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Modifications of standard GFRP sections shape and proportions for improved stiffness and lateral-torsional stability

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ABSTRACT

In this paper the results of a comprehensive numerical investigation regarding the axial–flexural–torsional response of pultruded slender beams is presented. The goal is to propose GFRP standard cross-sections of such proportions and shapes that would possess improved strength, stability and deformational characteristics compared to the corresponding existing sections whose proportions are generally based on standard steel sections. As GFRP sections are thin-walled but are significantly less stiff than similar steel sections, the study focuses on enhancing their appropriate stiffness and buckling strength. The novel and efficient numerical model used in this investigation was developed by the writers and can be used to trace the complete pre-buckling geometrically nonlinear response of any GFRP or steel thin-walled member with open or closed cross-section. The bucking load is computed by the asymptotic value of the load–displacement curve. Members with I-, L-, T- and box sections are analyzed, considering different loading and boundary conditions. It is demonstrated that due to their unsuitable proportions, available standard GFRP sections do not have adequate stiffness and buckling strength. Consequently, recommendations are made for new sectional proportions and modified shapes, and some graphical results are presented to demonstrate how the results of the proposed method could be utilized in practical design situations. The superiority of the proposed sections is quantified by an efficiency factor, defined in terms of ratio of strength gain to material volume increase.

1. Introduction

Historically, Fibre-Reinforced-Polymer (FRP) pultruded profiles were designed by the pultrusion industry and were intended for low-stress applications (cooling towers, water and waste-water treatment plants, etc.), taking into account their principal features such as their high stiffness and strength-to-weight ratio, magnetic transparency, corrosion resistance, and an effective manufacturing process. However, since the late nineties, FRP pultruded profiles reinforced with glass fibers (GFRP) have been used in civil engineering as primary structural members, complementing other conventional materials such as steel, concrete, and wood in pedestrian and highway bridges, railway lines [1–3], and in the construction of full-composite structures. One of the first, as well as one of the most famous, full-composite structures was the five-stories GFRP Eyecatcher Building erected in Basel, Switzerland in 1998 for the Swiss Building Fair. It is also the tallest FRP structure constructed until now.

In order to make pultruded members more appealing to the construction industry, most manufacturers produce profiles that imitate standard structural steel members (e.g. I-, H-, C-, and angle profiles), but in the field of composite research, the belief that these “steel-like” profiles do not represent the optimum geometry for composite sections is gradually gaining currency. Considering that standard engineering guidelines developed for conventional materials are not applicable to FRP shapes, several technical documents dealing with the design equations and methods, material properties, and safety factors for pultruded elements have been developed or under development [4–7].

In these documents it is specified that the pultruded elements could be considered as linear elastic, homogeneous, and transversely isotropic in the case of aligned fibers, with the plane of isotropy being normal to the longitudinal axis (i.e. the axis of pultrusion). Their mechanical behavior is strongly affected by warping strains as well as shear deformations, which, coupled with the time-dependent nature of these materials, govern their complex mechanical behavior.

FRP also present some less advantageous properties, which may hinder their more widespread use. One of their unfavorable

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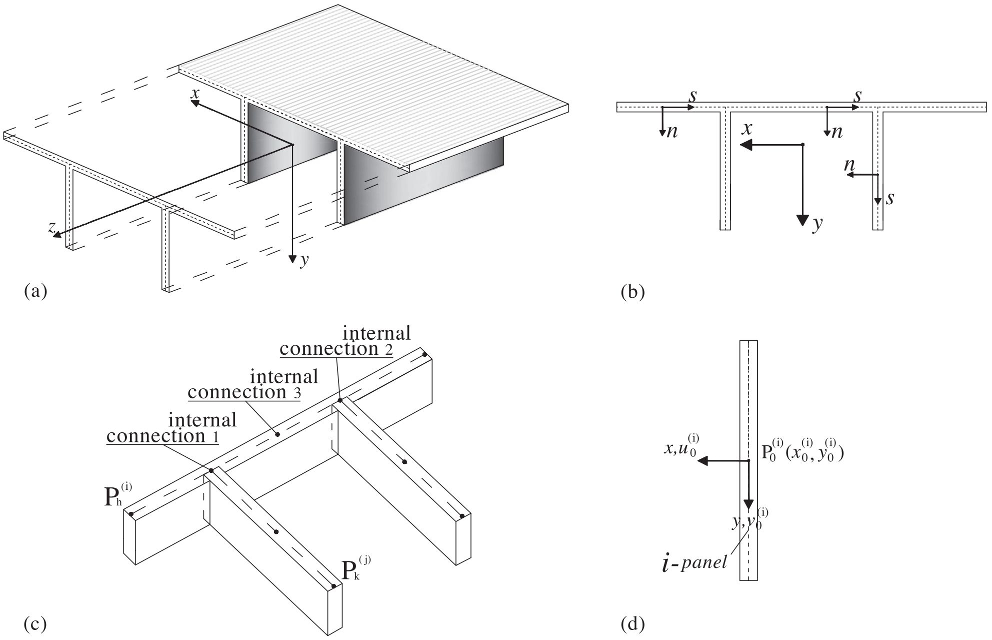

