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Flexural stiffness characterization of fiber reinforced plastic (FRP) pultruded beams

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Abstract

The design of GFRP beams is often governed by deflection limits in service, hence it becomes crucial to evaluate accurately their flexural stiffness. In this work, the flexural stiffness of GFRP pultruded profiles is evaluated experimentally, numerically and analytically. A procedure that simultaneously yields the flexural and the shear modulus of GFRP pultruded profiles directly from 3-point bending tests is applied. Direct tension and 3-point bending tests on coupons extracted from these profiles were also conducted. The TBT and the FEM were applied to analyze the profiles under bending, using material properties estimated by CLT. Comparisons of numerical, analytical and experimental results are presented and discussed at the end.

Keywords: Glass fiber reinforced polymers; Pultruded profiles; Flexural stiffness

1. Introduction

In recent years the use of advanced composite materials has gained wider space in the Civil Engineering sector, due to some favorable characteristics such as lightweight, high specific strength, resistance to corrosion and electromagnetic transparency. Particularly pultruded fiber reinforced polymers (FRP) profiles have been employed in structural components of bridge systems, crosswalks, structures exposed to corrosive environment and also where non-electromagnetic interference is required.

Glass fiber reinforced polymer (GFRP) profiles are more commonly employed, mainly due to the comparatively low cost of glass fibers. However, due to the relative low elastic moduli of GFRP profiles, design is often governed by limitations in deflection at service load levels, or by buckling, in the case of thin-walled sections, instead of ultimate strength limits. Also, due to the low ratio of shear-to-longitudinal elastic modulus, shear deformation becomes significant in the total element deformation and must be considered in the element deflection calculation, Roberts and Al-Ubaidi [1].

According to Kumar et al. [2], studies on the flexural behavior of GFRP profiles have shown that shear deformation plays an important role as compared to steel profiles due to the lower longitudinal modulus of the glass fibers as compared to steel and also due to the low shear modulus of the resin. These studies have also shown that due to high levels of strain attained at failure for both glass fiber and resin materials, composite materials behave linear-elastically even for large deflections imposed on the profiles. Davalos and Qiao [3] have analyzed several combined analytical and experimental studies on bending, torsion and lateral instability tests on FRP profiles. The authors concluded that in general buckling and deflection limitation tend to govern design criteria for usual FRP profiles.

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Since laminae of different fiber orientation are typically employed, advanced composite materials may display complex anisotropic behavior. However it is generally accepted that for profiles fabricated by the pultrusion process the section walls can be simulated as laminated composites with equivalent orthotropic mechanical properties in their longitudinal and transverse directions. For design of structures composed of FRP elements, Davalos et al. [4] explain that both stiffness and strength are equally important, and depend on the material and on the element cross-section. While changes in the profile section geometry are easily related to changes in stiffness, changes in the material and fiber orientation are not so obvious to be evaluated. Bank [5] has shown that, due to the difference in mechanical properties between a full size profile of thin-walled section and a solid bar of rectangular section, the longitudinal elastic modulus obtained from a flexural test on a FRP pultruded profile is different from the one obtained from a flexural test on a solid bar coupon extracted from the same profile. Moreover, the flexural elastic modulus of the profile also differs from the longitudinal elastic modulus obtained from a direct tension test on a solid bar coupon extracted from this profile. Another problem pointed out by Bank et al. [6] is the lack of homogeneity of fiber distribution in pultruded materials due to the manufacturing process, which can lead to different mechanical properties depending on the location where the solid bar coupon is extracted from the profile. On the other hand, Deskovic et al. [7] stated that tests on small coupons extracted from pultruded profiles could lead to reliable values of elastic moduli for FRP beams. Due to this divergence on research findings, Kumar et al. [2] justify the need for conducting more experimental tests and studies on the behavior of full-size pultruded beams and of coupons extracted from these beams.

The aim of this work is to evaluate the flexural stiffness of GFRP pultruded beams experimentally, numerically and analytically. In the experimental program, a procedure proposed by Bank [5], based on Timoshenko Beam Theory, that simultaneously yields the flexural and the shear modulus directly from flexural tests on simply supported beams, is initially applied. Two beam specimens made of GFRP pultruded profiles of wide flange I section were tested under 3-point bending, by using the same cross-section and varying the beam span. A direct tension test and a 3-point bending test on coupons extracted from these profiles were also conducted to obtain the longitudinal elastic modulus. Comparison of the longitudinal modulus obtained from the different experiments is performed by means of a statistical analysis. The prescriptions given by the American Codes ASTM D 790 [8] and ASTM D 3039 [9], for flexural and tensile properties, respectively, of advanced composite materials are also discussed. A Finite Element analysis of the profiles tested under 3-point bending was also performed, modeling the profile web and flanges by 4-noded shell elements, based on Discrete Kirchhoff Quadrilateral (DKQ) plate elements, Batoz and Tahar [10], with equivalent orthotropic material properties derived from the Classical Lamination Theory. The analyses were performed with the commercial computer program SAP 2000 [11]. The Timoshenko Beam Theory was also applied to analyze the profiles under bending, assuming isotropic material. Comparisons of numerical, analytical and experimental results are presented and discussed. Concluding remarks and a few recommendations are given at the end of the work.

2. Timoshenko Beam Theory

When beam theory is utilized for analyzing structural elements, the designer needs to obtain appropriate mechanical properties for the selected theory. The choice of beam theory depends on many factors, one of which is the degree of anisotropy of the composite material. Composite materials display in general a longitudinal-to-shear modulus ratio considerably higher than those found in isotropic materials and this ratio tends to increase as the anisotropy degree of the material increases. For this reason shear deformation in the beam will increase as the anisotropy degree of the material increases, Bank [5]. To account for shear deformation, Timoshenko Beam Theory (TBT) gives a better approximation of the actual behavior as compared to the traditional Euler-Beam Theory (EBT).

In Timoshenko Beam Theory, the plane sections of the beam are assumed to remain plane, but no longer normal to the beam neutral axis. For a Wide I flange beam under three-point bending, as shown in Fig. 1, the total deflection of the beam is given by the sum of v_f and v_c, which are the deflections corresponding to flexural and shear deformation, respectively. The maximum deflection, at midspan, is given by the expression:

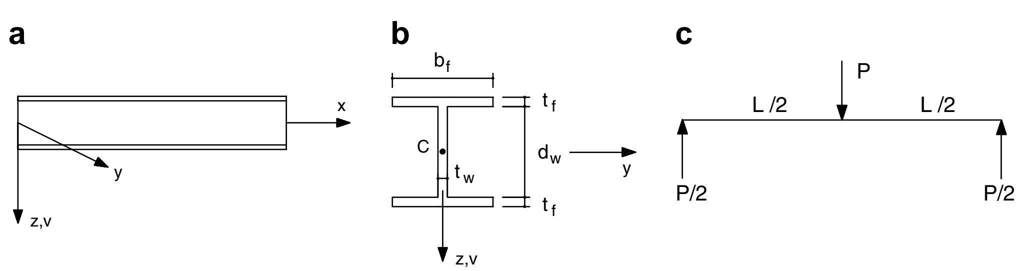

Fig. 1. Wide I flange beam: (a) front view and coordinate system; (b) cross-section; (c) three-point bending test scheme.