

Piezoresistive Strain Sensors in Printed Photopolymer Composites: Percolation, Gauge Factor, Hysteresis and Fatigue

Qualifying conductive printed strain sensors by network connectivity, strain-transfer fidelity, reversible resistance change and long-cycle stability

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ER-378 · Engineering Review · Version 0.1 · 4 October 2026

Abstract

Piezoresistive strain sensing in printed photopolymer composites depends on a conductive network whose connectivity changes with deformation. The useful response is controlled not only by gauge factor but also by percolation position, hysteresis, baseline resistance and cyclic rearrangement of the filler network. Printing can impose anisotropic strain fields and geometric variation that alter the apparent electrical response. Qualification therefore requires resistance and strain to be measured together through loading, unloading and fatigue, with the initial network state preserved in the record. The resulting evidence supports three engineering decisions: a qualified strain and gauge-factor range, an acceptable filler-network and build-orientation state, and a fatigue threshold linked to baseline drift and recalibration. [1,2,3]

Keywords: piezoresistive sensor; polymer nanocomposite; percolation; gauge factor; hysteresis; fatigue

1. Qualification problem: piezoresistive strain sensors in printed photopolymer composites

ER-378 qualifies a strain-sensing range together with its gauge response, the conductive-network state that makes that response reproducible, and the fatigue point at which recalibration is required. Distance from percolation, resistance change per strain and unloaded baseline drift remain separate because maximizing one can destabilise another.

1.1 Scope boundary.

ER-378 is restricted to strain sensing through resistance change in percolating or tunnelling conductive networks. ER-361 and ER-362 address mechanical response of architected structures, and ER-377 addresses triboelectric surface charging; mechanical deformation alone is therefore not evidence of a qualified piezoresistive transfer function.

2. Governing balances for piezoresistive strain sensors in printed photopolymer composites

Piezoresistive polymer composites convert deformation into resistance change by altering conductive contacts, tunnelling gaps and network topology. Near percolation, small geometric changes can strongly affect resistance, producing high sensitivity but also greater variability. The measured response includes the intrinsic conductive-network effect plus geometric resistance change and contact contributions. For printed specimens, filler orientation and layer interfaces can add anisotropy to both mechanics and conduction. [1,2,3,4]

Conductivity emerges when conductive fillers form connected or tunnelling networks through the polymer. [1,2,3]

Strain changes interparticle distance and contact topology, producing resistance changes that may be reversible only over a limited range. [1,2,3]

Near percolation, small structural changes can produce large electrical responses, increasing sensitivity but also amplifying process variability and environmental drift. [1,2]

The strain-sensor state is therefore defined by network conductivity, measured strain field and resistance history together; a gauge factor without those context variables is not transferable.

3. Regime boundaries for piezoresistive strain sensors in printed photopolymer composites

Below percolation the network is discontinuous and resistance is too high or unstable for reliable sensing. Just above threshold, gauge factor can be large but drift and noise may be significant. At higher filler loading, conductivity becomes more robust while sensitivity can fall and the matrix becomes stiffer or harder to print. Large strain introduces a further regime in which network rearrangement or cracking becomes irreversible. Qualification should locate the intended service window within these regimes. [1,2,3]

Table 1 resolves how close the composite is to percolation, how strongly resistance responds to strain and how much baseline drifts with cycling; those three quantities control different qualification decisions.

Table 1. Regime indicators and engineering use.

A qualified strain and gauge-factor range exists only where the network remains on the characterised side of percolation, gauge response is repeatable and baseline drift stays below the recalibration trigger.

Indicator	Engineering meaning	Use
filler fraction relative to the percolation threshold	Shows how close the conductive network is to the connectivity transition that amplifies resistance sensitivity.	Used to delimit formulations where high gauge response is not obtained at the cost of unstable baseline conduction.
fractional resistance change divided by applied strain	Defines gauge response for the measured strain field and loading direction.	Used to specify the strain interval over which sensitivity, linearity and hysteresis remain acceptable.
baseline resistance drift from one cycle block to the next	Tracks irreversible network rearrangement or contact change during fatigue.	Used to set recalibration or retirement before zero-strain resistance moves outside the validated transfer function.

