

Vibration and Random-Fatigue Qualification of Printed Photopolymer Components: Spectral Loading, Fixtures and Damage Accumulation

A state-resolved framework for resonance, power spectral density and prospective validation

Juan Seguro

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

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Abstract

Random vibration cannot be qualified by quoting an overall acceleration alone. A power spectral density distributes energy across frequency, and the response depends on resonances, damping, boundary conditions, fixture dynamics, preload, temperature and the evolving stiffness of the printed material. Printed photopolymers add orientation, surface state, cure history, ageing and viscoelastic frequency dependence. Consequently, two tests with the same root-mean-square acceleration can produce different stresses and damage.

This review defines a non-compensatory framework for vibration and random-fatigue qualification of printed photopolymer components. It separates input control from local response, requires low-level modal surveys before and after exposure, treats fixture and control strategy as parts of the experiment, and distinguishes resonance shift, crack initiation, functional interruption and final fracture. Spectral fatigue estimates may support test design, but they require validated stress transfer, an applicable fatigue model and a declared treatment of mean stress, bandwidth and non-Gaussian response. Miner summation is an assumption, not a material law. Direct fatigue evidence for printed photopolymers exists for selected material-jetting systems, while comprehensive random-vibration datasets remain limited. The defensible result is therefore a configuration-specific qualification, not a universal PSD or fatigue-life transfer rule.

Keywords: printed photopolymer; random vibration; power spectral density; resonance; fatigue; fixture; damping; spectral moments; qualification

1. Significance and scope

Transport, machinery, vehicles and portable systems expose components to broadband vibration, sine tones, shocks and combined environments. Local response can greatly exceed the base input near resonance. Printed polymer parts may also change stiffness and damping during the exposure, shifting the response while the test is running.

ER-238 addresses sine and random vibration used to qualify printed photopolymer components and assemblies.

1.1 Corpus boundary

ER-010 retains dimensional and geometric metrology. ER-039 retains general fatigue and creep. ER-069 retains general crack-growth kinetics. ER-070 retains fracture toughness. ER-073 retains anisotropy. ER-088 retains surface topography and finishing, including the surface state used by fatigue evidence. ER-171 retains design values and allowables; ER-238 provides no transferable allowable. ER-184 retains uncertainty. ER-207 retains residual stress. ER-231 retains statistical size effects. ER-232 retains notch sensitivity. ER-233 retains impact and high-rate response. ER-235 retains multiaxial failure. ER-236 retains environmental stress cracking. ER-237 retains thermal cycling. ER-238 owns vibration input, fixture dynamics, local response and damage attribution for the declared installed configuration.

2. Define the qualification claim

Declare whether the claim concerns survival, crack-free operation, retained stiffness, dimensional stability, optical alignment, electrical continuity, noise, seal integrity or residual strength. Define the installation, mass attachments, cables, fasteners and environmental state. A component qualified in one mounting configuration is not automatically qualified in another.

Specify exposure axes, duration, spectral shape, sine tones, notches, tolerances and abort limits. Overall root-mean-square acceleration is a useful summary but does not identify where the energy lies.

3. Freeze the printed state and conditioning

Record resin and lot, printer, wavelength, exposure, build location and orientation, layer thickness, support history, wash, drying, post-cure, storage, age, humidity and temperature. Photopolymer strength and stiffness depend on orientation and cure [2,3]. Fatigue data for PolyJet parts also show effects of material and surface condition [1]. These findings require state-bound qualification.

Viscoelastic modulus and damping depend on frequency and temperature. Characterise the relevant range by dynamic mechanical analysis or state why a simplified model is adequate. Do not use a room-temperature static modulus as the only basis for a broadband prediction.

4. Characterise the service environment

Acquire field acceleration with calibrated sensors and adequate sampling, anti-alias filtering, record length and operating-state annotation. Remove transients only under declared rules. Preserve time histories when non-stationarity, shocks or non-Gaussian behaviour may matter.

For a stationary process, the one-sided acceleration power spectral density $G_{aa}(f)$ integrates to the acceleration variance, so a_{rms}^2 equals the area under $G_{aa}(f)$ from f_1 to f_2 .

The same a_{rms} can arise from many spectral shapes. Qualification must therefore retain frequency limits, resolution and PSD breakpoints.

5. Perform modal surveys before exposure

Use a low-level sine sweep or random survey to identify resonances, antiresonances and damping without materially consuming life. Measure both base input and component response. Record sensor mass, location, orientation, attachment and cable routing.

Repeat the survey after defined exposure blocks. A resonance shift can indicate stiffness loss, contact change, preload loss or boundary-condition drift. It is an indicator requiring attribution, not automatically a crack measurement.

6. Qualify the fixture and boundary conditions

The fixture must reproduce service constraints while avoiding resonances that corrupt the control band. Measure fixture modes and transmissibility with the test article installed. Include fixture mass, fasteners, tightening sequence, torque, inserts and interface materials in the controlled configuration.

Multiple control accelerometers may be necessary for large or flexible fixtures. State whether control uses average, maximum or limiting logic. Notching that protects the shaker or article changes the test and must be documented with the limiting channels and rationale.

7. Separate input from local response

Base acceleration does not equal component stress. Establish transfer functions from input to local acceleration, strain or displacement under linear conditions. Validate the finite-element model against measured modes and response before using it to infer stress.

Printed geometry, notches, holes, layer interfaces and inserts can localise stress. ER-232 owns notch sensitivity, but ER-238 must preserve the actual local geometry in the vibration model. If response becomes nonlinear, a linear transfer function and Gaussian spectral estimate may no longer apply.