Fig. 1. (a) Typical beam; (b) cross section; (c) positions of the internal connections; (d) generic *i*-panel.

properties is their relatively low elastic moduli, which often make design for serviceability and stability the governing limit states and they inhibit taking greater advantage of the high strength of FRP. Due to their high strength-to-stiffness ratio, buckling is often the governing mode of failure for GFRP members. In particular, a long slender beam under bending about the strong axis may buckle through combined twisting and lateral bending of the cross section, a phenomenon known as flexural–torsional buckling.

The lateral buckling behavior of FRP beams has been widely investigated in the literature from the theoretical, numerical, and experimental points of view. Earlier studies on the mechanics of thin-walled open/closed sections were carried out by Vlasov [8] and Gjelsvik [9], who limited their investigations to isotropic materials. Razaqpur and Li [10–12] developed accurate semi-analytic finite elements to investigate the bending, axial, torsional, distortional, including torsional and distortional warping, and shear lag behavior of multi-cell thin-walled box girders. Bauld and Tzeng [13] extended Vlasov's thin-walled beam theory and developed linear and nonlinear theories for the bending and twisting of thin-walled composite beams. Davalos et al. [14], experimentally and numerically, studied the bending response of pultruded composite beams with different I- and box sections. At the same time, Turvey and Brooks [15] carried out a series of lateral buckling tests on small-scale pultruded E-glass FRP beams, highlighting the effects of load position and boundary conditions. Their results were compared with several numerical simulations and the differences were attributed to factors not included in the models, such as initial deflection, pre-buckling displacements, and geometric nonlinearities. Ascione et al. [16] examined the static behavior of FRP thin-walled beams, taking into account the effects of shear deformations. These studies present many comparisons with Vlasov's classical solution.

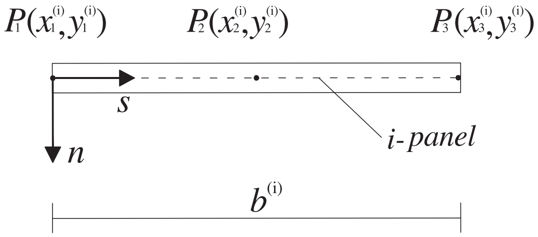

Fig. 2. Generic *i*-panel.

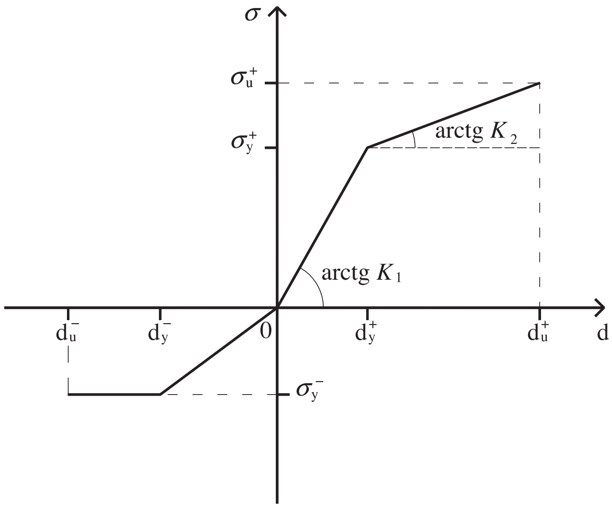

Fig. 3. Generic relationship between web–flange relative displacement, *d*, and the associate generalized force *σ*.

More recently more detailed studies have been conducted regarding the flexural–torsional behavior of I- shape composite beams, some of which are briefly described below:

- Lee and Lee [17], developed a one-dimensional finite element model specifically dedicated to this topic;
- Vo and Lee [18], developed an analytical study of thin-walled composite box beams subjected to vertical and torsional loads. Their model was based on a first-order shear-deformation beam theory and accounted for an arbitrary stacking sequence in the laminate. The same authors, two years later, developed a geometrically nonlinear model for thin-walled composite beams with arbitrary lay-ups under various loading configurations [19];
- Ascione et al. [20,21], investigated the local and global buckling of glass FRP I-beams by using a mechanical model developed by them.