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Design and digital fabrication of folded sandwich structures

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ABSTRACT

This paper presents a design-to-fabrication process for folded sandwich structures that comprises surface to pattern conversion, manufacture rationalisation, and integral connection superposition. Folded sandwich structures are shown to possess a tessellated, origami-like structural form in which building component parameters are inherently dependant upon building surface parameters. Structural forms can therefore be designed with a minimum number of unique parts and with simultaneous consideration of surface and component constraints. The design-to-fabrication process is demonstrated for the Plate House, a cardboard shelter designed to meet transitional shelter packaged and deployed volume requirements. Additional prototypes are presented to demonstrate an extended set of parametric edge connection details for the production of cardboard, plywood, or steel folded sandwich structures. Prototypes are also presented to demonstrate how the method can be applied generally for the digital fabrication of developable 3D surfaces with a known crease pattern.

1. Introduction

1.1. Generative design and digital fabrication

Generative architectural design is the ability to create “geometrically complex shapes from few basic shapes and rules” [1]. Generative systems therefore utilise shape grammars consisting of shape rules and a generative assembler [2]. More complex systems add parametric formulations [3] which allow for greater control of constituent shapes or the inclusion of optimisation processes for performance-based design drivers [4]. Digital fabrication refers to technologies that can manufacture building components from automated workshop machines, for example CNC routers or laser-cutters [5]. Generative design can be used in concert with digital fabrication to enable rapid construction of customised physical models [1,6]. However an intermediate translation step is required, defined as a *construction grammar* [7].

Using nomenclature from [8], a building *element* is defined as a fabricated component and a building *surface* is the final assembly of combined elements. A construction grammar is required to translate a surface into manufacturable elements. For example, to generate a traditional clad-frame structure, an input surface definition could include length, width, and height. An output element definition could include material type; joist/stud length, spacing, and section sizes; and fastener specifications and locations. With the exception of element length, there is complete independence between surface and element parameters and so a construction grammar must include many complex process definitions to generate necessary and manufacturable elements.

Integral attachments are mechanical jointing systems that can be CNC-fabricated into building elements [9]. Their use allows for the elimination of many fastener components, for example nails or adhesives, and thus can drastically streamline construction grammars and increase the feasibility of digital construction methods [8]. The “Instant House” for example is a plywood house assembled in 4 days from 984 CNC-manufactured plywood elements with integral attachments [10]. Similarly, “A House for New Orleans” consisted of 5000 elements and a 23-day assembly time, and additionally included integral ornamentations in the style of a New Orleans shotgun house [11]. Compared to legacy construction methods, digital construction methods also provide opportunities for value-added activities through geometric-based performance improvements, for example to structural or thermal behaviours [12].

1.2. Origami-inspired structures

Origami-inspired designs have recently been seen across a wide variety of engineering disciplines, including aeronautics [13], aerospace [14], automobile [15], impact [16], biomedical [17], robotics [18], subsea [19], manufacturing [20,21], and materials [22,23] engineering disciplines. In architecture and structural engineering, single-layer folded plate structures have long been proposed [24]. Many new deployable and structural forms have been developed based on tessellated rigid origami patterns [25,26,27]. Tessellation origami are patterns assembled from a repeated unit geometry [28] and rigid origami are patterns

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which have rigid panels that can fold about hinge lines without deformation [29]. The Miura-ori pattern [30] and its derivative geometries are the most commonly-used rigid origami patterns as they are developable [31], encompass a range of folded envelope curvatures [32], and can consist of a single repeated plate size. Numerous additional tessellated folded pattern families have been developed which are similarly able to form surface shapes with known curvature types, for example the sponge, cube, and eggbox families [33,34], curved-crease families [35,36], Resch and Huffman families [37,38], and design methods for generation of new families from some base module [39,28,40].

Most single-layer folded structures rely on load transfer through folded plate edges and so suffer from stress concentrations and poor mechanical performance. More efficient origami-inspired structures have been suggested, including designs that fold into frame or multi-layer sandwich forms [41,42,43]. These latter structures are termed *folded sandwich structures* and are based on folded core sandwich panels developed for aerospace applications [13,44,45]. However they differ in that faceted face sheets are attached to a folded core layer, allowing large-scale, curved sandwich forms to be assembled entirely from flat sheet stock.

1.3. Folded sandwich structures

Folded sandwich structures are simply designed by attaching faceted inner and outer sheets to a folded core sheet, Fig. 1(a). The core sheet is an idealised rigid origami pattern, with zero-thickness, rigid panels. There are numerous methods to parametrise such patterns and this paper shall adopt that developed by the authors in [32], where a finite number of independent parameters are defined to specify a unique pattern configuration. These parameters may include crease pattern (unfolded), angular, or volumetric (folded) parameters. Face sheet side length parameters can be determined as functions of these core parameters [43]. For example, the pattern shown in Fig. 1(a) uses a Miura pattern core that can be uniquely defined with six parameters. The structures shown in Fig. 1(b)–(c) use Arc-Miura and Non-Developable Miura core patterns, respectively, which each require seven independent parameters to define.