8. Design the random-vibration exposure

Define PSD, bandwidth, duration, axis order, temperature and ramp-up procedure. Use controlled low-level checks before full exposure. Monitor response channels, specimen temperature and functional outputs continuously where possible.

Axis order can matter when damage accumulates or fasteners settle. Random exposure in three sequential axes is not equivalent to simultaneous multi-axis excitation. If service is multi-axis and correlated, justify the chosen simplification or test the coupled condition.

9. Treat spectral fatigue as a model

Spectral methods estimate cycle distributions from stress-response PSDs and their moments. Narrow-band, Dirlik, Tovo-Benasciutti and related formulations make different assumptions about bandwidth and peak statistics [5]. Their agreement with one another does not validate the input stress model or the fatigue curve.

For linear accumulation, a common estimate is

$$D = \sum \text{over } i \text{ of } n_i / N_i$$

where n_i is the applied number of cycles in a range and N_i is the corresponding life. Failure at $D = 1$ is not universal. Sequence, mean stress, environment, ageing and damage interaction can violate the assumption.

10. Establish applicable fatigue data

Use fatigue specimens printed, washed, cured and conditioned in the same state and tested with relevant stress ratio, frequency, temperature and surface condition. Moore and Williams reported fatigue behaviour for PolyJet material-jetted parts and identified surface-finish effects [1]. Such evidence establishes that printed photopolymer fatigue can be process-sensitive; it does not provide a universal curve for vat-printed resins.

State runout definition, censoring treatment, replicate count and statistical model. A median S-N curve is not a lower-bound design allowable. Do not mix crack initiation and complete fracture without explicit conversion.

11. Control self-heating and environmental coupling

Viscoelastic dissipation can heat a polymer near resonance. Measure critical-location temperature during testing. A temperature rise can reduce modulus, shift resonance and amplify or reduce response, creating feedback that a fixed linear model misses.

Humidity, absorbed solvents and thermal state can change damping and fatigue resistance. If service combines vibration with temperature or humidity, sequential testing may not reproduce simultaneous coupling. ER-236 and ER-237 retain the underlying environmental mechanisms; ER-238 must declare whether they are controlled, combined or excluded.

12. Detect and attribute damage

Combine continuous monitoring with scheduled inspections. Useful indicators include transmissibility, resonance frequency, damping, strain amplitude, acoustic emission, crack imaging, electrical continuity and functional output. Set detection thresholds and abort limits before exposure.

After testing, document failure location and morphology. Distinguish resin cracking, layer-associated fracture, insert pull-out, adhesive failure, fastener loosening, cable failure and fixture damage. A system interruption caused by a connector is not a material fatigue point for the resin.

13. Validate with holdout profiles

Calibrate models on one subset of specimens or spectra and reserve a different spectral shape, duration or mounting configuration for prospective validation. Compare resonance, local response, damage indicator and residual performance, not only final survival.

If an accelerated PSD is used, demonstrate that it preserves the controlling modes and failure mechanism. Increasing broadband level can activate fixture nonlinearities, contact slip or self-heating absent in service.

14. Build a non-compensatory qualification matrix

Gate	Required evidence	Unsupported shortcut prevented
Printed state	Resin, orientation, cure, age and environment	Pooling unlike material states
Input	PSD or time history, axes, duration and tolerances	Using overall rms alone
Dynamics	Modal survey, damping and measured response	Treating base acceleration as stress
Fixture	Modes, control logic, preload and interfaces	Calling fixture behaviour article response
Fatigue model	Applicable data, bandwidth and accumulation assumptions	Universal Miner or spectral prediction
Validation	Holdout profile, damage attribution and residual function	Calling calibration qualification

The gates are independent. A well-controlled PSD cannot compensate for an unrepresentative fixture, and a correct modal model cannot compensate for an inapplicable fatigue curve.

15. Minimum reporting set

Report printed state and conditioning; article geometry and mass; attachments, fasteners, cables and preload; service-data acquisition and processing; PSD or time history, resolution, axes, duration and tolerances; fixture modes; control and notching logic; sensors and calibration; modal results; local response and temperature; fatigue basis; spectral assumptions; inspections and aborts; damage morphology; residual function; uncertainty; acceptance criteria; and transfer limits.

16. Knowledge boundary

Direct fatigue evidence exists for selected material-jetted photopolymers [1], and broader printed-photopolymer studies establish state, orientation and rate sensitivity [2,3]. Reference [4] provides rate context without an orientation variable. Standards provide general random-vibration procedures for transport packages [6,7]. Direct random-vibration qualification datasets for neat vat-printed photopolymers remain sparse. The evidence supports a controlled framework, not a universal PSD or life model.

17. Limitations

Published fatigue studies differ in technology, resin, surface state, loading mode and endpoint. General vibration standards do not substitute for material-specific fatigue evidence. References [2], [3] and [5] were read at full-text depth; references [1] and [4] were used at publisher-abstract depth; references [6] and [7] were verified at bibliographic-record depth. This review does not supply a universal S-N curve, damping ratio, Miner threshold, PSD, test duration or acceleration factor.

18. Conclusions

Random-vibration qualification must connect measured input to configuration-specific local response and a state-matched damage model. Modal surveys, fixture validation, response monitoring, self-heating control and failure attribution are mandatory. Spectral fatigue and linear accumulation apply only within demonstrated assumptions. The defensible outcome is bounded to a defined printed state, fixture and service spectrum.

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