

Creep Rupture and Long-Term Load Retention in Printed Photopolymers: Physical Ageing, Environment and Extrapolation Limits

A state-resolved framework for sustained-load qualification

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ER-240 · Engineering Review · Version 0.2 · 21 September 2026

Abstract

A printed photopolymer that survives a short tensile test can still lose preload, accumulate strain, buckle or rupture under sustained service load. Creep, stress relaxation and creep rupture are distinct endpoints. Their rates depend on temperature, humidity, absorbed chemicals, cure, orientation, specimen age, stress level and geometry. Physical ageing can reduce short-time compliance while embrittlement or environmental damage reduces rupture resistance. Time-temperature superposition and accelerated ageing are powerful only when the same mechanism and material state persist across the shift.

This review defines a non-compensatory framework for long-term load retention. It separates constant-stress, constant-load, constant-strain and structural tests; requires true geometry and evolving stress to be tracked; distinguishes recoverable viscoelastic strain, permanent strain, damage and final rupture; and treats censored runouts explicitly. Extrapolation must declare the constitutive form, shift factor, reference state and validation horizon. A short master curve, one apparent power law or one heat-deflection temperature cannot release a long-life claim. Direct creep evidence for printed photopolymers remains limited and formulation-specific. The defensible result is a bounded real-time or validated extrapolated envelope for a defined printed state, environment and failure criterion.

Keywords: printed photopolymer; creep; creep rupture; stress relaxation; physical ageing; time-temperature superposition; load retention; extrapolation

1. Significance and scope

Sustained loads occur in clamps, seals, fixtures, springs, supports and pressurised components. The engineering question is not only how much strain develops, but whether function, geometry and integrity remain within limits for the declared time.

ER-240 addresses creep rupture and retained function under sustained load. ER-010 retains dimensional metrology; ER-039 retains general creep and time-dependent deformation; ER-070 retains fracture toughness; ER-072 retains environmental ageing; ER-170 retains accelerated-ageing factors and life-claim extrapolation; ER-171 retains design values and allowables; and ER-184 retains uncertainty. ER-240 owns sustained-load failure under declared real-time conditions. It may define qualification conditions for admitting extrapolated evidence, but it does not own accelerated-ageing factors or life-claim extrapolation.

1.1 Corpus boundary

The distinctive scope of ER-240 is creep rupture and retained function under sustained load; ER-039 retains the general creep and time-dependent-deformation framework. ER-207 (residual stress), ER-231 (statistical size effects), ER-234 (buckling and crushing) and ER-236 (environmental stress cracking) are planned forward references, not published incumbents. They do not supply authority for this review. Structural instability, coupled environmental cracking and population effects remain boundary conditions rather than transferred ownership.

2. Define the load mode and endpoint

Constant load, constant engineering stress, constant true stress and constant strain are not equivalent. Geometry changes can raise true stress during tensile creep, while relaxation reduces force under fixed displacement. Structural tests add contact, leverage and instability.

Define endpoints such as specified strain, loss of preload, stiffness reduction, dimensional drift, first crack or rupture. State whether runout means survival without detected damage or simply no rupture before test termination.

3. Freeze the printed state and ageing clock

Record resin, lot, printer, wavelength, exposure, build location and orientation, layer thickness, supports, wash, drying, post-cure, storage, conditioning and age at loading. Post-cure can change modulus and creep response strongly in some commercial photopolymers [1]. Orientation and processing state also influence printed mechanical response [3,4].

Define time zero. Polymer ageing can continue after print, wash, post-cure or conditioning. Mixing specimens of different ages can mimic stress dependence or hide it.

4. Characterise the service environment

Control temperature, humidity, immersion medium, oxygen and light where relevant. Measure specimen temperature, not only chamber setpoint. Absorbed liquids can plasticise, swell or damage the network and must be treated as a coupled state, not a correction factor.

ER-041 retains chemical resistance and uptake; ER-072 retains environmental ageing. Planned ER-236 will address coupled stress-environment cracking but is not a current incumbent. ER-240 uses environmental variables only to qualify sustained-load response.

5. Use real-time tests as the anchor

Include real-time tests over the longest practical fraction of the service horizon. Accelerated conditions must overlap real-time data so that shift and constitutive assumptions can be tested. A master curve without overlap is an extrapolation hypothesis.

Use multiple stress levels and replicates. Creep compliance and rupture life may show different stress dependence, so deformation data alone cannot release rupture life.

6. Measure evolving geometry and true stress

Track cross-section and gauge length when changes are material. Under constant force,

$$\sigma_{\text{true}}(t) = F/A(t)$$

so necking, swelling or thinning changes the actual driving stress. Report whether feedback control maintains force, engineering stress, true stress or displacement.

For bending, contact and structural tests, validate the stress reconstruction and detect instability. A buckling event belongs to the structure, not automatically to material creep rupture.

