

Dynamic Mechanical Damping and Viscoelastic Energy Dissipation in Vat-Printed Photopolymers: Frequency, Temperature, Cure State, Architecture and Qualification

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Statement of Significance

A vat-printed part that feels soft, stretches far, survives cyclic loading or absorbs impact energy is not automatically a good vibration damper. Dynamic damping is a frequency-, temperature-, amplitude- and state-dependent manifestation of viscoelastic energy loss. Its most direct material descriptors arise from dynamic mechanical analysis (DMA): storage modulus, loss modulus, phase angle and loss factor $\tan \delta$. Vat photopolymerisation adds further dependencies because exposure, conversion, post-cure, print orientation, filler alignment, crystallinity and architecture can all change the dynamic response. This review defines a qualification framework that keeps oscillatory damping separate from creep, fatigue, fracture toughness, impact absorption and thermal-transition reporting.

Keywords: vat photopolymerisation; dynamic mechanical analysis; DMA; viscoelasticity; damping; vibration; storage modulus; loss modulus; $\tan \delta$; loss factor; energy dissipation; SLA; DLP; LCD

Abstract

Vat-photopolymerised thermosets are frequently described using static tensile modulus, Shore hardness, elongation or impact strength, yet vibration control and dynamic energy dissipation require a different measurement architecture. In linear viscoelastic response, an oscillatory strain produces a phase-shifted stress that can be decomposed into storage and loss components; the ratio of loss to storage response is commonly expressed as $\tan \delta$. Primary DLP research demonstrates that the dynamic mechanical response of printed photopolymers depends on temperature, loading frequency and degree of cure, while recent VPP-specific methodological work shows that specimen preparation, linear-viscoelastic-region determination, residual stress and print protocol can materially affect intercomparison. Composite studies further show effects of filler loading, alignment, post-print thermal treatment and semicrystalline morphology. This Engineering Review develops a state-aware qualification architecture for dynamic damping in VPP. It separates DMA material loss from structural damping, cyclic hysteresis and high-strain-rate energy absorption; defines frequency, temperature, amplitude, deformation mode, cure state, orientation and architecture as mandatory reporting variables; and positions time-temperature superposition as a conditional extrapolation tool rather than a universal prediction method. ISO 6721-1:2019, ISO 6721-4:2019, ISO 6721-12:2022 and ASTM D4065-20 are used as current method anchors. 3Dresyns elastomeric and damping-oriented products are included only as manufacturer implementation examples; no $\tan \delta$, damping coefficient, resonance attenuation or service-life claim is inferred from commercial positioning.

1. Scope and boundaries

ER-90 addresses the dynamic viscoelastic response of cured VPP materials and printed structures under oscillatory or vibration-relevant loading. The principal measurands are storage modulus E' or G' , loss modulus E'' or G'' , phase angle δ and loss factor $\tan \delta$, together with frequency- and temperature-dependent master curves where methodologically justified. Structural frequency response and resonance attenuation are included only as downstream qualification endpoints that require geometry-specific testing.

The scope is deliberately separated from neighbouring publications. ER-20 addresses thermal qualification and the interpretation of T_g /HDT/service temperature; ER-39 addresses fatigue, creep and time-dependent deformation; ER-50 addresses true foam formation and foam mechanics; ER-67 addresses hierarchical/double-network hydrogel toughening and sacrificial-bond energy dissipation; ER-70 addresses fracture toughness and damage tolerance; ER-24 treats device-level soft-robotic actuation. ER-90 does not reopen those questions. It asks how dynamic mechanical loss is measured, how VPP process state changes it, and how material-level DMA can or cannot be transferred to a vibration-damping part.

2. Dynamic response requires four separate quantities

For a sinusoidal deformation in the linear viscoelastic region, the material response contains an in-phase component associated with recoverable elastic storage and an out-of-phase component associated with dissipative processes. The complex modulus combines both components. The loss factor $\tan \delta$ is the ratio of loss to storage modulus for the stated deformation mode. None of these quantities is interchangeable with static Young's modulus or Shore hardness.

Table 1. Dynamic-mechanical quantities and evidence boundaries

Quantity	Physical meaning	What it does not establish
Storage modulus E' / G'	In-phase stiffness under the stated oscillatory mode, frequency, temperature and amplitude.	Static tensile modulus at arbitrary strain or a universal structural stiffness.
Loss modulus E'' / G''	Out-of-phase component associated with mechanical energy loss per oscillatory cycle.	A complete impact-energy absorption or fatigue-life metric.
Phase angle δ	Lag between imposed deformation and measured stress response.	A geometry-independent resonance attenuation value.
Loss factor $\tan \delta$	Ratio of loss to storage response under the same test state.	A universal “damping percentage” transferable across temperature/frequency/mode.
Master curve	Shifted frequency-dependent modulus/loss representation at a chosen reference temperature.	Validity when material is thermorheologically complex, ageing, reacting or outside the tested regime.
Structural transmissibility / modal damping	System-level response of a particular geometry, mass, boundary condition and excitation.	An intrinsic resin property that can be read from a TDS alone.

