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An equivalent model of corrugated panels with axial and bending coupling

Chen Wang [*], Hamed Haddad Khodaparast, Michael Ian Friswell, Alexander David Shaw

College of Engineering, Swansea University, United Kingdom

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ABSTRACT

In this paper, modification of an existing equivalent model of the corrugated panel is investigated. The axial and bending coupling of the corrugated panel supplements the previous equivalent properties when the corrugated panel has a fixed boundary condition. The analytical expressions of the coupling vertical deflections are obtained and verified by the finite element method. A method to eliminate the vertical deflection is proposed, and the importance of the coupling effect is demonstrated by the application of the modified model in a compliant structure.

1. Introduction

Corrugated panels are made of plate with periodic profiles and are often used as cores in sandwich structures. Although the finite element method can be used to evaluate the stiffness of the corrugated structures, the detailed modelling of the profiles will lead to a high computational cost, which motivates the study of equivalent models [1–3].

In recent years the study of morphing aircraft becomes another motivation of the research into corrugated structures [4–6]. The low axial stiffness of the corrugated structure allows for a large deformation with limited actuation force while the high anisotropy of the corrugated structure still provides a large out-of-plane stiffness to carry aerodynamic loads.

The study of equivalent models of corrugated panels plays a significant role in research and applications. Yokozeki et al. [4] developed the analytical solution of the equivalent axial and transverse tensile and flexural modulii with the round corrugation. The analytical solution provided a reasonable accuracy compared to the experimental results. Samanta and Mukhopadhyay [7] derived analytical solutions of the axial and transverse equivalent modulii of the trapezoidal corrugated panel. The experimental investigation of Thill et al. [8] showed a three-stage stress-strain relationship of the trapezoidal corrugated panel, in which the first linear stage had a relatively good agreement with the analytical solution modified from [7]. Xia et al. [9] developed a more complete approach of the corrugated panel, which gives the equivalent model of round and trapezoidal corrugations. The method provides the closed forms of the six effective components in the stiffness matrix of the equivalent orthotropic plate. Comparisons to other analytical results and the finite element method have shown the accuracy of the equivalent model. In this method, the equivalent orthotropic plate is a classical Kirchhoff plate, which does not consider the transverse shear. A recent publication from Mohammadi et al. [10] derived the transverse shear modulus, which few researchers have studied. The equivalent models of corrugated cores with elastomeric coatings were also derived by Dayyani et al. [11].

Although the equivalent properties of the corrugated panel have been studied extensively, this paper investigates another aspect, namely the axial and bending coupling when the corrugated panel has a fixed boundary condition, to which little attention has been paid in the literature. The corrugated panel will have a vertical deflection caused by the pure extension load when it has a fixed boundary condition. If the corrugated panel has a pinned boundary condition, no vertical deflection will occur. This deflection-extension coupling effect could be negligible in some cases. But it can also have significant influence on the entire structure, especially for the morphing applications where the corrugated structures are often required to have a relatively large deformation. For example, if the corrugated structure is used as the morphing skin, the tendency of the out-of-plane deflection could change the wing shape or increase the actuation energy. The current investigation can also provide guidelines for installing the corrugated panels in real-world applications. In the previous

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[*] Corresponding author.
E-mail address: 804685@swansea.ac.uk (C. Wang).

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references, the symmetry of the structure is usually applied and only half [7] or quarter [4,10] of the corrugation unit is analysed. The fixed boundary condition is applied to calculate the strain energy and internal moment. For the homogeneous method [9] the boundary condition will not affect the equivalent properties of the entire structure since the boundary conditions are constrained when calculating the strain energy.

In this paper, with the fixed boundary condition, vertical deflections under pure extension load will be analysed together with axial deflections. The axial deflections are applied to calculate the equivalent axial modulii, which are compared to those from the existing models. The coupling effect can be represented as an effect of the boundary condition if the entire corrugated panel is separated into two segments. As a supplement to the previous equivalent model, a modification to the equivalent model proposed in Ref. [9] is made by introducing a coupling component. After representing this deflection, the influence of considering this coupling effect is shown on its potential application to a compliant structure. The method to eliminate this coupling is also proposed by using an offset boundary condition.

2. Deflections caused by extension loads

Fig. 1 shows the shape of the trapezoidal and round corrugation panels, which are the subject of this study. As a periodic structure in the *xz* plane, the entire shape and size of a corrugated structure is determined by the shape of a basic single unit and the number of units.

Fig. 2 shows the unit geometry and the internal bending moment for the corrugated shapes. The corrugation unit is fixed at one end and under extension load *T* at the other end. As shown in the figure, the trapezoidal unit consists of the straight beams *AB*, *BC*, *CD*, *DE*, *EF* and *FG*, and the round unit is made of straight beams *AB*, *CD*, *EF* and curved beams *BC*, *DE*.

