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Comprehensive local buckling equations for FRP I-sections in pure bending or compression

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ABSTRACT

In this work, explicit equations to determine local buckling critical stress of thin-walled fiber reinforced polymer (FRP) profiles in pure bending or compression are proposed. Interaction between flange and web is considered and the expressions allow for different orthotropy ratios and ranges of flange-to-web widths and thicknesses. To obtain the equations, Rayleigh Quotient energy method is adopted for assumed approximate buckled shapes. As quality of selected functions affects the accuracy, different shapes are investigated and the results are compared with those obtained with Generalized Beam Theory (GBT) for typical I-section dimensions and material properties. A comparison is made to the solutions based on discrete plate with simplified support conditions as well as to a recently proposed equation for major-axis bending. Finally, a general form for the local buckling critical coefficient is also presented along with tabulated parameters for prompt assessment of critical stresses, consisting in a simple and reliable alternative for design approach.

1. Introduction

Fiber reinforced polymer (FRP) material is gaining more acceptance among engineers and its use in structures is growing rapidly. To allow for safe structural design, standard provisions are currently under development, including the American and European standards for pultruded FRP structures [1,2]. Although modern, these documents still contain old-fashioned conservative formulae for local buckling of columns and beams, based on discrete plate analysis with simplified support conditions. Alternatively, a reliable method is proposed in the recently released Italian Code [3] and in the European standard, based on a rotationally restrained discrete plate analysis. This approach, however, needs the computation of several parameters and cannot be easily adopted for prompt assessment of local buckling critical loads.

Methods to predict local buckling critical stresses for thin-walled sections can be divided into three categories: i) discrete plate analysis assuming simplified edge support conditions; ii) discrete plate analysis assuming rotationally restrained edges; and iii) plate assembly (or full-section) analysis. Fig. 1 illustrates the three different methods and Fig. 2 presents the definitions of I-section parameters used in this work. In the next sections, a review on the existing approaches within each category is presented. 'In-house' equations recommended by pultruded FRP manufacturers were presented by Mottram [4] and are not discussed hereafter, as well as previous works addressing specifically numerical and experimental analyses.

Throughout this work, the term 'reliability' refers to the consistency between the results obtained with approximate methods and those resulting from solving the governing differential equilibrium equation for the problem considering representative mechanical properties for the material ('exact'). In this work, a reliable approach is characterized as the one able to provide results within a ± 10% difference margin with respect to the 'exact' value for the range of material properties and geometries studied.

1.1. Discrete plate analysis assuming simplified edge support conditions

In this approach, flange and web are treated as independent plates with simplified support conditions. For an I-section, simply supported condition is assumed at the web-to-flange junctions. Therefore, each half of the flange is assumed as a long plate with one of the longitudinal edges free and the other simply supported (F-S), while the web is assumed as having both longitudinal edges simply supported (S-S). Solutions for orthotropic long plates with F-S and S-S boundary conditions were obtained by Lekhnitskii [5]. Flange and web buckling critical stresses are presented in Eqs. (1) and (2), respectively:

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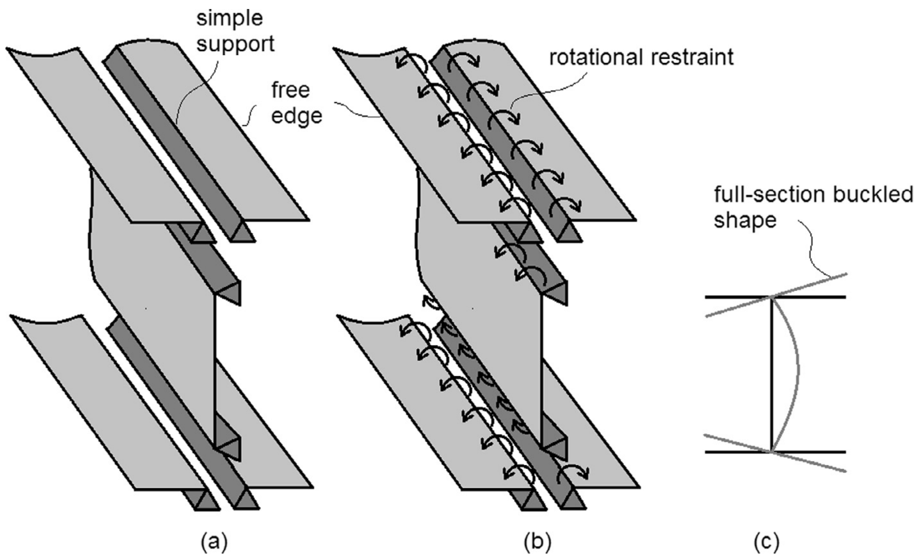

Fig. 1. Approaches to determine local buckling critical loads: a) discrete plates with simply supported conditions; b) discrete plates with rotationally restrained edges; and c) full-section.

