

Fracture Toughness and Damage Tolerance in Vat-Photopolymerised Thermosets: Crack Preparation, Cure State, Anisotropy and Qualification

Juan Segurola

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

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Statement of Significance

A material can absorb substantial energy in an unnotched tensile test and still fail abruptly from a small crack. Conversely, a high notched-impact value does not establish a valid plane-strain fracture toughness. Vat photopolymerisation adds further uncertainty because the crack tip can interact with layer interfaces, voxel stepping, cure gradients, residual stress, surface roughness and post-cure history. This review separates tensile toughness, impact strength, notch sensitivity, conditional fracture values and valid KIC, GIC or J-R measurements, then defines the minimum evidence required before a printed thermoset can be described as fracture-tough or damage-tolerant.

Keywords: vat photopolymerisation; stereolithography; digital light processing; fracture toughness; damage tolerance; stress-intensity factor; strain-energy release rate; J-R curve; notch sensitivity; build orientation; post-cure; anisotropy; thermoset

Abstract

Vat-photopolymerised thermosets are frequently described as tough, impact resistant or thermoplastic-like using tensile elongation, work-to-break, flexural response or pendulum-impact data. These quantities are useful, but none is interchangeable with resistance to the initiation and propagation of a sharp crack. This review develops a qualification framework for fracture toughness and damage tolerance in SLA, DLP and LCD/MSLA printed thermosets. It distinguishes unnotched tensile toughness, work of fracture, impact strength, notch sensitivity, conditional stress-intensity values, valid plane-strain KIC and GIC, and elastic-plastic J-R behaviour. Primary studies demonstrate that apparent fracture response can change with printing orientation, exposure, layer thickness, post-cure, specimen size, notch geometry, resin colour, environment and crack-plane alignment. They also show that different experimental geometries can produce different orientation rankings because crack deflection and layer-interface interactions alter the fracture path. Printed notches are valuable for rapid screening, but they are not automatically equivalent to a sufficiently sharp precrack under ISO 13586 or ASTM D5045. Toughening routes based on urethane-acrylate blending, graphene, phase-separated aromatic polyester modifiers and reversible intermolecular interactions can improve resistance to failure, yet each route requires crack-valid testing before a fracture-toughness claim is made. The review proposes a minimum reporting set covering material identity, printer and exposure state, specimen geometry, crack preparation, build orientation, conditioning, loading rate, validity checks, statistics and fractography. The central conclusion is that fracture toughness is a method- and state-qualified property of a cracked printed material, while damage tolerance is a broader structural demonstration linking validated fracture data to the actual flaw population, geometry, environment and service loading.

1. Scope and evidence-selection method

ER-70 addresses final, polymeric thermoset parts produced by vat photopolymerisation. The principal evidence set comprises peer-reviewed studies that used cracked, notched or fracture-mechanics specimens produced by SLA or DLP, together with formulation studies that explicitly measured fracture toughness or used the word toughness for a different mechanical quantity [1-14].

The review does not pool numerical values across resins. Commercial photopolymers differ in network chemistry, conversion, modulus, Poisson ratio, residual stress, layer thickness, optical history and post-cure. The published studies also use different geometries, crack-generation methods, orientations, conditioning states and validity criteria. Numerical values are therefore retained only as source-specific examples.

The scope excludes:

- fatigue-life and time-dependent deformation qualification, which are treated in ER-39;
- shrinkage, residual stress and warpage as primary topics, which are treated in ER-31;
- hydrated hydrogel fracture, which requires hydration-specific methods and is bounded by ER-67;
- self-healing efficiency, which is treated in ER-13;
- fracture of debond or sintered ceramics and metals, where the final converted material rather than the printed green body governs the claim.

Shared measurement conventions, reporting rules, and disclosure boundaries for this series are defined in [RP-02](#); this review states only the topic-specific content.

Damage tolerance is used here in its engineering sense: the ability of a defined structure to sustain service loading in the presence of a known or bounded flaw population. It is not treated as a synonym for high elongation, impact resistance or a single K value.

2. Toughness is not one quantity

Table 1. Mechanical quantities that should not be treated as synonyms

Quantity	How it is obtained	Typical unit	What it does not establish
Tensile toughness	Area under an unnotched stress-strain curve to failure.	J/m ³ or MJ/m ³	Resistance to a pre-existing sharp crack.
Work of fracture	External work normalised using a stated ligament or fracture area; definition is method-specific.	J/m ² or kJ/m ²	A universal GIC unless the fracture method and validity are established.