3. Damping is not the same as toughness, hysteresis or impact absorption

Several commonly reported mechanical outputs describe energy but answer different questions. The area of a large-strain loading-unloading loop measures hysteretic work for that cycle and amplitude. Fracture energy measures resistance to crack extension. Izod/Charpy and high-rate compression quantify impact or rapid-deformation response. Fatigue describes damage accumulation over repeated loading. DMA, by contrast, normally probes small oscillations within a defined linear viscoelastic region. A material can show a high $\tan \delta$ near a transition yet perform poorly in impact, or absorb substantial impact energy while exhibiting modest small-amplitude damping at the service frequency.

This distinction is especially important for architected VPP parts. A lattice may dissipate energy by local buckling, contact or geometric friction even when its base resin has modest material loss. Conversely, a high-loss elastomer can be arranged in a stiff geometry that transmits vibration efficiently. Material damping and structural damping must therefore be reported as different evidence layers.

4. Frequency, temperature and amplitude define the result

Rehbein and co-workers demonstrated directly in DLP photopolymers that viscoelastic properties vary with frequency, temperature and degree of cure. Their DMA treatment decomposed the complex shear modulus into storage and loss terms and used the phase shift to calculate tan delta. The same study used time-temperature superposition to extend the measured frequency domain, while showing strong changes in modulus with cure state. This establishes a central VPP rule: a single room-temperature tan delta without frequency, amplitude and cure state is not a transferable damping specification [1].

ISO 6721-1:2019 [S1] likewise emphasizes that deformation mode matters and that results from tensile and flexural configurations are not automatically comparable. ISO 6721-4:2019 [S2] covers non-resonant tensile vibration, while ISO 6721-12:2022 [S4] addresses compressive vibration for semi-rigid polymers. ASTM D4065-20 [S5] provides general practice for gathering and reporting dynamic mechanical data over temperature and frequency. The relevant method should be selected by modulus range, geometry and intended deformation mode, rather than by instrument availability alone.

5. The linear viscoelastic region is a qualification gate

DMA results assume that the oscillatory response is measured at sufficiently small deformation that the moduli are not themselves functions of amplitude. Highly compliant VPP elastomers, filled systems, cellular materials and soft hydrogels can leave this region at relatively small strains. A strain- or stress-amplitude sweep should therefore precede frequency/temperature sweeps when the linear range is not already established for the exact material state.

Schittecatte and co-workers proposed a VPP-specific DMA protocol in 2025 that explicitly includes determination of the linear viscoelastic region and a stress-relief annealing step. Their work showed that print protocol and residual stress can influence dispersion in storage-modulus measurements and that controlled preparation can bring repeatability/reproducibility closer to a molded reference material [2]. ER-90 adopts the methodological lesson rather than treating any one annealing schedule as universal.

6. Cure state and post-cure move the damping window

Photopolymer network state is not fixed at the end of layer exposure. Additional light or thermal post-cure can increase conversion, change network heterogeneity, relax residual stress, alter Tg and change both storage and loss response. Rehbein et al. showed degree-of-cure-dependent viscoelasticity in a commercial DLP resin [1]. In stereolithographically printed graphene-polymer nanocomposites, Lai et al. found that post-print thermal treatment increased dynamic modulus and dynamic strength alongside evidence of increased cure [4].

For damping qualification, “post-cured” is therefore insufficient metadata. The report should identify wavelength, irradiance/dose when available, temperature, time, delay between print and post-cure, and any later thermal conditioning. If damping is intended near Tg, small changes in cure state can move the transition relative to the service temperature and strongly alter tan delta.

7. Filler, morphology and orientation can change dynamic loss

Filled VPP systems introduce additional mechanisms: interfacial load transfer, particle/fibre friction, filler alignment, altered cure gradients and changed thermal transitions. Moharana, Singh and Dixit used DMA and

time-temperature superposition on DLP-fabricated short-glass-fibre photopolymer composites and reported filler-fraction-dependent viscoelastic response, with an intermediate filler fraction producing the highest reported Tg and storage modulus in their system [3]. These values are formulation-specific and should not be used as universal optima.