$$F_{\text{crf,FS}} = 4G_{\text{LT}}\left(\frac{t_{\text{f}}}{b_{\text{f}}}\right)^2 \quad (1)$$

$$F_{\text{crw,SS}} = k\frac{\pi^2 E_{\text{L}}}{12(1-\nu_{\text{LT}}\nu_{\text{TL}})}\left(\frac{t_{\text{w}}}{b_{\text{w}}}\right)^2 \quad (2)$$

in which E_{L}, E_{T} and G_{LT} are longitudinal, transverse and shear moduli; ν_{LT} and ν_{TL} are major and minor Poisson's ratio; b_{f} and b_{w} are flange and web widths; t_{f} and t_{w} are flange and web thicknesses; and k is the buckling coefficient, defined in Eqs. (3a) and (3b) for pure compression ($k = k_{\text{c}}$) and pure bending ($k = k_{\text{b}}$), respectively.

$$k_{\text{c}} = 2\sqrt{\frac{E_{\text{T}}}{E_{\text{L}}}} + 2\nu_{\text{LT}}\frac{E_{\text{T}}}{E_{\text{L}}} + 4\frac{G_{\text{LT}}}{E_{\text{L}}}(1-\nu_{\text{LT}}\nu_{\text{TL}}) \quad (3a)$$

$$k_{\text{b}} = 13.9\sqrt{\frac{E_{\text{T}}}{E_{\text{L}}}} + 11.1\nu_{\text{LT}}\frac{E_{\text{T}}}{E_{\text{L}}} + 22.2\frac{G_{\text{LT}}}{E_{\text{L}}}(1-\nu_{\text{LT}}\nu_{\text{TL}}) \quad (3b)$$

Due to simplicity of the approach, these expressions are recommended by the majority of codes and guidelines to determine critical stresses [1–3,6,7]. However, researchers have pointed out that the method leads to very conservative results and, therefore, to inefficient use of material. McCarthy and Bank. [8] for instance, reported average ratios of 2.68 and 1.64 between experimental results and Eq. (1) for beams and columns, respectively, and Cardoso et al. [9] observed a difference up to 49% for typical commercially available I-sections in compression when compared to results obtained with Finite Strip Method (FSM).

In local buckling phenomenon, bending of the constituent plates occurs and the moduli of elasticity adopted in calculations must be those corresponding to plate bending – e.g. those obtained by ASTM D790 or D6272. Tolf and Clarin [10] and Cardoso et al. [11] have pointed out that the moduli in tension/compression and bending may differ greatly depending on the number of roving layers in FRP plates.

1.2. Discrete plate analysis assuming rotational restraint between adjacent plates

This method was firstly proposed by Bleich [12] to analyze steel plate assemblies and consists in considering each constituent wall as an individual element rotationally restrained by its adjacent plates. In Bleich's original work, the critical local buckling stress is determined from a transcendental equation. This method would allow engineers to

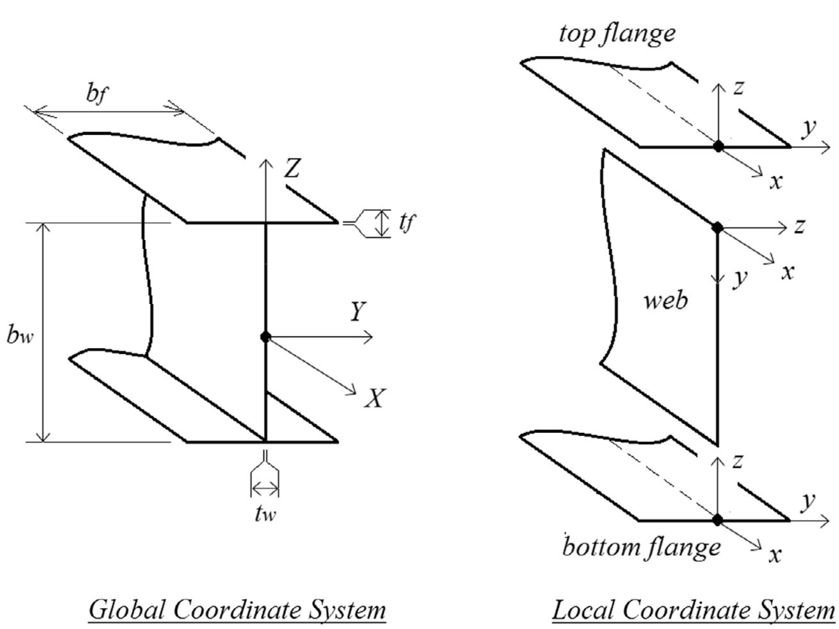

Fig. 2. Global and local coordinate systems and I-section parameters definition.