

# Origami and Kirigami Photopolymer Structures: Hinge Design, Folding Path, Damage and Deployment Repeatability

*Qualifying deployable printed architectures by crease mechanics, collision-free kinematics and retained motion over repeated folding cycles*

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## Abstract

Origami and kirigami photopolymer structures couple fold kinematics with local hinge mechanics, self-contact and time-dependent material response. Build orientation changes hinge fatigue and panel anisotropy, while multimaterial hinges can decouple panel stiffness from fold compliance at the cost of interface risk. Qualification therefore requires fold angle versus moment or actuation input, DIC-based hinge curvature, cycle-to-cycle residual angle and microscopy or micro-CT of accumulated hinge damage. Single-hinge coupons establish the local constitutive response before full deployment sequences introduce collision and path constraints. The resulting evidence supports a minimum hinge radius or thickness for the required life and defines the deployment-force envelope that can be transferred to a more complex mechanism.

**Keywords:** origami; kirigami; flexure hinge; deployment; fatigue; photopolymer

## 1. Qualification problem: origami and kirigami hinges

The scope of origami and kirigami hinges is set by the decisions that must remain valid after printing and testing. The review addresses minimum hinge radius/thickness for required life, acceptable deployment-force envelope, and single-material versus multimaterial hinge architecture; regime changes are tracked by hinge-thickness to panel-thickness ratio, normalised fold radius, and elastic energy per hinge. [6]

### 1.1 Scope boundary.

ER-370 owns folding-structure response, including hinge mechanics, folding path, damage and deployment repeatability. ER-364 owns snap-through stability, ER-365 impact lattices, and ER-369 pneumatic networks; they are referenced only where bistability, impact or actuation couples to folding.

## 2. Governing balances for origami and kirigami hinges

Folding and deployment are reduced to relations for hinge geometry, fold radius, and stored elastic energy.

*fold kinematics define admissible configurations while hinge stiffness defines the force path between them*

*flexural strain scales with hinge thickness, radius and rotation, concentrating damage in intentionally compliant regions*

*self-contact and collision impose geometric constraints not captured by ideal crease models*

These measures keep hinge design, geometric self-contact, and accumulated elastic damage as separate controls on deployment.

## 3. Regime boundaries for origami and kirigami hinges

For origami and kirigami hinges, the table directs testing toward hinge life, deployment force, or material architecture as conditions change.

Table 1. Regime indicators for folding-structure response.

| Indicator                                | Engineering meaning                                   | Use                                                                                                                                                                                                                          |
|------------------------------------------|-------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| hinge-thickness to panel-thickness ratio | hinge thickness relative to panel thickness           | State 'minimum hinge radius/thickness for required life' together with its tested range of hinge-thickness to panel-thickness ratio; that range is the defensible boundary for hinge thickness relative to panel thickness.  |
| normalised fold radius                   | fold radius expressed on the local geometric scale    | State 'acceptable deployment-force envelope' together with its tested range of normalised fold radius; that range is the defensible boundary for fold radius expressed on the local geometric scale.                         |
| elastic energy per hinge                 | hinge elastic energy relative to panel-bending energy | State 'single-material versus multimaterial hinge architecture' together with its tested range of elastic energy per hinge; that range is the defensible boundary for hinge elastic energy relative to panel-bending energy. |

Deployment qualification remains confined to the hinge geometry, radius, and energy regime represented by the evidence set.

## 4. Couplings that move the origami and kirigami hinges

Build orientation changes hinge fatigue and panel anisotropy. [6]

Multimaterial hinges decouple panel stiffness from fold compliance but add interface risk. [1,4]

Viscoelastic relaxation changes deployment force and final angle.

## 5. Failure signatures and false diagnoses

The engineering fault tree starts with hinge cracking, then tests alternatives panel warpage that blocks folding path and self-collision or jamming. Evidence from fold angle versus moment or actuation input, DIC/curvature at hinges and cycle-to-cycle residual angle determines which branch survives the diagnostic challenge. The four Table 2 rows form a falsification sequence: each candidate mechanism must survive the interventions that are not used to support it.

Table 2. Failure-mode discrimination for folding-structure response.

| Failure mode                                   | Observable signature                        | Discriminating evidence                           |
|------------------------------------------------|---------------------------------------------|---------------------------------------------------|
| hinge cracking                                 | fold angle versus moment or actuation input | single-hinge coupons before full mechanisms       |
| panel warpage that blocks folding path         | DIC/curvature at hinges                     | fold-rate and dwell-time sweeps                   |
| self-collision or jamming                      | cycle-to-cycle residual angle               | build-orientation comparison                      |
| deployment-force drift and incomplete recovery | micro-CT or microscopy of hinge damage      | full deployment cycling with collision monitoring |

## 6. Measuring origami and kirigami hinges with traceable uncertainty

The uncertainty model retains three separate Table 2 measurement channels and carries each contribution forward to the relevant acceptance boundary. The origami and kirigami hinges workflow deliberately separates an uncertainty-controlled perturbation of flexural strain from independent resolution of fold kinematics and hinge stiffness; this avoids fitting the challenge into the quantity being qualified; during metrology of origami and kirigami hinges, flexural strain is resolved against self-contact. Separate monitoring of self-contact is then examined on its own terms before any transfer statement is retained; the uncertainty record for origami and kirigami hinges keeps self-contact separate from fold kinematics.

