

Superimposed Curved-Crease Origami with Multiple States

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keywords: curved-crease origami, elastica surface, superimposed creases

Abstract

The majority of origami-inspired engineering applications seek to utilise a single sheet to achieve multiple design objectives. In the simplest and most typical case, the two design objectives arise naturally in a single degree-of-freedom (DOF) crease pattern: the deployed (folded) state and packaged (unfolded or flat-folded) state. Methods for design of crease patterns capable of achieving more than two design states have been proposed, for example with multi-DOF or universal crease patterns. Either of these approaches allow for a sheet to achieve a huge number of folded configurations and design objectives, but encounter substantial complexity in practice. An alternative approach has recently been proposed in which multi-state patterns are generated by superimposing multiple 1DOF patterns within a single sheet with preserved kinematic independence. Transition between states occurs via the unfolded configuration.

Regardless of approach, multi-state origami design methods have only been developed for rigid-foldable origami. Curved-crease origami is a different class of geometries which possess a non-zero principal curvature when folded. This is a highly desirable performance attribute for many origami-inspired applications, for example adaptive structures and compliant mechanisms, but these benefits could be extended further with the ability to design multi-state curved-crease origami. This paper seeks to explore whether the multiple state superposition method, previously developed for rigid-foldable origami, remains valid for curved-crease origami.

Ten curved-crease prototypes were constructed with two superimposed states: a constant primary pattern and varied secondary patterns. 3D scanning and subsequent surface error analysis was conducted for the ten different superimposed patterns. The recently-proposed elastica surface generation method is used for prototype design and this is shown to be an accurate analytical model for curved-crease origami, with a scanned primary reference surface shown to be accurate within half of the 2mm sheet thickness. Analysis shows the primary and secondary patterns to interact in a range of different ways, including complete distortion, partial distortion, or no distortion, i.e. fully-preserved kinematic independence. A framework is presented to predict in which cases distortion or independence could be expected to occur, based on the inclination between the tangential gradient of the secondary pattern and notional straight-line rulings on the primary pattern. This framework is used to design two multi-state curved-crease origami with extended dual-state functionality: the first with an introduced flat-foldable configuration and the second with a transformation between curved folded states.

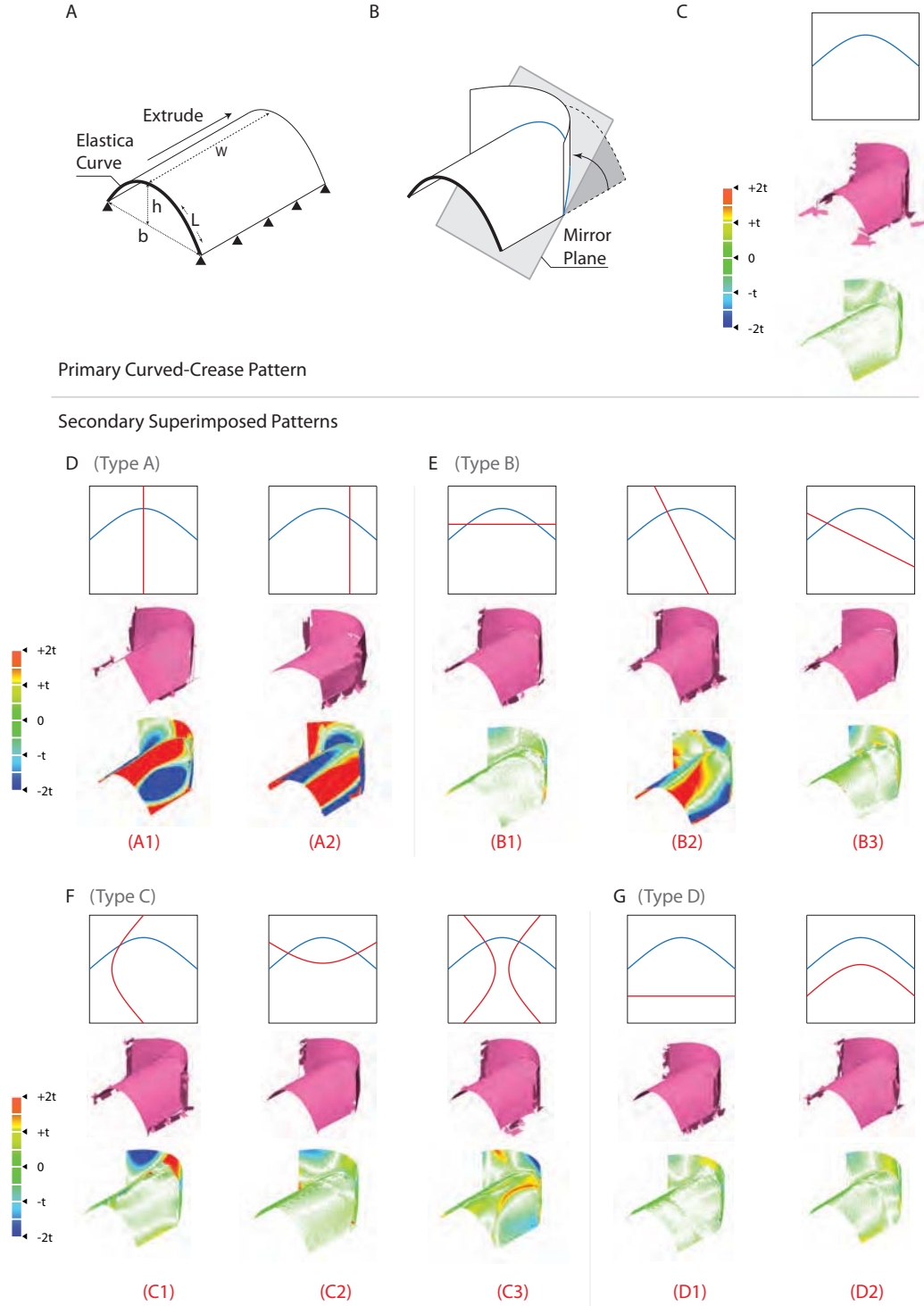


Figure 1: Experimental result of multi-state curved-crease origami. For primary curved-crease pattern: (A) Extruded elastica curve demonstrates the deformed 3D shell, and (B) intersecting cutting plane for mirror reflects folded curved-crease component. (C) Surface error measurement result illustration. The secondary patterns, are divided into four sub-categories: Straight-line patterns (D) perpendicular and (E) non-perpendicular to the elastica construction plane. (F) Curved-crease patterns. (G) Patterns without intersection to the primary pattern. From (C)-(G), each sub-figure includes planar pattern design, scanned mesh, and elastica surface comparison.