Quantity	How it is obtained	Typical unit	What it does not establish
Impact strength	Pendulum energy absorbed by a specified notched or unnotched specimen.	J/m or kJ/m ²	Quasi-static KIC, GIC or crack-growth resistance.
Conditional KQ or GQ	Cracked-specimen result before every validity condition is satisfied.	MPa·m ^{0.5} ; J/m ²	A plane-strain material property.
Valid KIC or GIC	Mode-I initiation result from a sufficiently sharp crack under stated LEFM validity conditions.	MPa·m ^{0.5} ; J/m ²	Mixed-mode resistance, fatigue crack growth or service damage tolerance.
J-R curve	Resistance curve for stable crack extension in ductile or semi-ductile polymers.	J/m ² versus crack extension	Applicability where the crack front cannot be separated from diffuse deformation.
Notch sensitivity	Change in strength or fracture load with notch geometry or root radius.	Ratio or geometry-specific load/stress	A sharp-crack fracture toughness.
Damage tolerance	Structural assessment combining flaw size, geometry, loading, environment and validated fracture data.	Application-specific	A resin-only label independent of the printed component.

The word tough is incomplete unless the measured quantity, specimen geometry, state and loading history are named. Fang and co-workers, for example, reported 38.3 ± 4.3 MJ/m³ from unnotched tensile loading of a VPP shape-memory polymer [12]. That result demonstrates high tensile energy absorption under the stated test, but it is not a KIC or GIC value. Kuenstler and co-workers likewise reported ultimate toughness for recyclable thiol-ene thermosets without thereby establishing sharp-crack resistance [13].

A defensible claim uses the quantity actually measured. “High tensile toughness”, “high notched Izod impact strength” and “valid mode-I fracture toughness” are three different statements.

3. Fracture-mechanics framework

For a cracked specimen under mode-I opening, the provisional stress-intensity result can be written in the general form:

$$KQ = [PQ / (B W^{0.5})] f(a/W)$$

PQ is the selected critical load, B is thickness, W is a characteristic specimen dimension, a is crack length and f(a/W) is the geometry function. The equation does not make KQ a material property by itself. The load-displacement linearity, crack sharpness, crack-length range, specimen dimensions and plane-strain constraint must satisfy the applicable method before KQ is reported as KIC.

Under appropriate linear-elastic and isotropic assumptions, the corresponding critical energy-release rate can be related to KIC by:

$$GIC = KIC^2 / E'$$

E' depends on the stress state and elastic constants. The modulus and Poisson ratio must refer to the same material state, temperature, orientation and conditioning as the fracture test. For an anisotropic printed material, a scalar isotropic conversion can obscure direction dependence and should not be applied without justification.

When the crack grows stably with substantial non-linearity, ISO/TS 28660 provides a J-R route for ductile and semi-ductile plastics. A single maximum load is then insufficient; crack extension and resistance evolution must be resolved. If a distinct crack front cannot be separated from widespread deformation, even the J-R method may be unsuitable.

The suffix matters. KQ or a conditional fracture toughness should remain conditional when any validity requirement is not met. Removing the qualifier because the number appears reproducible converts a test result into an unsupported material claim.

4. A printed notch is not automatically a sharp crack

ISO 13586 and ASTM D5045 require a crack sufficiently sharp that further sharpening would not materially reduce the measured toughness. In conventional polymer testing, a machined starter notch is commonly extended with a razor or another controlled precracking procedure. The actual crack length and front must then be measured.

Vat photopolymerisation can print a narrow geometric notch directly. This is useful for repeatable screening and for research on notch effects, but the root remains limited by pixel or laser width, cure broadening, layer stepping, file tessellation and resin optics. A nominal CAD tip radius of zero is not a physical crack radius of zero.

Feng and co-workers explored directly printed 30° and 45° notch tips in DLP specimens. The 30° design produced a higher rate of clean crack initiation, while the 45° design generated more failed tests and potentially artificial KIC values. The authors presented the approach as a rapid way to screen nanofiller reinforcement, not as proof that printed notches universally replace crack preparation [10].

A crack-preparation record should therefore include:

- starter-notch manufacturing method and nominal root geometry;
- final sharpening or precracking method, blade type, loading history and temperature;
- measured crack length on both faces and, where relevant, through the thickness;
- evidence that the crack initiated from the intended tip and remained within the valid ligament;
- fractography or imaging sufficient to distinguish a printed notch, craze, void cluster and true crack.

A net-shape printed notch may be fully appropriate for quality-control screening if it is labelled as such. It should not be reported as ISO 13586 or ASTM D5045 KIC merely because the specimen dimensions resemble an SENB or CT geometry.

