. Several studies were designed to compare means or process variables rather than to resolve extreme lower tails. Reference depth was classified as **full-text**, **abstract** or **record**: references [1–4] and [6–8] were checked at full-text depth, while [5] was checked at abstract depth; no claim relies only on a record. No common printer, resin, cure, specimen geometry, stress field or failure mode spans the corpus. Consequently, the review establishes neither a universal Weibull law nor a universal numerical design value.

18. Conclusions

Statistical size effects in printed photopolymers can be interpreted only after the tested population and failure mode are frozen. Strength level, scatter, Weibull shape, characteristic strength and lower-tail reliability answer different questions. Distribution choice, estimation, censoring, confidence intervals and model checks must be explicit. Weakest-link transfer requires an applicable flaw population, a validated stress field and an effective stressed area or volume matched to the origin class. Geometric, energetic, surface and process-state effects must remain separate from statistical defect opportunity. Validation at another size and physical evidence from fracture origins are required before a fitted relation becomes a design transfer.

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