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Folded assembly methods for thin-walled steel structures

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ABSTRACT

There has been significant recent interest in origami-inspired foldable structures for applications in which transportability and rapid construction are primary design drivers, for example, emergency shelters and staging structures. However, widespread application is not yet seen due to complexities in folded geometry and modelling the structural behaviour of folded sheet material. This paper proposes a fundamentally new approach whereby folded assembly methods are developed for conventional thin-walled steel construction and benchmarked in terms of their assembly effort, manufacturing accuracy, and structural performance. Manufacturing accuracy was benchmarked with 3D digital image correlation and 3D scanning and showed a folded assembly method to be accurate to within ±50% of plate thickness with assembly by unskilled persons. Structural performance under uniaxial compressive load was assessed with experimental and numerical analyses, with consistent predictions showing that conventional thin-walled steel analysis techniques are sufficient to model folded structure behaviours. Modelling of the novel folded steel structures is therefore also shown to avoid much of the complexity normally encountered in folded structure analysis, such as characterisation of fold-line rotational stiffness or folding plasticity behaviours.

1. Introduction

1.1. Origami inspired structures

Origami-inspired design techniques have seen much recent technological development due to their potential for delivering a relatively large structure in a compact package. They are thus useful when transportation capacity is a driving design concern with famous examples including solar power arrays [1], a space telescope [2], and biomedical devices [3]. Recent examples in civil engineering include transportable shelters [4], bridges [5], and prefabricated modular structures [6].

A second major benefit of origami-inspired design is its capability to achieve a significant increase in stiffness at minimal expense of weight. This has been utilised for example in military shelters, in which the folds can provide structural stiffness when deployed [7,8] but also facilitate packaging into a smaller volume for transportation or storage [9,10]. High-stiffness folded core sandwich constructions, which consist of two outer faces attached to an origami core, have also been developed as lightweight or morphing building components [11,12] and impact-resistant or isotropic sandwich panels [13,14].

Most of the above structural applications utilise shell forms developed from a known origami pattern. This requires advanced geometric design methods [15–17] and structural analysis methods. Characterising the rotational stiffness of fold lines has been shown to be critical for accurately modelling the structural behaviour of most origami-inspired or folded structures [18,19]. Despite extensive research into the creasing mechanism of common folded sheet materials, including paper [20,21], paperboard [22–24], Mylar sheets [25], and steel [26], understanding of this phenomenon is still limited. Development of engineering analysis methods and widespread applications for folded structures have therefore also been limited.

1.2. Folded sheet metal fabrication

Folded sheet metal fabrication is widely applied in automotive, manufacturing, and building industries. The bending brake and press are typically used to form a bend line along the sheet metal [27], however considerable force is required. Additionally, the bending tolerance, accumulation of errors, and geometric constraints from the bending machine mean that traditional sheet metal bending processes are difficult to apply for origami-inspired designs, particular as small eccentricities in fold-line location can significantly alter sheet mechanics [28].

Industrial Origami has proposed a precise sheet metal folding method based on a notional geometric fold line composed of curved

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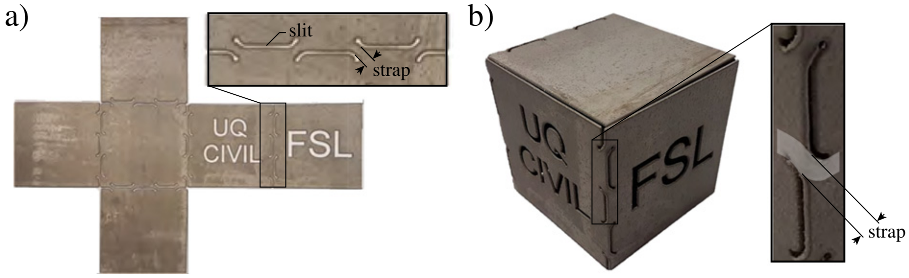

Fig. 1. Sheet-metal bending technique with slits and straps along fold lines. a) Unfolded and b) folded configurations.

slits [29], shown in Fig. 1. Adjacent edges are connected by the area between slits, termed 'straps', which are torqued during folding and thus achieve a much reduced bending force [30,31]. The slits have additional structural benefits including a reduction in stress concentrations at the curved slit ends and 'edge to face' engagement during the bending process, with the twisted strap acting to pull together adjacent surfaces [32]. Faces are therefore able to transfer shear forces directly across folded edges. Slits can be precisely placed in a sheet with computer numerical control (CNC) manufacturing processes for high-accuracy part production. The combination of CNC fabrication methods with folded geometries has also previously been shown to be a cost-efficient means for production of modular structures [33].

