Engineering Structures 158 (2018) 1–12

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Determination of critical load for global flexural buckling in concentrically loaded pultruded FRP structural struts

Yang Zhan[a], Gang Wu[b,*], Kent A. Harries[c]

[a] School of Civil Engineering and Architecture, Jiangsu University of Science and Technology, Zhenjiang 212003, China
[b] Key Laboratory of Concrete and Prestressed Concrete Structures of the Ministry of Education, School of Civil Engineering, Southeast University, Nanjing 210096, China
[c] Department of Civil and Environmental Engineering, University of Pittsburgh, Pittsburgh, PA 15261, USA

ARTICLE INFO

Keywords:
PFRP struts
Global flexural buckling loads
New closed-form equations
Numerical simulations
Prediction accuracy

ABSTRACT

This paper presents a comprehensive test database of concentric compression experiments on pultruded fiber-reinforced polymer (PFRP) specimens that failed in a global flexural buckling mode published in literature between 1969 and 2016. A new closed-form equation to determine the reduction factor for global flexural buckling of PFRP structural struts under axial compression is developed on the basis of the Ayrton-Perry formula and observed initial out-of-straightness of PFRP members measured by other researchers. Recognizing that data on initial imperfections may be unavailable, a second new empirical closed-form equation is derived based upon the experimental database. Validation of the two explicit expressions is performed by both comparison to experimental data and comparison with validated numerical simulations. In addition, the accuracies of the two proposed equations are compared with those of five closed-form solutions available in the literature; both results in more accurate predictions than the extant equations. Both new proposed equations can be conveniently used by structural engineers at the preliminary engineering design stage for accurately assessing the reliability and safety of composite structures under concentric compressive loading.

1. Introduction

The use of pultruded fiber-reinforced polymer (PFRP) profiles and systems in structural engineering applications has been increasing in the past two decades, due to their favorable properties of lightweight, relatively high tensile strength, excellent corrosion resistance, ease of handling, transportation and erection, low life-cycle costs and – increasingly important – positive environmental aspects, such as lower energy consumption and carbon dioxide emission than comparable material systems [1,2]. PFRP structural members consist of thin plates pultruded to form open or closed cross-sectional shapes typically mimicking those found in steel construction [3]. From a macro-mechanical point of view, PFRP thin-walled shapes can be considered to be linear elastic, homogeneous and orthotropic, with the axes of orthotropy coinciding with the principal axes of the cross sections. Because of the thin-walled sectional geometry and relatively low stiffness-to-strength ratio, PFRP profiles are susceptible to buckling before reaching their material strength limit states; that is, the full capacity of the material typically may not be realized. Accurate prediction of buckling strength is essential for the reliable, efficient, and safe design of thin-walled PFRP structural elements. Determination of a compression member's concentric buckling load is therefore a fundamental first step in design.

Previous studies of axial behavior of PFRP have identified the following general conclusions as summarized by Cardoso et al. [4]: (a) short columns, those having plate relative slenderness ratios, $\lambda_p = (F_c/F_{crl})^{0.5} \leq \approx 0.7$, in which F_c is the material compressive strength and F_{crl} is the local buckling critical stress, are dominated by local buckling of plate elements (e.g., [5]); (b) long columns, those having $\lambda_p \geq \approx 1.3$, are dominated by global buckling (e.g., [6,7]); and c) so-called intermediate columns, having slenderness falling between short and long columns exhibit a complex interaction between local and global buckling (e.g., [4,5,8]). The focus of the present study is long columns whose behavior is dominated by global flexural buckling.

Although substantial studies have been performed addressing the global buckling behavior of PFRP shapes under concentric compression and five corresponding closed-form solutions (i.e., classical Euler formula [9], Engesser [10] and Haringx [11] shear correction formulas and design equations recommended by Strongwell Corporation [12] and Fiberline Composites [13]) have been proposed, there is little consensus among researchers on the best calculation method for such applications. Moreover, no study has been reported up to the present to

* Corresponding author.
E-mail addresses: y_zhan@126.com (Y. Zhan), g.wu@seu.edu.cn (G. Wu), kharries@pitt.edu (K.A. Harries).

https://doi.org/10.1016/j.engstruct.2017.12.008
Received 28 July 2017; Received in revised form 3 December 2017; Accepted 5 December 2017
0141-0296/

Nomenclature

A_g	gross cross section area
E_{LC}	longitudinal compressive modulus
F_{LC}	longitudinal compressive strength
I_{min}	weak axis moment of inertia of section
K	end-restraint coefficient
L_{eff}	effective length
r	weak axis radius of gyration of section
S	section modulus
β	cross section shape-dependent shear coefficient
ε_0	relative initial bending (imperfection)
λ	slenderness ratio = KL_{eff}/r
λ_n	universal slenderness ratio
v_0	the maximum initial deflection at the midspan of the PFRP member
σ_{cr}	critical buckling stress
σ_E	Euler buckling stress

evaluate the existing five solutions.