5. VPP creates a process-specific crack-tip environment

The cracked body produced by VPP is not defined only by formulation. Its local fracture process zone can intersect layer interfaces, voxel or pixel steps, surface stair-stepping, trapped bubbles, particulate agglomerates, undercured regions, overcured boundaries and residual-stress gradients. The relevant defect scale can be comparable with the crack-tip process zone or the printed notch radius.

Yuswanda and co-workers tested compact-tension SLA specimens and reported a mean conditional fracture toughness of $0.79 \pm 0.04 \text{ MPa}\cdot\text{m}^{0.5}$ for their as-printed material. Their calibrated XFEM model required an effective notch-tip strength of 17 MPa compared with a bulk tensile strength of 46 MPa, and they linked initiation to voxel-step microdefects [8]. The values are source-specific, but the methodological lesson is general: bulk tensile strength may not represent the local strength governing a printed crack tip.

Yudha and co-workers combined CT testing with digital image correlation, SEM-EDX and FTIR. Their specimens showed predominantly linear-elastic loading followed by unstable crack propagation, with a highest reported toughness of $0.8426 \text{ MPa}\cdot\text{m}^{0.5}$ for the tested set [7]. Full-field strain and fractography supplied information that a single load value could not.

Khosravani and co-workers examined printed V-notches with opening angles from 15° to 90° using fracture load, finite-element modelling and digital image correlation [4]. This is a notch-fracture study, not a sharp-crack KIC determination. Its value lies in showing how structural discontinuity geometry changes load capacity.

The minimum microstructural question is therefore: what feature actually initiated the crack? Without this answer, a fracture number can be assigned to the CAD notch while failure was controlled by a void, layer boundary or surface flaw elsewhere.

6. Exposure, orientation and post-cure alter the measured response

Brighenti and co-workers used dog-bone and SENB specimens to examine DLP process parameters. For one translucent-green resin and its stated post-processing, they reported a maximum KIC of $1.311 \text{ MPa}\cdot\text{m}^{0.5}$ at 0° and a minimum of $0.382 \text{ MPa}\cdot\text{m}^{0.5}$ at 90° . Exposure, printing direction and cleaning/UV treatment all affected the measured mechanical and fracture properties [1]. These values are not transferable targets; they demonstrate the size of the process contribution within one material system.

Li and Teng used tensile and edge-cracked semi-circular-bend specimens printed in five orientations. Tensile strength decreased with increasing orientation angle, but fracture toughness followed a non-monotonic relation and peaked at an intermediate orientation because the crack path deflected relative to the layer structure [2]. The study illustrates why tensile anisotropy and fracture anisotropy cannot be assumed to have the same ranking.

Baban, Coşa and Linul tested SENB specimens and found measurable effects from printing orientation, resin colour and environment. Their highest source-specific KIC values occurred at 45° orientation, for white resin, and after saline-solution conditioning, respectively [6]. These independent variables were not interchangeable, and the result does not establish that saline conditioning generally improves fracture toughness.

Post-cure can raise conversion and modulus, reduce residual reactive groups and change the crack-tip plastic zone. It can improve KIC in one undercured system and reduce it in another by increasing brittleness or residual stress. The direction must be measured for the complete formulation-printer-wash-post-cure sequence.

At minimum, orientation must define:

- build direction and layer plane;
- crack plane and intended crack-growth direction;
- loading direction relative to both;
- whether the specimen was printed in final geometry or cut from a printed plate;
- which surfaces retained the as-printed skin and which were machined or polished.

7. Mixed-mode fracture and crack-path deflection

Service cracks rarely experience pure mode I. Shear components, asymmetric support, curved geometry and residual stress can create mixed mode I/II loading. A mode-I KIC value is necessary for many comparisons but does not define a complete mixed-mode fracture envelope.

Marghitas and co-workers tested DLP semi-circular-bend specimens under symmetric mode I, asymmetric mixed mode and mode II loading. They compared the normalised experimental results with maximum tangential stress, strain-energy density, maximum energy-release-rate and equivalent-stress-intensity criteria; most results fell within the corresponding fracture envelopes [3].

Layer interfaces can either facilitate propagation or deflect the crack. Deflection can raise the apparent critical load by increasing the fracture path and introducing shear, yet it can also direct a crack toward a weak interface. A higher value at one orientation is therefore not automatically evidence of a tougher isotropic network.

Mixed-mode qualification requires the crack-tip mode mixity, support geometry, crack inclination, fracture criterion and observed initiation angle. Reporting only the external loading angle is insufficient.

8. Size effect, notch effect and conditional values

A material-property interpretation assumes that the specimen is large enough relative to the fracture process zone and satisfies the selected validity model. Printed components often occupy the transition between strength-controlled failure and LEFM. Their apparent resistance can therefore change with specimen size even when the resin and print settings are unchanged.