Lai and co-workers investigated stereolithographically printed graphene-PMMA nanocomposites and linked anisotropic dynamic response to graphene alignment along the printing axis; post-print baking further changed the response [4]. Pitawala and co-workers showed in 2026 that VPP process variables can change semicrystalline morphology, with DMA used to connect morphology to bulk mechanical response [5]. These studies support orientation, filler state and morphology as reporting variables, not a general claim that adding filler always improves damping.

Table 2. Variables that can move a measured damping response

Variable	Mechanism / confounder	Minimum reporting
Frequency	Changes the timescale available for molecular relaxation.	Frequency or angular frequency; sweep direction and spacing.
Temperature	Moves relaxation processes relative to the test timescale.	Test temperature, ramp/step protocol, equilibration, reference temperature.
Amplitude / strain	Can leave the linear viscoelastic region.	Strain/stress amplitude and prior LVER determination.
Deformation mode	Tension, bending, shear and compression weight material regions differently.	Fixture, specimen geometry, mode and preload.
Degree of cure	Changes network mobility, equilibrium modulus and transition behaviour.	Print exposure + post-cure + independent cure-state evidence where available.
Build orientation	Layer interfaces and filler orientation can produce anisotropic response.	Specimen orientation relative to layer/build axes.
Filler / morphology	Interface, dispersion, crystallinity or fibre/platelet orientation alters dynamics.	Identity, fraction, dispersion/orientation evidence and morphology state.
Conditioning	Water/solvent uptake and physical ageing alter mobility.	Medium, RH, temperature, time and equilibrium criterion.

8. Time-temperature superposition is conditional, not automatic

Time-temperature superposition can extend a limited experimental frequency window by horizontally shifting isothermal curves to a selected reference temperature. Rehbein et al. used this approach for degree-of-cure-dependent DLP photopolymer data, and Moharana et al. generated master-curve representations for VPP glass-fibre composites [1,3]. The method is powerful when the material behaves approximately thermorheologically simply across the relevant range.

However, VPP materials can violate that assumption through multiple relaxations, evolving conversion, phase change, moisture loss, crystallization, filler-interface transitions or ageing during the temperature sweep. Shift-factor quality and overlap of adjacent curves should be shown. Extrapolated decades of frequency should be labeled as model-assisted predictions, not as directly measured damping performance.

9. Material DMA does not directly predict a vibration-isolation component

A vibration isolator or damper is a system, not only a resin. Its transmissibility and modal damping depend on mass, geometry, preload, boundary conditions, resonance frequencies and the distribution of strain energy through the part. DMA can supply material functions needed for constitutive models, but geometry-specific dynamic testing remains necessary for final validation. A soft part can transmit strongly when operated above

its isolation region; a stiff part with local high-loss zones may attenuate selected modes more effectively than a homogeneous soft block.

For architected VPP structures, base-resin DMA should therefore be paired with structural measurements such as frequency-response functions, resonance decay, transmissibility or application-specific vibration tests. If a lattice or foam contributes geometric damping, the tested relative density, topology, dimensions and orientation are part of the result. ER-50 already covers the distinct mechanics of true foams; ER-90 only uses architected structures to define the transfer boundary from material loss to system damping.

10. 3Dresyns implementation boundary

The controlled 3Dresyns product corpus contains a Self-Heal Elastomer booster for hydrophobic elastomeric SLA/DLP/LCD systems. Its TDS positions the material for vibration and impact dampers and describes “sustained damping and energy absorption” while also emphasizing self-healing, interlayer fusion and chemical resistance. The Engineering & Functional portfolio and 4D technical content also identify vibration-damping mounts as application examples for flexible/TPU-like grades. These statements establish that damping is a real industrial design requirement within the 3Dresyns portfolio; they do not establish a measured tan delta, loss modulus, transmissibility, resonance attenuation or service-life performance [M1-M3].

A defensible qualification route for any 3Dresyns damping-oriented formulation would therefore begin with the exact printed/post-cured state, determine the linear viscoelastic region, measure $E'/E''/\tan \delta$ over application-relevant temperature and frequency, and then test the final geometry dynamically. Manufacturer statements should be replaced by quantified damping claims only when the exact specimen, method and conditions are documented.