4. Couplings that move the piezoresistive strain sensors in printed photopolymer composites

Dispersion, filler aspect ratio and hybrid networks influence percolation, while cure shrinkage can move particles and change tunnelling gaps. Printing orientation may align elongated fillers or create resin-rich interfaces. Temperature affects both polymer dimensions and carrier transport, and humidity can affect some conductive phases. Consequently, a gauge factor is meaningful only with the process, environmental state and baseline resistance that produced it. [1,2,3,4]

Filler loading changes resin viscosity, cure depth and mechanical modulus as well as conductivity. [1,2,3]

Build orientation and flow history can orient anisotropic fillers, creating direction-dependent conductivity and gauge factor. [1,2,4]

Temperature can shift polymer dimensions and conductive-network resistance, so thermal drift is measured separately from mechanical strain before gauge response is accepted. [1,2]

5. Failure signatures and false diagnoses

A rising zero-load resistance after cycling signals permanent network change or contact degradation; an unchanged baseline with larger hysteresis points toward viscoelastic mechanics. Sudden resistance jumps can indicate crack formation or loss of an electrode connection. Four-wire measurements, independent strain tracking and post-test imaging help distinguish these cases. Overload tests are useful because they reveal whether the sensor returns to its pre-overload calibration. [1,2,3]

Resistance drift during cycling is challenged against irreversible filler rearrangement, contact/electrode change, viscoelastic strain offset and thermal drift. Unloaded resistance, independent strain measurement and temperature controls provide the required discriminating evidence.

Table 2. Failure-mode discrimination and required evidence.

Failure mode	Observable signature	Discriminating evidence
network rupture or irreversible rearrangement	baseline resistance remains shifted after unloading	load-unload cycle with long recovery hold
hysteresis and viscoelastic lag	different resistance at the same strain on loading and unloading	controlled triangular strain waveform at multiple rates
temperature cross-sensitivity	resistance changes without mechanical strain during thermal excursion	zero-load temperature sweep
fatigue drift	gauge factor or baseline changes progressively with cycle count	periodic calibration cycles during long fatigue test

6. Measuring piezoresistive strain sensors in printed photopolymer composites with traceable uncertainty

Piezoresistive qualification requires resistance and strain to be measured on the same gauge length and time base. Gauge factor should be calculated from the incremental strain range actually used, not from a broad nonlinear curve treated as if it were linear. Baseline resistance, temperature and loading rate must be recorded because conductive polymer composites can be strongly viscoelastic and temperature sensitive. [1,2,3]

The conductive network should be characterised relative to percolation. Compositions just above the percolation threshold can show high sensitivity because small geometric changes strongly affect tunnelling paths, but they can also exhibit large drift and specimen-to-specimen variability. Bulk conductivity alone is therefore insufficient; resistance distribution across replicate printed specimens and orientation-dependent response are needed when the printing process can align fillers or create layer interfaces. [1,2,3,4]

Measure four-wire or otherwise contact-corrected resistance when feasible, together with local strain from extensometry or digital image correlation. Gauge factor must be reported over a stated strain interval and loading direction. Baseline resistivity, hysteresis, creep and temperature coefficient should be measured separately. Electrode/contact resistance requires its own check because it can dominate high-resistance composites. [1,2,3]

7. Experiments that discriminate competing mechanisms

Mechanical hysteresis and network hysteresis can be separated by measuring an independent strain field. If the mechanical strain returns while resistance does not, conductive-path rearrangement is implicated. Conversely, residual specimen strain with proportionate resistance change indicates mechanical set. Step-hold tests are useful because resistance relaxation during constant strain reveals time-dependent tunnelling or polymer relaxation. [1,2,3]

Filler architecture should be challenged through controlled composition or hybrid-filler changes while preserving specimen geometry. Hybrid networks can lower percolation threshold and broaden conductive pathways, but apparent gains in gauge factor should be tested against noise, drift and fatigue. Cyclic tests should include both small service strains and occasional overloads because a single high-strain event can permanently reconfigure the network. [1,2]