Marghitas, Popa and Marsavina demonstrated a strong size effect in DLP semi-circular-bend specimens made from two commercial resins. Their results followed a transition from strength-of-materials behaviour toward LEFM, and theory-of-critical-distance predictions captured the detrimental effect of V- and U-notches for most tested cases [5]. For their parameter sets, the calculated critical distance was approximately 8 to 18 times the 0.05 mm layer thickness. This ratio is not a universal VPP constant.

The distinction between crack and notch is central. A sharp-crack test seeks an initiation property under a defined asymptotic field. A notch test evaluates a finite-radius structural discontinuity. Both are useful, but they answer different questions and should carry different names in tables, product data and design allowables.

Where plane strain, linearity, crack sharpness or dimensional requirements are not satisfied, the result should be reported as KQ, GQ, conditional fracture toughness, fracture load, nominal notched strength or another method-accurate quantity. Reproducibility does not repair invalid nomenclature.

9. Toughening strategies and evidence boundaries

Several routes can improve crack resistance, but the mechanism and evidence level must be separated.

9.1 Co-reactive network blending

Idrees and co-workers blended a brittle methacrylated Bis-GMA resin with a urethane-acrylate commercial resin. A substantial urethane-acrylate fraction was required before fracture resistance improved, while higher contents reduced other mechanical properties. SEM showed no observed nanoscale phase separation, so the authors attributed the improvement to chemistry and network structure within a single-network blend [9]. The study is important because it shows that a second phase is not mandatory for higher KIC or GIC.

9.2 Particulate crack bridging and deflection

Feng and co-workers added 0.5 wt% graphene nanoplatelets and reported a 28% increase in fracture toughness relative to the neat resin, with rougher fracture surfaces, sheet pull-out and crack-deflection features [10]. The formulation remained printable, but the directly printed notch method should be retained as part of the result definition.

9.3 Controlled phase separation and covalent compatibility

Lin and co-workers incorporated 10 wt% of a tailored aromatic copolyester into a commercial stereolithography resin. They reported simultaneous increases in KIC, elongation, modulus and hardness, including an approximately 18.2% increase in fracture toughness, while AFM and SEM showed a phase-separated morphology that promoted energy dissipation [11]. The result demonstrates that a phase-separated toughener can be designed without abandoning resin stability and processability.

9.4 Reversible interactions and tensile energy absorption

Sacrificial hydrogen bonding, dynamic covalent exchange and semicrystallinity can increase unnotched tensile energy absorption [12,13]. These mechanisms may also affect crack growth, but tensile toughness alone does not prove the direction or magnitude of KIC, GIC or J-R resistance. A formulation can stretch before failing in a smooth specimen while remaining sensitive to a sharp flaw.

The correct development sequence is:

formulation mechanism -> printability and cure state -> unnotched mechanics -> valid cracked-specimen test -> crack-path evidence -> environmental and structural qualification

10. Conditioning, ageing and loading rate

Fracture response in polymers depends on temperature, loading rate, absorbed solvent or water, physical ageing and post-cure. These variables can change modulus, yield behaviour, residual stress and crack-tip dissipation. The conditioning state is part of the material definition, not an auxiliary laboratory detail.

Mann and Ruse compared conventional, milled and 3D-printed denture-base materials after 7 and 90 days. Water storage altered KIC and work of fracture in a material-specific way, and the tested printed product retained a high product-specific result [14]. The study does not support transfer to unrelated VPP resins, but it demonstrates that ageing duration and medium can change the fracture ranking.

ISO 17281 extends mode-I fracture-toughness guidance to moderately high loading rates up to 1 m/s and explicitly addresses vibration and inertia. Pendulum impact methods operate in another test architecture. A quasi-static KIC should not be used as a dynamic value without rate-dependent evidence, and an Izod or Charpy value should not be converted into KIC.

A conditioning record should state:

- temperature, relative humidity or immersion medium;
- conditioning time and equilibrium criterion;
- test temperature and time between conditioning and loading;
- as-printed, washed, dried, post-cured and aged state;
- loading or displacement rate and data-acquisition rate;
- whether the crack was prepared before or after conditioning.