11. Minimum qualification architecture

- Define whether the requirement is material damping, vibration isolation, resonance suppression, impact absorption or cyclic hysteresis before selecting the test.
- Record resin identity/batch/state, printer, wavelength, irradiance/exposure strategy, layer thickness, build orientation, washing, drying and post-cure history.
- Determine or verify the linear viscoelastic region for the exact specimen state before frequency/temperature sweeps.
- Report deformation mode, fixture, dimensions, preload, oscillation amplitude, frequency range, temperature protocol and equilibration time.
- Report storage modulus, loss modulus and tan delta together where the instrument/method supports them; avoid quoting tan delta without E' and E'' .
- If T_g is derived from DMA, state whether it is taken from tan-delta peak, loss-modulus peak or another defined criterion; do not treat different T_g definitions as interchangeable. ISO 6721-11:2019 addresses determination of the glass transition temperature by dynamic mechanical methods [S3].
- For filled/composite systems, document filler fraction, dispersion, orientation and relevant morphology.
- For time-temperature superposition, show shift factors, reference temperature, curve overlap and the measured versus extrapolated frequency ranges.
- Condition specimens for humidity, immersion or service-fluid exposure when damping will be used in those environments.
- Validate the final damping component with geometry-specific dynamic testing under realistic preload, boundary conditions and excitation.

12. Failure-mode and interpretation matrix

Table 3. Common interpretation failures in VPP damping studies

Observation / claim	Possible misinterpretation	Required discriminator
High elongation or soft Shore hardness	Assumed to mean high damping.	DMA E' , E'' , $\tan \delta$ over service frequency/temperature.
Large tensile hysteresis loop	Assumed transferable to small-amplitude vibration.	Amplitude sweep + small-signal DMA + structural vibration test.
High $\tan \delta$ near T_g	Quoted as broad service damping.	Temperature/frequency map; verify actual service state and stiffness.
Higher filler content raises E'	Assumed to raise damping.	Measure E'' and $\tan \delta$; inspect dispersion/orientation.
Post-cure raises modulus	Assumed dynamically beneficial.	Repeat full DMA; transition may shift and loss may rise or fall.
Good DMA loss factor	Assumed to guarantee isolation.	Geometry/preload-specific transmissibility or modal test.
Master curve predicts long times/high frequencies	Treated as direct measurement.	State measured window, shift model and thermorheological validity.
Architected part absorbs energy	Attributed entirely to resin damping.	Compare solid-material DMA with topology-matched structural tests.

13. Research priorities

- round-robin DMA protocols for vat-printed photopolymers across SLA, DLP and LCD platforms using common specimen and post-cure states;
- frequency-temperature maps for elastomeric VPP resins extending beyond single 1 Hz T_g scans;
- paired measurements of cure conversion and dynamic mechanical loss to separate network-state effects from printer effects;
- orientation-resolved DMA for anisotropic layers and filled systems;
- ageing-conditioned damping after humidity, water, fuels, oils, solvents and thermal cycling where relevant;
- correlation studies between coupon DMA and component-level transmissibility/modal damping for VPP isolators;
- architected-material studies that separate base-resin viscoelastic loss from contact, buckling and geometric dissipation;
- minimum reporting conventions for $\tan \delta$ claims in commercial VPP materials.

14. Conclusions

Dynamic damping in vat-printed photopolymers is a state-dependent viscoelastic property, not a synonym for softness, toughness, fatigue resistance or impact absorption. The minimum material-level evidence consists of storage and loss response under a declared deformation mode, frequency, temperature and amplitude, with the linear viscoelastic region and cure state controlled. $\tan \delta$ is meaningful only within that test context.

VPP processing makes those controls unusually important. Exposure and post-cure change network state; build orientation and fillers can introduce anisotropy; temperature and conditioning move molecular relaxation; morphology and architecture can add further dissipation mechanisms. Time-temperature superposition can extend the usable frequency window but requires demonstrated curve superposition and transparent separation of measured from extrapolated domains.

For application release, DMA should be treated as the material layer of evidence. The final vibration-damping component still requires geometry-, preload- and boundary-condition-specific dynamic validation. The existing 3Dresyns damping-oriented product positioning therefore defines an engineering target, not a quantified damping result, until the relevant dynamic tests are performed.

Limitations

The VPP literature contains substantially more DMA data than dedicated component-level vibration-isolation studies. Many papers use DMA primarily to determine Tg or storage modulus rather than to qualify damping over a full service-frequency window. Numerical tan-delta peaks, modulus values and master curves are formulation-, fixture-, orientation-, cure- and temperature-specific and are not pooled here. This review does not prescribe universal damping targets, resonance limits or acceptance criteria.

Author contributions

Juan Seguro: conceptualisation, industrial problem definition, literature synthesis, dynamic-mechanical qualification framework, writing and critical review.

Competing interests

The author is founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L. Manufacturer documentation is included only as implementation context and is separated from independent scientific evidence.

Data availability

No new experimental dataset was generated for this review. Scientific statements derive from the cited literature and standards; manufacturer examples derive from controlled 3Dresyns documentation.

Company information

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