Map conductivity versus filler loading around the intended formulation, then test strain response in at least two build orientations. Use repeated loading-unloading at several rates to separate elastic piezoresistance from viscoelastic lag. Temperature sweeps at zero mechanical load quantify cross-sensitivity. Long-cycle tests should pause for a standard calibration waveform, allowing gauge factor drift and baseline drift to be tracked independently. [1,2,3]

8. Model identification and validation for piezoresistive strain sensors in printed photopolymer composites

Models range from empirical gauge-factor relations to percolation and tunnelling descriptions. A useful engineering model should reproduce baseline conductivity, nonlinear resistance-strain response and hysteresis over the intended strain window. Fitting only gauge factor cannot distinguish changes in network connectivity from changes in geometry. [1,2,3]

Validation across print orientation and specimen size is important because vat-photopolymer mechanics can be anisotropic and size dependent. A sensor model calibrated in one orientation should not be transferred unless both mechanical modulus and resistance-strain response remain comparable. Temperature compensation or a reference resistor may be required when thermal resistance changes are of similar magnitude to the strain signal. [1,4]

Piezoresistive identification begins with the conductive network: baseline conductivity and percolation position are established before gauge factor is fitted. Resistance change is then decomposed into geometric effects and network rearrangement or tunnelling, with the strain field measured independently.

Identifiability is challenged by testing more than one strain amplitude and loading direction. Near percolation, two formulations can have similar initial resistance but very different nonlinearity and hysteresis, so a single gauge-factor value is insufficient. Build orientation is treated as a configuration variable when it changes the mechanical strain field rather than assumed to change electrical transport directly.

Resistance metrology, strain measurement and specimen dimensions contribute differently to the decision limits. The qualified strain and gauge-factor range includes uncertainty in both axes, while cycle-to-cycle baseline drift is evaluated against instrument stability using unloaded reference readings.

9. Qualification envelope and technology decisions

The acceptance envelope should include strain range, loading rate, cycle count, temperature, baseline resistance, gauge-factor tolerance, hysteresis, drift and noise. Sensitivity alone is not enough: a high gauge factor with unstable baseline may provide poorer measurement capability than a lower but reproducible response. Transfer to another print orientation or filler-processing route requires replicated calibration. [1,2,3,4]

Table 3. Technology-decision matrix.

The qualified strain and gauge-factor range, the acceptable network/build state and the fatigue recalibration threshold each require their own evidence. Sensitivity near percolation is accepted only when hysteresis and baseline stability remain within the stated application limits.

Decision	Minimum evidence	Acceptance logic
qualified strain and gauge-factor range	Calibrated measurements spanning the proposed limit for qualified strain and gauge-factor range, with at least one independent replicate near the boundary and the controlling filler fraction relative to the percolation threshold reported with uncertainty.	Accept only while the measured response remains inside the stated boundary and the challenge 'load-unload cycle with long recovery hold' does not trigger network rupture or irreversible rearrangement or move baseline resistance remains shifted after unloading outside the qualified range.
acceptable filler-network and build-orientation state	Calibrated measurements spanning the proposed limit for acceptable filler-network and build-orientation state, with at least one independent replicate near the boundary and the controlling fractional resistance change divided by applied strain reported with uncertainty.	Accept only while the measured response remains inside the stated boundary and the challenge 'controlled triangular strain waveform at multiple rates' does not trigger hysteresis and viscoelastic lag or move different resistance at the same strain on loading and unloading outside the qualified range.
fatigue and recalibration threshold	Calibrated measurements spanning the proposed limit for fatigue and recalibration threshold, with at least one independent replicate near the boundary and the controlling baseline resistance drift from one cycle block to the next reported with uncertainty.	Accept only while the measured response remains inside the stated boundary and the challenge 'zero-load temperature sweep' does not trigger temperature cross-sensitivity or move resistance changes without mechanical strain during thermal excursion outside the qualified range.