11. Standards and method selection

Table 2. Current polymer fracture and impact standards relevant to ER-70

Document	Primary scope	Use in VPP qualification	Principal boundary
ISO 13586:2018	Mode-I KIC and GIC for rigid and semi-rigid plastics using cracked three-point-bend or compact specimens.	Primary LEFM route when crack, linearity, dimensions and constraint are valid.	Not a VPP-specific standard; AM process state and anisotropy must be added.
ASTM D5045-14(2022)	Plane-strain KIC and GIC using SENB and CT geometries.	Widely used for cracked VPP thermosets and explicit KQ/KIC validity.	Requires sufficiently sharp crack, linear elastic response and adequate thickness.
ISO/TS 28660:2022	J-R curves for ductile and semi-ductile plastics.	Alternative when stable crack growth cannot be represented by LEFM.	Unsuitable where the crack front cannot be distinguished from diffuse deformation; excludes fibre-reinforced polymers.
ISO 17281:2018	KIC and GIC at moderately high loading rates up to 1 m/s.	Rate-dependent fracture extension of ISO 13586.	Dynamic effects, inertia and vibration require control or correction.
ISO 179-1:2026; ISO 180:2023; ASTM D256-26 (confirmed via 2025/2026 catalogue review)	Charpy or Izod pendulum impact response.	Comparative impact and quality-control data.	Impact strength is not KIC, GIC or a damage-tolerance demonstration.
ASTM D6110-26 (confirmed via 2026 catalogue review)	Charpy impact resistance of notched plastic specimens.	Comparative response to flexural shock and specimen processing.	Results depend strongly on notch, fabrication, dimensions and conditioning.

ISO 13586:2018 remains current after confirmation in 2025. ISO/TS 28660:2022 was confirmed in 2026. ISO 179-1:2026 replaced the 2023 edition in March 2026. The applicable edition must be verified at the date of testing rather than copied from an older paper.

No published ISO or ASTM method identified in this review is specific to vat-photopolymerised thermosets. The polymer fracture standard supplies the mechanical framework; the laboratory must add the VPP process, cure-state, orientation, surface and defect records needed to define the printed material.

12. Minimum reporting framework

Table 3. Minimum evidence required for a fracture-toughness claim

Domain	Minimum record	Why it is required
Material identity	Resin name/version, lot, colour/filler content, storage and mixing history.	Optics, dispersion and chemistry can change cure and fracture.
Printer and exposure	Machine, wavelength/spectrum, irradiance, layer thickness, exposure, temperature and orientation.	Defines the optical and layerwise manufacturing state.
Post-processing	Drain, wash solvent/time, dry, post-cure source, dose, temperature and delay before test.	Conversion, residual stress and crack-tip response depend on the complete workflow.
Specimen geometry	Standard/designation, B, W, span, a/W, support and machining or polishing.	Geometry determines the stress-intensity or energy function.
Crack preparation	Starter notch, sharpening/precrack method, crack-front imaging and measured a on both faces.	Separates a finite notch from a sufficiently sharp crack.
Orientation	Build direction, layer plane, crack plane, crack-growth direction and load direction.	Fracture anisotropy cannot be reconstructed from “0°” alone.
Conditioning	Temperature, humidity/medium, time, equilibrium and timing of crack preparation.	Defines the tested polymer state.
Loading and acquisition	Control mode, rate, machine compliance, load/displacement sampling and crack monitoring.	Required for linearity, initiation and rate interpretation.
Validity	KQ/KIC or GQ/GIC decision, all dimensional/linearity checks and any deviations.	Prevents conditional values from becoming material properties.
Statistics and fracture path	Replicate count, individual values, exclusions, uncertainty, initiation location and fractography.	Reproducibility alone cannot reveal an invalid or unintended crack path.

A mean and standard deviation are not enough if invalid specimens were removed without a declared rule. Every exclusion should be linked to a predefined validity criterion, such as crack deviation, incomplete break, dimensions, excessive non-linearity or initiation outside the intended tip. For development screening, a shorter method is acceptable if it is explicitly labelled. The screening method should still freeze crack/notch geometry, orientation, cure state and environment so that formulation changes are not confounded by process drift.

13. From material screening to damage tolerance

Fracture qualification should progress through evidence levels rather than one headline test.

- Level 1 - unnotched screening: tensile, flexural and impact response under frozen process conditions;
- Level 2 - notch screening: repeatable finite-radius notch or net-shape discontinuity for formulation comparison;
- Level 3 - cracked-specimen characterisation: valid KIC/GIC or J-R testing in each relevant orientation and state;
- Level 4 - structural validation: representative geometry, flaw population, residual stress, environment and load spectrum;
- Level 5 - damage-tolerance demonstration: inspection threshold, allowable flaw, life or proof-load logic and failure consequences.

Only Level 3 can support a properly bounded fracture-toughness claim. Damage tolerance requires Level 4 or 5 evidence because the allowable crack size depends on component geometry and service stress, not solely on resin chemistry.