7. Separate deformation components

Use loading, hold, unload and recovery segments where compatible with the claim. Separate instantaneous strain, delayed recoverable strain, permanent strain and damage. Recovery duration and environment must be declared.

Nano-reinforced bio-based photopolymer research demonstrates that creep response can change with formulation [2]. It does not authorise transfer of a reinforcement factor to another resin.

8. Distinguish creep rupture from environmental cracking

Inspect for crazes, cracks, interface failure and necking. If a liquid or humidity participates, include unloaded exposed and loaded unexposed controls. Mass recovery or dimensional recovery does not prove restoration of rupture resistance.

Planned ER-236 is assigned the stress-sorption-damage mechanism but is not a current incumbent. ER-240 retains only the sustained-load time-to-endpoint architecture.

9. Treat physical ageing explicitly

Physical ageing changes relaxation times below the glass transition and can shift short-time compliance. Chemical post-cure, oxidation, hydrolysis and solvent loss are different processes. Use thermal, spectroscopic or mechanical evidence to distinguish them where the interpretation matters.

High-temperature storage studies show continuing chemical and mechanical evolution in specific printed resins [5]. Such evolution invalidates a stationary constitutive model unless incorporated and validated.

10. Apply time-temperature superposition conditionally

Time-temperature superposition requires thermorheological simplicity over the fitted range. Build separate shift factors only after confirming comparable curve shape and mechanism. Report reference temperature, shift-factor model, fitting range and residuals.

Do not shift across glass transition, post-cure onset, phase change or environmental transition without direct evidence. Agreement inside the fitted window is calibration, not lifetime validation.

11. Model stress dependence without hiding rupture

Power-law, logarithmic, Prony-series and nonlinear viscoelastic models can describe bounded deformation data. Rupture models require their own evidence and censoring treatment. Report parameter identifiability and correlation.

An apparent straight line on log axes does not prove a mechanism. Reserve stress levels and durations as prospective holdouts.

12. Handle runouts and scatter correctly

Rupture datasets include right-censored specimens. Do not assign runouts an invented failure time. Report specimen count, censoring, confidence or credible intervals and the population represented.

Lot, build position and surface defects can broaden lifetime distributions. Planned ER-231 will address statistical size effects but is not a current incumbent; ER-240 must nevertheless preserve geometry and population boundaries.

13. Verify load train stability

Calibrate load, displacement and temperature over the full duration. Record power interruptions, control drift, grip slip and chamber excursions. Use redundant displacement or force monitoring where failure consequences are high.

Fixture creep can be mistaken for specimen creep. Characterise or subtract it only with a validated method and report the correction uncertainty.

14. Measure residual performance

After specified hold times, unload selected specimens and measure recovery, dimensions, modulus, strength or fracture response. Compare with unloaded aged controls. A specimen can retain shape yet lose margin to rupture.

Define whether destructive residual tests are cross-sectional or longitudinal. Do not pool them without a model for specimen-to-specimen variability.

15. Build a non-compensatory qualification matrix

Gate	Required evidence	Unsupported shortcut prevented
Printed state	Process, cure, age and conditioning	Pooling unlike networks
Load mode	Force, stress, strain and evolving geometry	Calling nominal load material stress
Environment	Part temperature, humidity and chemicals	Hidden ageing or plasticisation
Time response	Real-time overlap, recovery and runouts	Extrapolating one short curve
Mechanism	Deformation, crack, instability and rupture	Mixing structural and material failure
Validation	Holdout stress, time and acceptance limits	Calling calibration lifetime proof

16. Minimum reporting set

Report printed state, age and conditioning; specimen and fixture geometry; load-control mode; force, stress, strain and time histories; evolving dimensions; temperature and environment; recovery protocol; crack and rupture observations; runouts and censoring; replicates and exclusions; constitutive model, shift factors, fitting range and uncertainty; real-time overlap; holdout validation; residual performance; acceptance criteria; and transfer limits.

17. Knowledge boundary

Direct evidence demonstrates formulation-, post-cure-, orientation-, ageing- and temperature-dependent response in specific printed photopolymers [1-5]. Standards provide general tensile-creep and creep-rupture frameworks [6,7]. Broad, replicated rupture datasets for neat vat-printed photopolymers remain sparse. The evidence supports a qualification architecture, not a universal master curve or lifetime factor.

18. Limitations

References [1], [2], [3], [4] and [5] were read at full-text depth; references [6] and [7] were verified at bibliographic-record depth. Commercial resin composition is often incompletely disclosed, and available studies use different geometries and endpoints. No universal creep coefficient, shift factor, rupture law, service life or design allowable is supplied.

19. Conclusions

Long-term load retention must be anchored by state-matched real-time tests, explicit load control, evolving geometry, environmental control and separate rupture evidence. Physical ageing, post-cure and damage cannot be collapsed into one shift factor. Extrapolation requires overlap, mechanism equivalence and prospective validation. The defensible output is a bounded envelope for a defined printed state, environment, load mode and endpoint.

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