## 7. Experiments that discriminate competing mechanisms

Experimental evidence is read across the four Table 2 rows as a pattern of expected and absent responses rather than as four unrelated pass/fail tests. For origami and kirigami hinges, the evidence chain starts with a causal contrast between fold kinematics and flexural strain; during the causal challenge for origami and kirigami hinges, self-contact is tested against fold kinematics. It then adds a boundary challenge involving hinge stiffness, while a replicate test of self-contact is retained as a separate control so the three sources of information cannot compensate silently; the experiment for origami and kirigami hinges separates fold kinematics from hinge stiffness.

## 8. Model identification and validation for origami and kirigami hinges

Fitting, prediction and identifiability use three different Table 2 branches. That partition is maintained when uncertainty is propagated to the qualification envelope. [2] [3,5] Uncertainty is resolved at the level of the individual Table 3 decisions, which is where qualification is granted or refused. The working sequence for origami and kirigami hinges has three parts: parameter estimation for fold kinematics and hinge stiffness; prediction against flexural strain; and an uncertainty-bounded check on self-contact; within model identification for origami and kirigami hinges, fold kinematics is not fitted through hinge stiffness. Each part answers a different engineering question, so uncertainty or failure in one part is not repaired by a favourable result in another; prediction for origami and kirigami hinges keeps hinge stiffness independent of flexural strain.

## 9. Qualification envelope and technology decisions

Table 3. Technology-decision matrix for folding-structure response.

| Decision                                              | Minimum evidence                                                                                                                                                                                                                                 | Acceptance logic                                                                                                                                                                                            |
|-------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| minimum hinge radius/thickness for required life      | The evidence set for minimum hinge radius/thickness for required life should contain calibrated fold angle versus moment or actuation input measurements from baseline through the proposed limit, with independent replication near that limit. | The qualified decision holds when 'single-hinge coupons before full mechanisms' does not move fold angle versus moment or actuation input beyond the measured boundary and does not trigger hinge cracking. |
| acceptable deployment-force envelope                  | Evidence must include calibrated DIC/curvature at hinges in reference and candidate states, with replicate measurements that resolve the margin for acceptable deployment-force envelope.                                                        | The claim passes when the response to 'fold-rate and dwell-time sweeps' is reproducible in DIC/curvature at hinges and panel warpage that blocks folding path remains absent at the decision boundary.      |
| single-material versus multimerial hinge architecture | Demonstrate single-material versus multimerial hinge architecture using paired cycle-to-cycle residual angle records from the baseline and transfer cases, together with an uncertainty estimate and repeat series.                              | Acceptance requires agreement of repeated cycle-to-cycle residual angle measurements after 'build-orientation comparison' and no onset of self-collision or jamming across the qualified states.            |

Three independent checks structure the origami and kirigami hinges assessment; inside the origami and kirigami hinges envelope, hinge stiffness and flexural strain define different transfer limits. Tested ranges in fold kinematics and hinge stiffness establishes the primary state, an explicit transfer limit on self-contact tests whether that state survives transfer, and a separate boundary for flexural strain is the perturbation used when the two disagree; qualification of origami and kirigami hinges bounds flexural strain separately from self-contact.

## 10. Design consequences for origami and kirigami hinges

Final design control records the three Table 3 limits independently and links each one to its own evidence route. A practical consequence of the model is to modify a design change governed by fold kinematics under the constraint imposed by an implementation check on flexural strain, while acceptable deployment-force envelope is controlled independently; a requalification trigger tied to self-contact defines when fresh evidence is required; during design implementation for origami and kirigami hinges, flexural strain is constrained by self-contact. This makes the design consequence testable and prevents transfer by undocumented compensation; the origami and kirigami hinges design record separates self-contact from fold kinematics.

## 11. Evidence gaps for origami and kirigami hinges

The unresolved question is how far the three Table 2 diagnostics can be transferred together. Future work should therefore expand state coverage without dropping any one of the independent channels. Rather than reduce origami and kirigami hinges to one surrogate, the analysis combines independent replication of self-contact with scale transfer of fold kinematics; for unresolved origami and kirigami hinges transfer, self-contact is studied separately from fold kinematics. A separate uncertainty in hinge stiffness versus flexural strain is used to challenge that interpretation, making disagreement between the two routes visible instead of averaging it away; the evidence gap in origami and kirigami hinges distinguishes fold kinematics from hinge stiffness.

## 12. Qualification outcome for origami and kirigami hinges

No universal transfer is claimed. Qualification is restricted to the joint domain demonstrated by the three Table 3 decisions. An acceptable record for origami and kirigami hinges must show a renewed-evidence trigger when self-contact changes without inferring it from agreement between measurement and prediction for fold kinematics; at final qualification of origami and kirigami hinges, fold kinematics is reconciled with hinge stiffness. In parallel, causal evidence that separates hinge stiffness from flexural strain probes the boundary condition most likely to change the interpretation, and the resulting uncertainty is carried forward explicitly; the closing origami and kirigami hinges claim keeps hinge stiffness distinct from flexural strain.

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## Competing interests

The author is Founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L. No comparative product recommendation is made.

## Data availability

No new experimental dataset was generated for this review.