

Folding Fabrication of Curved-Crease Origami Spindle Beams

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Abstract

Curved-crease origami have been utilised as the basis for development of numerous engineering applications, including as thin-walled beams, sandwich panels, and facades. The manufacturing methods utilised for these are correspondingly diverse, however, the accuracy of these methods is largely unknown and quantification of manufacturing error is not straightforward. Curved-crease origami possesses component panels that deform during folding, yet consideration of material deformation behaviours during manufacture is often excluded from the geometric design process.

This paper presents two folding manufacturing methods for accurate and reliable manufacture of curved-crease thin-walled structures. The specific geometry considered is a ‘spindle’ geometry, which is a closed and symmetric curved-crease origami form generated using the elastica extrusion method. The spindle is well-suited for application as a thin-walled structural element. It tapers from a large depth at mid-span to a small depth at each end and thus possesses a non-uniform structural capacity akin to the non-uniform bending moment distribution of a simply-supported beam under point or uniform distributed loading conditions.

Manufacturing methods are developed for two disparate structural sheet materials: typical structural steel and a novel hybrid fibre-reinforced polymer timber (FRP-timber) material. Steel spindle beams are made with a computer numerical control (CNC) manufacturing technique in which curved ‘slits’ are CNC-cut into the sheet metal along a notional geometric fold line. Adjacent panels remain connected with ‘straps’ of material, which can plastically deform at a low load so as to allow the steel spindle to be folded manually. Hybrid FRP-timber spindles are folded using a cured-in-place manufacturing process which utilises a differential curing time between two types of resins impregnated a glass-fibre sheet. A 24-hour slow-cure resin is used on crease lines and a 3-hour fast-cure resin is used on panel regions. The 2D sheet is folded into a 3D section between the fast-cure and slow-cure periods, when panel regions are rigid while hinge regions remain flexible.

The manufacturing quality of both methods has been verified through 3D scanning and surface error analysis. This showed both methods to be accurate to within $\pm 50\%$ of plate thickness for a range of curved-crease spindle configurations, which is in conformance with requirements for acceptable surface imperfections in thin-walled structures.

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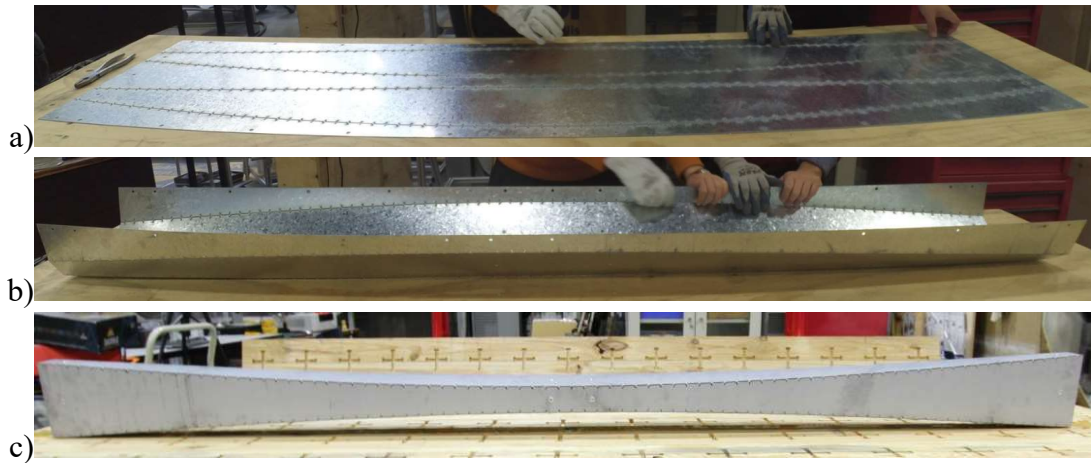


Figure 1: Steel spindle beam manufacturing process. a) CNC-cut unfolded steel sheet. b) Partially-folded sheet. c) Folded prototype.