The deflection of each separate beam is calculated using classical mechanics and Castigliano's second theorem. The deflection of the unit corrugation is then calculated by accumulating the local deflections of the beams and considering the rigid translation caused by the rotation angles of the beam cross sections. Fig. 3 shows the schematic of the deflection components. For a beam with the inclined angle θ, the deflection of the beam *p*, which is

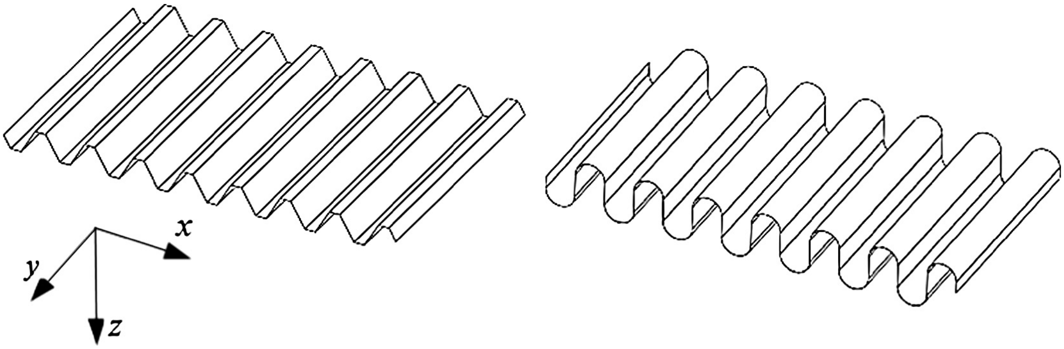

Fig. 1. (a): trapezoidal corrugation panel, (b): round corrugation panel.

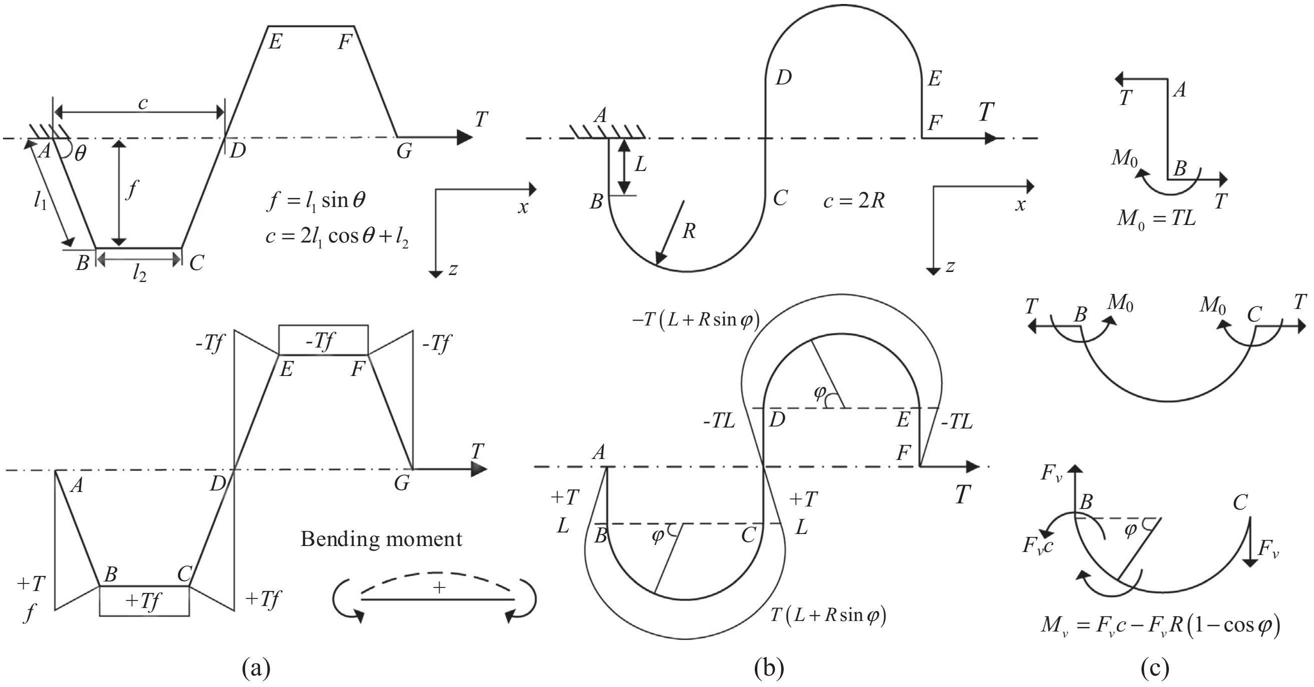

Fig. 2. Geometry and bending moment in the corrugation unit: (a): trapezoidal, (b): round, (c): separate beams in the round unit.