A convenient engineering statement is:

material fracture data + process-specific flaw map + structural stress field + environment + inspection or proof strategy = damage-tolerance case

14. Failure modes and interpretation errors

Table 4. Common failure modes in VPP fracture qualification

Observation	Interpretation error	Required response
High area under tensile curve	Called high fracture toughness.	Use tensile toughness terminology; add a valid cracked-specimen method.
High notched Izod or Charpy value	Converted into KIC or damage tolerance.	Retain impact terminology and test geometry; do not convert quantities.
Directly printed sharp-looking notch	Assumed to satisfy crack-sharpness requirements.	Measure root/crack front and compare with a controlled sharpening method.

Observation	Interpretation error	Required response
Repeatable KQ with invalid thickness or non-linearity	Reported as KIC because scatter is low.	Keep the conditional suffix and redesign specimen or select J-R.
Higher fracture load after post-cure	Attributed solely to higher conversion.	Measure modulus, residual stress, crack path and state before assigning mechanism.
Different best orientation in two studies	One study declared wrong or orientation called universal.	Reconcile crack plane, geometry, material, process and path deflection.
Crack turns along a layer boundary	Treated as homogeneous mode-I propagation.	Report initiation angle, path and mixed-mode contribution.
Large specimen fails at lower nominal stress	Dismissed as fabrication scatter.	Evaluate size effect and the transition from strength control to LEFM.
Fracture initiates from a void away from the notch	Notch-tip K assigned to the event.	Reject or separately classify; map the controlling defect.
Finite-element fit matches peak load	Model treated as independently validated.	Calibrate local properties and verify crack path, not only global load.

15. Scope boundaries within the Engineering Review series

ER-70 is restricted to crack initiation, crack-growth resistance, notch sensitivity and damage-tolerance evidence in final VPP thermosets.

- ER-31 addresses cure shrinkage, residual stress and warpage. ER-70 includes residual stress only where it changes crack driving force or test interpretation.
- ER-39 addresses fatigue and time-dependent deformation. ER-70 does not convert monotonic KIC into fatigue-crack-growth resistance or lifetime.
- ER-61 addresses gelation, vitrification and mobility arrest. ER-70 begins with the printed and conditioned solid state but records cure history as a material variable.
- ER-67 addresses hierarchical and double-network hydrogels. ER-70 does not transfer dry-thermoset fracture standards to hydrated soft networks without separate validation.
- ER-13 addresses self-healing and interlayer repair. Recovery after crack closure does not by itself restore KIC, GIC or the original crack path.
- ER-20 addresses thermal performance. ER-70 requires test temperature but does not replace HDT, Tg or service-temperature qualification.

16. 3Dresyns implementation boundary

Current 3Dresyns product pages use engineering labels such as tough, ultra-tough, ABS-like, PET-like and PEEK-like, and publish tensile, flexural, elongation, modulus or impact data for selected grades [M1-M4]. These labels and properties are implementation context, not independent fracture-mechanics evidence.

For example, 3Dresyn ABS-like publishes notched Izod impact resistance below 40 J/m, 3Dresyn CT MF publishes 20-30 J/m, and 3Dresyn PEEK-like publishes above 30 J/m under the stated product-page conditions [M1-M3]. These are impact values. They are not KIC, GIC, J-R curves or a damage-tolerance assessment.

No current standard 3Dresyns product is identified in this review as independently qualified by a published, valid sharp-crack KIC/GIC or J-R programme across orientation, conditioning and post-cure. A future fracture-toughness claim should therefore state the exact resin version, printer, process, crack method, standard edition, orientation, conditioning, validity outcome and uncertainty.

The product-page disclaimer that properties may vary with printer, exposure, layer thickness, orientation and post-processing is consistent with the evidence reviewed here [M1-M4]. It should be retained alongside any future fracture or impact result.

17. Research and standardisation priorities

- interlaboratory comparison of ISO 13586 and ASTM D5045 applied to VPP specimens;
- validated miniature CT or SENB geometries for limited build volumes without losing crack-tip constraint;
- quantitative comparison of printed notches, razor sharpening, fatigue precracking and laser-machined starters;
- three-dimensional crack-front imaging linked to voxel, layer and surface topography;
- orientation maps that define crack plane and propagation direction rather than one build angle;
- coupled measurement of conversion, residual stress, modulus and KIC through post-cure;
- J-R methods for semi-ductile VPP networks and clear criteria for when crack growth is distinguishable;
- fracture testing after solvents, humidity, water, temperature cycling, sterilisation or chemical exposure;
- defect-population and size-effect models that connect coupon data to printed components;
- standard reporting language separating tensile toughness, impact, conditional fracture values and valid fracture toughness.

