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Torsional and flexural buckling of composite FRP columns with cruciform sections considering local instabilities

H.R. Naderian [a], H.R. Ronagh [b,*], M. Azhari [c]

[a] Department of Civil Engineering, Yazd University, Yazd, Iran
[b] School of Civil Engineering, University of Queensland, Brisbane Qld 4072, Australia
[c] Department of Civil Engineering, Isfahan University of Technology, Isfahan, Iran

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ABSTRACT

In this paper, a semi-analytical finite strip method is developed for the prediction of torsional and flexural buckling stresses of composite FRP columns under pure compression. Numerical finite strip results will be compared with those obtained from closed-form equations for doubly symmetric open thin-walled FRP sections. The accuracy of the proposed finite strip method in determining critical flexural and torsional stresses of FRP columns will be assessed. Among the composite FRP columns with doubly symmetric open sections, buckling behavior of stiffened and unstiffened FRP cruciform sections will be evaluated and case studies performed. The effect of material properties and longitudinal stiffeners applied at the end of the web-plate and flange-plate on buckling modes of composite FRP cruciform sections is also reviewed.

1. Introduction

Among the thin-walled sections made from orthotropic materials, FRP profiles are known to many engineers and researchers and are more popular. These members have wide applications in different industries, including aero structures, civil engineering, mechanical engineering, and the construction industry. There exists a growing demand for composite FRP structural members, which is owing to a combination of their structural efficiency, low fabrication costs and excellent behavior under aggressive environmental conditions. A large percentage of research in the field of orthotropic plate-structures is devoted to FRP sections. The mechanical properties of FRP sections clearly indicate that their behavior is strongly affected by instability phenomena. In fact, composite FRP members can be classified as thin-walled structures. Hence, it is necessary to investigate the buckling behavior of FRP sections in different boundary, dimension and loading conditions in order to achieve more accurate recognition of these structural members as well as optimum designs.

In recent years, special attention has been paid to buckling of FRP sections. There exists a considerable amount of research work, both analytical and experimental, concerning the local and global buckling of thin-walled composite FRP members. Among these studies, research carried out by Pecce and Cosenza [1] on local buckling of FRP sections should be mentioned. Additionally, Qiao and colleagues have presented research about local buckling of FRP sections in different boundary and loading conditions [2–4]. They also succeeded in developing analytical solutions in the field of flexural–torsional buckling of composite FRP members made of I and U sections [5,6]. Silvestre and Camotim extended GBT method to analyze the local-plate, distortional and mixed flexural-distortional buckling modes of FRP-lipped channel members [7].

Among the various sections made from FRP, open sections have more applications. On the other hand, torsional buckling is usually critical for open thin-walled section columns due to their low torsion–rigidity. Torsional buckling, generally, occurs under compressive loads, where the section of column twists on the rigid torsion. In fact, if the amount of torsion is too large, torsional instability will dominate. Displacements derived from torsional buckling are in-plane, and for the same reason, this buckling mode is regarded as a global mode.

In this study, a semi-analytical finite strip method will be developed to analyze the torsional and flexural buckling of composite FRP columns. In conjunction with FSM, closed-form equations are used to study the torsional and flexural buckling behavior of composite FRP sections under pure compression stresses. The finite strip method can be considered as a special form of finite element procedure using the displacement approach. Unlike the standard finite element method which uses polynomial displacement functions in all directions, the finite strip method calls for use of simple polynomials in some directions and continuously differentiable smooth series in the other directions, with the stipulation that such

* Corresponding author. Tel.: +61 7 336 59117; fax: +61 7 336 54599.
E-mail address: h.ronagh@uq.edu.au (H.R. Ronagh).

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series should satisfy *a priori* the boundary conditions at the end of strips. The philosophy of the finite strip method is similar to that of the Kantorovich method [8], which is used extensively for reducing a partial differential equation to an ordinary differential equation. In this method, especially for plates, Hermitian displacement functions are usually suitable for transverse direction [9].

Undoubtedly, the advantage of the finite strip method in comparison with other numerical methods is obvious in evaluating the buckling of plates. On the one hand, the simplicity of inputs and calculations, and on the other hand, reducing the problem to a standard eigenvalue problem (besides ease of programming) are factors which make the finite strip method superior. The first use of the finite strip method for buckling appears to be the work of Prezemieniecki [10], who showed how this method can be used to predict the initial elastic local buckling of plates and sections made of plates under biaxial compression. His approach utilized the approximate finite strip formulation of Cheung and Cheung [11]. Plank and Wittrick [12] employed the semi-analytical complex finite strip method to investigate buckling under combined loading of thin-walled structures. The advantage of their method over the formulations of the ordinary finite strip method is the ease with which it can handle shear forces. Wittrick [13] developed an exact finite strip method for buckling analysis of stiffened panels in compression. Azhari and Bradford [14] developed the bubble finite strip method, which augmented finite element formulations to obtain rapid convergence. They also extended the finite strip method to analyze the buckling of plates with different end conditions [15]. Adany and Schafer [16–18] derived a constrained finite strip method for decomposing the buckling modes of thin-walled open cross-section members. Azhari and Amoushahi [19] used the complex finite strip method for analyzing the buckling of composite FRP structural plates.