In the current paper we present a new process that combines the folded sandwich structural form with a parametric edge connection library. This enables the design and digital fabrication of a variety of folded plate structures without requiring a complex surface-element translation process. Section 2 first presents the new process, which includes surface to pattern conversion, manufacture rationalisation, and integral connection superposition. Section 3 demonstrates the process with the Plate House, a cardboard transitional shelter design to meet Shelter Centre guidelines. Section 4 shows variations in material, assembly types, and surface curvatures possible within the proposed translation method. Finally, Section 5 concludes the paper.

2. Folded sandwich construction grammar

The following section describes a new process that enables the translation of a surface to manufacturable folded sandwich elements. The folded sandwich structural form possesses a tessellated unit geometry and an inherent geometric dependency between folded and unfolded plate geometry. If used for a surface-element translation process, these features would provide two major advantages over existing translation processes. First, the tessellated unit can be harnessed to minimise the number of unique component sizes that need be designed. Second, the geometric dependency means that a surface definition provided by a designer will already constrain most of the necessary element parameter definitions. The translation process itself is therefore much simplified as it only needs to evaluate remaining element parameters and connection details, which can be done with consideration of

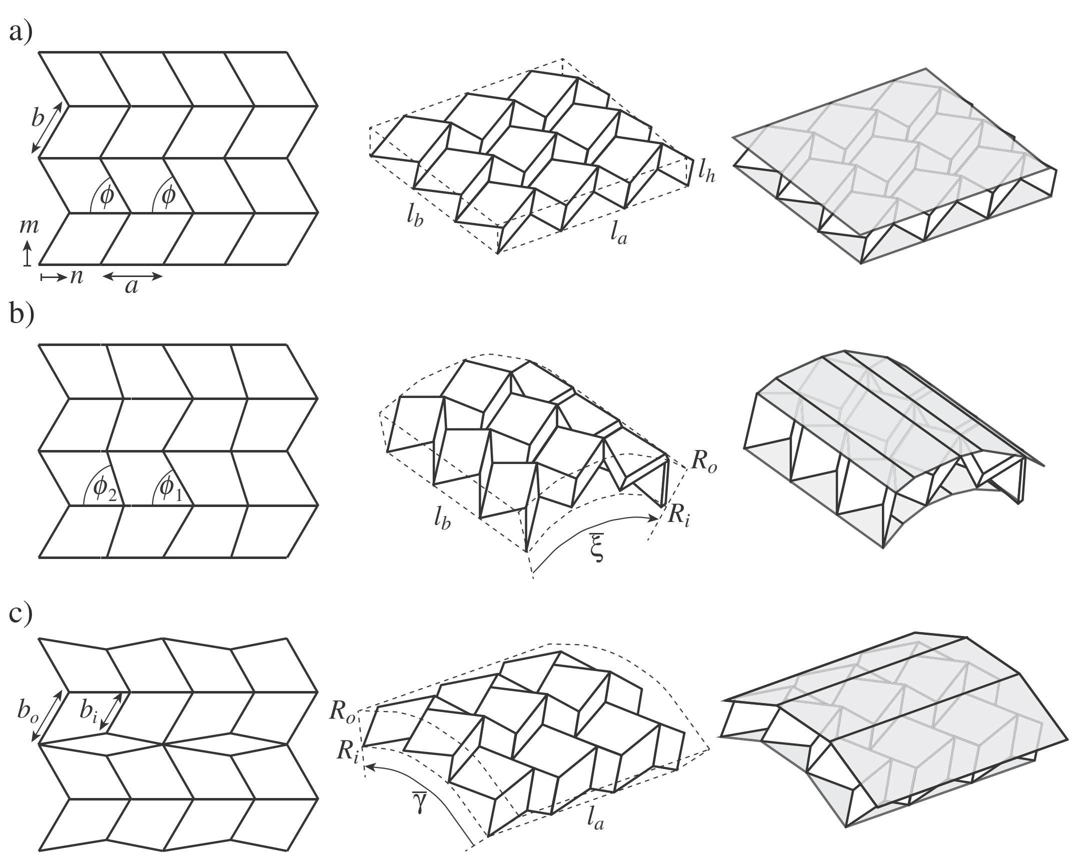

Fig. 1. Folded sandwich structures. From left to right: unfolded pattern parameters, folded pattern parameters, assembled structure with attached faceted face sheets. Core patterns from top to bottom: a) Miura pattern, b) Arc-Miura pattern, c) Non-Developable Miura pattern.