18. Conclusions

Fracture resistance in vat-photopolymerised thermosets cannot be reduced to one unnotched stress-strain curve or one impact number. A crack concentrates stress at a scale where cure gradients, interfaces, voxel steps, voids and residual stress can dominate the response.

The defensible sequence is:

defined printed state -> controlled notch and sharp crack -> valid KIC/GIC or J-R method -> orientation and environment map -> structural flaw assessment -> damage-tolerance case

A printed notch is useful for screening, but it is not automatically a standard crack. A KQ is useful, but it is not automatically KIC. An impact value is useful, but it is not fracture toughness. Damage tolerance is achieved only when validated material fracture data are connected to the component geometry, flaw population, service environment and inspection or proof strategy.

The central engineering principle is that fracture toughness belongs to a cracked, conditioned and process-defined material state; damage tolerance belongs to the complete printed structure.

Limitations

The evidence base is heterogeneous. Some studies apply ISO 13586 or ASTM D5045-type cracked specimens, while others use research SCB geometries, printed V-notches, alternative crack methods or tensile toughness. The review preserves these distinctions and does not pool values. Commercial resin compositions are incompletely disclosed, and source-specific orientation rankings cannot be transferred without reproducing crack plane, process and post-cure. The 2026 references were checked to the bibliographic status available on 22 August 2026; online-first records should be rechecked before deposit.

This review does not establish design allowables, safety factors, inspection intervals or application-specific acceptance limits. Those require a controlled material-process specification and structural validation for the intended use.

Author contributions

Juan Seguro: conceptualisation, literature synthesis, engineering framework, writing and critical review.

Competing interests

The author is founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L. Manufacturer documentation is used only to define the commercial claim boundary and is not treated as independent validation of fracture toughness.

Data availability

No new experimental dataset was generated for this review.

Company information

Legal company name: 3Dresyns by Resyner Technologies S.L.

Registered tax address: General Etxague 15B, 20003 Donostia / San Sebastián, Gipuzkoa, Spain

VAT number: ESB24827511

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

References

- [1] Brighenti, R.; Marsavina, L.; Marghitas, M. P.; Montanari, M.; Spagnoli, A.; Tatar, F. The Effect of Process Parameters on Mechanical Characteristics of Specimens Obtained via DLP Additive Manufacturing Technology. *Materials Today: Proceedings* 2023, 78, Part 2, 331-336. DOI: 10.1016/j.matpr.2023.01.092.
- [2] Li, Y.; Teng, Z. Effect of Printing Orientation on Mechanical Properties of SLA 3D-Printed Photopolymer. *Fatigue & Fracture of Engineering Materials & Structures* 2024, 47(5), 1531-1545. DOI: 10.1111/ffe.14265.
- [3] Marghitas, M.; Marsavina, L.; Popa, C.-F.; Brighenti, R. On the Mixed Mode Fracture of DLP Manufactured SCB Specimens. *Procedia Structural Integrity* 2024, 56, 26-32. DOI: 10.1016/j.prostr.2024.02.033.
- [4] Khosravani, M. R.; Frohn-Sörensen, P.; Schwarzkopf, A.; Engel, B.; Reinicke, T. Brittle Fracture of Notched Components Fabricated by Stereolithography. *Journal of Materials Research and Technology* 2024, 33, 8071-8078. DOI: 10.1016/j.jmrt.2024.11.052.
- [5] Marghitas, M.; Popa, C.-F.; Marsavina, L. On the Size and Notch Effect in AM Photo-Polymerized Components. *Fatigue & Fracture of Engineering Materials & Structures* 2025, 48(9), 3790-3804. DOI: 10.1111/ffe.70001.
- [6] Baban, M. V.; Coşa, A. V.; Linul, E. Effect of Different Parameters on Mode I Fracture Toughness of Resin Samples Manufactured by DLP. *IOP Conference Series: Materials Science and Engineering* 2024, 1319(1), 012018. DOI: 10.1088/1757-899X/1319/1/012018.
- [7] Yudha, N. K.; Muwaffaq, A. M.; Putro, A. J. N.; Wu, Y. C.; Widagdo, D.; Darmanto, S.; Santos, G. N. C.; Muflikhun, M. A. Crack in Stereolithography: Material and Surface Characteristics Based on DIC. *Next Research* 2025, 2(2), 100323. DOI: 10.1016/j.nexres.2025.100323.
- [8] Yuswanda, I.; Muwaffaq, A. M.; Nugroho, G.; Muflikhun, M. A. Experimental and Numerical Investigation of Crack Propagation in Additively Manufactured Model Using Extended Finite Element Method (XFEM). *International Journal of Polymer Analysis and Characterization* 2026, online ahead of print. DOI: 10.1080/1023666X.2026.2644590.
- [9] Idrees, M.; Yoon, H.; Palmese, G. R.; Alvarez, N. J. Engineering Toughness in a Brittle Vinyl Ester Resin Using Urethane Acrylate for Additive Manufacturing. *Polymers* 2023, 15(17), 3501. DOI: 10.3390/polym15173501.
- [10] Feng, Z.; Li, Y.; Xin, C.; Tang, D.; Xiong, W.; Zhang, H. Fabrication of Graphene-Reinforced Nanocomposites with Improved Fracture Toughness in Net Shape for Complex 3D Structures via Digital Light Processing. *C* 2019, 5(2), 25. DOI: 10.3390/c5020025.