In the present study, the finite strip method is extended in order to study the instability of the pultruded FRP section as an orthotropic material. For this purpose, a semi-analytical finite strip formulation is developed, validated and applied to solve the eigenvalue problem associated with the torsional and flexural buckling of doubly symmetric open thin-walled section FRP columns. The present explicit finite strip formulation can be applied effectively to determine the torsional and flexural buckling capacities of simply-supported composite FRP columns under axial compression. It will be shown that the semi-analytical predictions for torsional and flexural buckling of various FRP columns based on the present analysis are in excellent agreement with closed-form results. Numerical studies of unstiffened and stiffened FRP cruciform sections (which are among the weakest open sections in torsional buckling) will be carried out. Flexural buckling of these sections, in addition to torsional buckling, will be evaluated for prediction of dominant global buckling mode in different column lengths. It can be said about FRP cruciform sections under pure compression that torsional buckling usually occurs before flexural buckling. In addition, the results of an investigation concerning the influence of longitudinal stiffeners, section geometry, and material properties on the member buckling behavior are presented, which required the completion of a number of parametric studies. In these investigations, careful consideration is given to the occurrence and characterization of torsional and flexural buckling modes.

2. Semi-analytical finite strip method for torsional and flexural buckling

2.1. General

One of the most important advantages of the semi-analytical finite strip method in comparison with other kinds of numerical methods is the ability to handle in-plane (membrane) as well as out-of-plane (flexural) displacements. On the other hand, displacements caused by torsional buckling and flexural buckling are of the in-plane type and occur in the long wavelengths. Therefore, the semi-analytical finite strip method can be a suitable tool for the prediction of torsional and flexural buckling of columns which are under compression loading. However, this method is only applicable for structures whose ends are simply supported. More complicated boundary conditions may be treated in the finite strip method developed by Bradford and Azhari [15].

Here, the purpose is studying the global buckling of FRP composite columns under pure compression, so the equations will be extracted only for compression loading and membrane (in-plane) displacements.

2.2. Definition of the problem

In the finite strip method (FSM) a thin-walled member, such as the composite FRP cruciformsection of Fig. 1 is divided into longitudinal strips. The advantage of FSM over other methods, such as the finite element method which applies discreteness in both the longitudinal and transverse direction, is dependent on a judicious choice of the shape function for the longitudinal displacement field. In Fig. 1, a single strip is highlighted. The geometry, loading and degrees of freedom (DOF) for the strip are illustrated in Figs. 2 and 3. As it is shown in Fig. 2, the strip is loaded by a uniform longitudinal compressive stress σ_L. In this procedure, the elastic membrane stiffness and stability matrices of a composite FRP strip are obtained through standard finite element techniques based on the energy method.

2.3. Membrane stiffness and stability matrices

In this derivation, the in-plane, or membrane, displacements of a strip u and v are assumed to be given by

$$u = \langle f_1(\eta)\rangle\{d_l\}cos\left(\frac{n\pi x}{L}\right) \quad (1)$$

and

$$v = \langle f_2(\eta)\rangle\{d_l\}sin\left(\frac{n\pi x}{L}\right) \quad (2)$$

where $\{d_l\}$ is the nodal in-plane displacement in local coordinates shown in Fig. 3 and may be explicitly written as

$$d_l = [u_1, v_1, u_2, v_2] \quad (3)$$

and $f_1(\eta)$ and $f_2(\eta)$ are linear shape functions employed in the transverse direction in the semi-analytical treatment given by

$$\langle f_1(\eta)\rangle = \left\langle 0, \quad \frac{1}{2(1-\eta)}, \quad 0, \quad \frac{1}{2(1+\eta)}\right\rangle \quad (4)$$

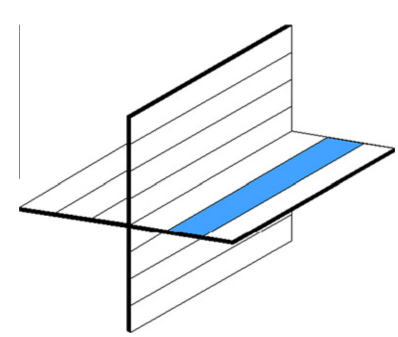

Fig. 1. Finite strip discreteness.