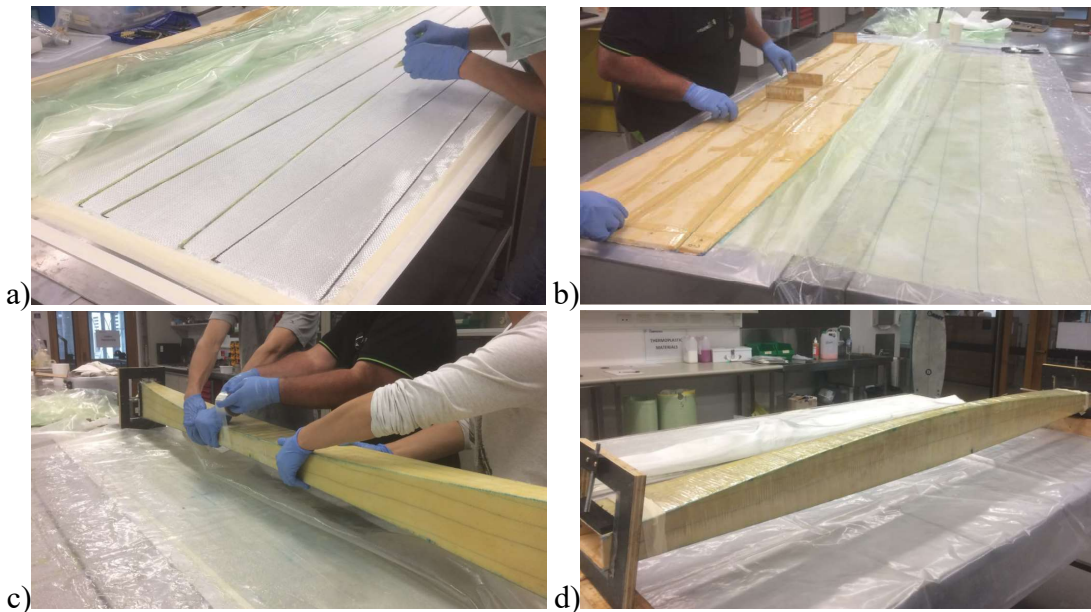


Figure 2: FRP-timber spindle beam manufacturing process. a) Application of slow-cure resin to crease lines. b) Application of fast-cure resin to plywood and non-crease regions. c) Folding and wrapping with the use of clamps and shrink tapes. d) Folded prototype.

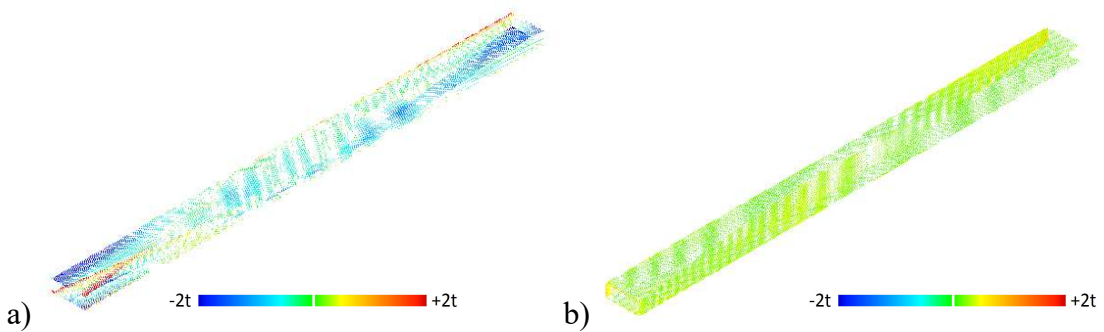


Figure 3: Manufacturing defect analysis. a) Surface error of steel spindle beam with $t=1.0\text{mm}$. b) Surface error of FRP-timber spindle beam with $t=7.2\text{mm}$.