10. Design consequences for piezoresistive strain sensors in printed photopolymer composites

Design should position the conductive composition far enough above percolation to obtain reproducible baseline continuity while retaining adequate sensitivity. Very high filler loading can reduce printability, increase optical attenuation during cure and stiffen the matrix. Hybrid filler systems can reduce this trade-off but introduce dispersion and orientation as additional process variables. [1,2]

Sensor geometry should limit strain concentration at electrical contacts and printed transitions. Four-wire measurement can reduce contact-resistance error when absolute resistance matters. Encapsulation should be qualified because it can change strain transfer and environmental stability. Requalification is triggered by changes in filler batch, mixing, print orientation, post-cure or electrode attachment. [1,2,3,4]

The most sensitive formulation is not automatically the most robust. Operating too close to percolation can produce unacceptable lot variation and thermal sensitivity. Filler loading should provide sufficient connectivity margin while preserving printability and fatigue resistance. Electrode geometry, strain concentration and gauge placement should be designed to measure the intended structural strain rather than local grip or contact effects. [1,2,3]

Piezoresistive manufacturing control records filler dispersion, cure state, orientation and electrode/contact geometry because each can move the network resistance. A new build orientation is first checked by strain mapping and baseline resistance, while a formulation change is challenged against percolation and hysteresis before its gauge factor is accepted.

11. Evidence gaps for piezoresistive strain sensors in printed photopolymer composites

Long-term fatigue datasets remain insufficient to separate conductive-network ageing from substrate fatigue. Future work should report resistance loops, mechanical loops and zero-load baseline after defined cycle blocks. Microscopy or tomography of crack/filler evolution would help connect electrical drift to physical damage. [1,2,3]

Another gap is uncertainty propagation. Gauge factor is often reported without confidence intervals even though thickness, strain measurement, contact resistance and specimen-to-specimen conductivity all contribute. Replicated printed sensors and explicit uncertainty budgets are needed before small differences between formulations or architectures can be treated as engineering improvements. [1,4]

The largest evidence gap is reproducibility across printed lots and printers for formulations near electrical percolation. More studies are also needed on combined humidity, temperature and mechanical fatigue because absorbed moisture can alter both polymer mechanics and interfaces. Qualification should include raw resistance-strain loops and report contact architecture and post-cure. [1,2]

A strong piezoresistive dataset would link full loading histories to resistance, strain-field measurements, baseline drift and network state across several specimens and orientations. Samples that lose reversibility near percolation should remain in the dataset because they define the practical edge of the sensitivity gain.

Direct DLP nanocomposite experiments demonstrate that architecture itself can change apparent piezoresistive sensitivity. Saadi, Schiffer and Kumar measured CNT/photopolymer nanocomposites under monotonic and cyclic loading [5]. In a separate DLP lattice study, Saadi, Uddin, Schiffer and Kumar reported that the gauge factors of the tested hexagonal and chiral architectures increased by roughly 300% and 500%, respectively, when relative density increased from 20% to 40%; reentrant and triangular lattices were much less sensitive to that density change [6]. These figures are specific to those lattice topologies, relative densities, CNT-loaded photocurable resin and loading protocol; they are not transferable as formulation constants. The result supports reporting topology, relative density and local strain field with gauge factor rather than treating gauge factor as formulation-only.

12. Qualification outcome for piezoresistive strain sensors in printed photopolymer composites

A qualified printed piezoresistive sensor is therefore a defined composite-process-geometry state with demonstrated calibration stability. Changes in filler dispersion, orientation, post-cure, electrode attachment or strain-transfer geometry alter the conductive network and trigger requalification.

Qualification is limited to the tested formulation, filler dispersion state, build orientation, temperature, strain range and cycle history. Gauge factor, hysteresis and fatigue drift are independent acceptance limits, and no universal sensitivity is claimed.

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Competing interests

The author is Founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L.; ER-378 contains no comparative recommendation between commercial products.

Data availability

ER-378 is a literature-based engineering review; no new experimental dataset was generated.