- [11] Lin, L.; Cao, W.; Liu, H.; Zhou, Z.; Wang, H.; Chen, Q.; Pu, X.; Kuzhandaivel, D.; Weng, Z.; Wu, L. Synthesis of an Aromatic Polyester for Enhanced Mechanical Properties of Stereolithography Resins. *Reactive and Functional Polymers* 2026, 221, 106656. DOI: 10.1016/j.reactfunctpolym.2026.106656.
- [12] Fang, Z.; Lu, R.; Chen, J.; Zhao, Q.; Wu, J. Vat Photopolymerization of Tough Glassy Polymers with Multiple Shape Memory Performances. *Additive Manufacturing* 2022, 59, Part B, 103171. DOI: 10.1016/j.addma.2022.103171.
- [13] Kuentler, A. S.; Hernandez, J. J.; Trujillo-Lemon, M.; Osterbaan, A.; Bowman, C. N. Vat Photopolymerization Additive Manufacturing of Tough, Fully Recyclable Thermosets. *ACS Applied Materials & Interfaces* 2023, 15(8), 11111-11121. DOI: 10.1021/acsaami.2c22081.
- [14] Mann, R. S.; Ruse, N. D. Fracture Toughness of Conventional, Milled and 3D Printed Denture Bases. *Dental Materials* 2022, 38(9), 1443-1451. DOI: 10.1016/j.dental.2022.06.029.

Standards and test methods

- [S1] ISO 13586:2018. Plastics - Determination of fracture toughness (GIC and KIC) - Linear elastic fracture mechanics (LEFM) approach. www.iso.org/standard/67721.html (accessed 22 August 2026).
- [S2] ASTM D5045-14(2022). Standard Test Methods for Plane-Strain Fracture Toughness and Strain Energy Release Rate of Plastic Materials. store.astm.org/standards/d5045 (accessed 22 August 2026).
- [S3] ISO/TS 28660:2022. Plastics - Determination of J-R curves - Fracture toughness. www.iso.org/standard/76546.html (accessed 22 August 2026).
- [S4] ISO 17281:2018. Plastics - Determination of fracture toughness (GIC and KIC) at moderately high loading rates (1 m/s). www.iso.org/standard/68099.html (accessed 22 August 2026).
- [S5] ISO 179-1:2026. Plastics - Determination of Charpy impact properties - Part 1: Non-instrumented impact test. www.iso.org/standard/91071.html (accessed 22 August 2026).
- [S6] ISO 180:2023. Plastics - Determination of Izod impact strength. www.iso.org/standard/84394.html (accessed 22 August 2026).
- [S7] ASTM D256-26. Standard Test Methods for Determining the Izod Pendulum Impact Resistance of Plastics. store.astm.org/standards/d256 (accessed 22 August 2026).
- [S8] ASTM D6110-26. Standard Test Method for Determining the Charpy Impact Resistance of Notched Specimens of Plastics. store.astm.org/d6110-26.html (accessed 22 August 2026).

Manufacturer documentation

- [M1] 3Dresyn ABS-like Acrylonitrile Butadiene Styrene Engineering Resin. www.3dresyns.com/products/3dresyn-abs-like (accessed 22 August 2026).
- [M2] 3Dresyn CT MF Clear & Tough Monomer Free. www.3dresyns.com/products/3dresyn-clear-tough (accessed 22 August 2026).
- [M3] 3Dresyn PEEK-like Polyetheretherketone-like Ultra-Tough Engineering Resin. www.3dresyns.com/products/3dresyn-peek-like-polyetheretherketone-like (accessed 22 August 2026).
- [M4] 3Dresyn ENG2 Tough Functional Resin. www.3dresyns.com/products/3dresyn-eng2-tough-functional-resin (accessed 22 August 2026).

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