This paper investigates manufacturing, assembly, and analysis methods for thin-walled steel structures developed through the combination of sheet metal bending techniques and folded structural geometry. Section 2 describes the geometric design and assembly method of the new steel prototypes, manufactured with waterjet-cut fold line and edge connection details. Analysis of prototype surface imperfections is conducted in Section 3 for quantification of the accuracy of the fabrication method. Section 4 presents an experimental study of prototype structural performance under uniaxial compressive loads, followed by comparative numerical analyses in Section 5. A discussion of results and effects of fold-line behaviours are given in Section 6.

2. Folded assembly methods

2.1. Geometry

For investigation of folded assembly techniques, a foldable variant of a conventional thin-walled steel structure is first developed. The proposed structure is a triangular hollow section with patterned windows that form integral internal bracing, shown in Fig. 2a. This module is selected as it is hypothesised to have a simple compression behaviour similar to a typical triangle truss, that is with compressive loads carried by angle sections that run continuously along the element axis and with an effective compressive length as set by hexagonal plate bracing, shown in Fig. 2b. Structural members with openings [34,35] or high-strength fabricated square and triangular sections [36] are also well-understood, should complexities be encountered due to hexagonal openings or fold-induced residual stress, respectively.

There are two further benefits to the geometry. First, the unfolded model forms a rectangular sheet and so can be sized to fit typical metal sheet stock with minimal waste off-cuts. Second, in comparison with typical origami-inspired foldable structures, this geometry can be specified with a small number of uncoupled parameters as shown in Fig. 3. Wall plates are specified with axial length L and side length W. Hexagonal plates must meet at all three wall plates and so hexagonal plate side length is dependant and equal to $W_H = \frac{W}{3}$.

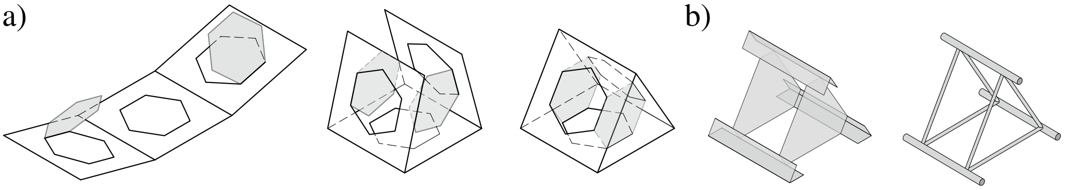

Fig. 2. a) Proposed folded module and b) hypothesised load-carrying model with analogous triangle truss model.

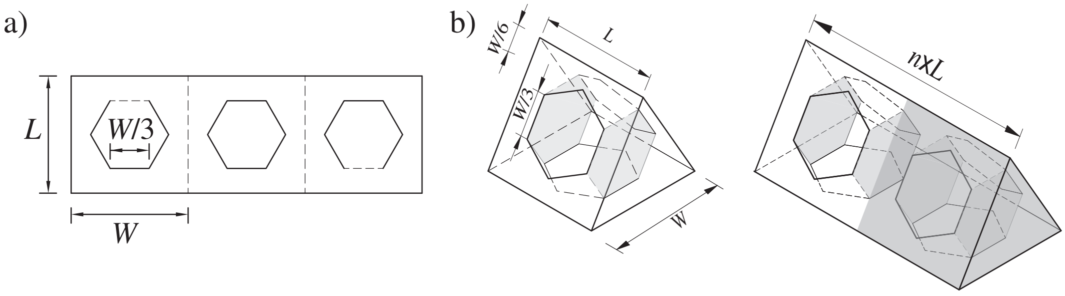

Fig. 3. Parameters of the module. a) Unfolded and b) folded and tessellated geometries.