In this paper, a database of concentrically loaded PFRP experimental specimens that failed in a global flexural buckling mode is first presented. The database was assembled through an extensive review of literature published between 1969 and 2016. These test results were evaluated according to criteria that had been critically determined to establish a reliable database. This database serves as a valuable reference document for future solution development and validation, assessment of existing solutions and future database establishment. Subsequently, a new closed-form equation to determine the reduction factor for global flexural buckling of PFRP members subjected to axial compression was developed based on the well-known Ayrton-Perry formula [14] and the initial crookedness of PFRP struts tested by other researchers. In this case, the reduction factor for PFRP members is applied to the EC3 [15] equation used to calculate the buckling capacity of steel members. Meanwhile, a second new closed-form equation was also derived based upon the test results from the database. The two explicit expressions were then verified in the light of experimental and validated numerical results. In addition, the performance of the two proposed equations was compared with predictions based on the existing five solutions.

2. Existing closed-form solutions

Existing closed-form solutions intended to predict global flexural buckling are presented in the following sections.

2.1. Classical Euler formula

For PFRP structural struts of sufficient slenderness that they fail by global flexural buckling, a number of researchers have demonstrated through experimental and analytical work that the critical global buckling load can be predicted with reasonable accuracy using the classical Euler formula [9] given by Eq. (1) [6,16–20].

$$P_E = \pi^2 E_{LC} I_{min}/(KL_{eff})^2 = \pi^2 E_{LC} A_g/\lambda^2 \quad (1)$$

Currently, the classical Euler formula is adopted by the EUROCOMP Design Code Handbook [21], Bedford Reinforced Plastics Inc. [22] and Creative Pultrusions Inc. [23].

2.2. Engesser shear correction formula

PFRP members typically have a relatively high ratio of longitudinal elastic modulus to in-plane shear modulus (E_{LC}/G_{LT}). Lee and Hewson [24] presented experimental data for PFRP members subject to axial loading and proposed that the critical buckling capacity of PFRP struts can be better estimated using the Engesser shear correction formula [10] given by Eq. (2).

$$P_{Esh1} = P_E/[1 + \beta P_E/(G_{LT} A_g)] \quad (2)$$

where P_E is given by Eq. (1).

Thereafter, Zureick's group [7,25], Roberts [26], Mottram et al. [27], Bank's group [3,28] and Boscato et al. [29] all advocated using the Engesser shear correction formula to calculate the buckling capacity of PFRP members, since it has more accurate predictions. On the other hand, Barbero and DeVivo [17] claimed that the effect of shear deformation is usually small on weak axis buckling and can be neglected accordingly.

2.3. Haringx shear correction formula

Kardomateas and Dancila [30] derived a three-dimensional elasticity solution for the problem of an orthotropic hollow cylinder under axial compression, and concluded that the classic Euler formula may overestimate the critical capacity of PFRP profiles, whereas the Haringx shear correction formula [11] may always underestimate the buckling capacity of PFRP sections. The Haringx shear correction formula can be given as:

$$P_{Esh2} = [\sqrt{1 + 4\beta P_E/(G_{LT} A_g)} - 1][G_{LT} A_g/2\beta] \quad (3)$$

where P_E is given by Eq. (1).

2.4. Design equations recommended by Strongwell Corporation

Based on in-house experimental tests, Strongwell Corporation [12] developed empirical equations according to different cross sections for slender PFRP members, as follows:

For I-sections and wide-flange sections (W-sections):

$$P_{ES} = 4.9 E_{LC} A_g/(KL_{eff}/r)^{1.7} \quad (4a)$$

For angles (L-sections):

$$P_{ES} = E_{LC} A_g/56(KL_{eff}/r)^{0.55} \quad (4b)$$

For round and square tubes:

$$P_{ES} = 1.3 E_{LC} A_g/(KL_{eff}/r)^{1.3} \quad (4c)$$

2.5. Design equations recommended by Fiberline Composites

The critical buckling load equation provided by Fiberline Composites [13] for global buckling is:

$$P_{EF} = N_C/(1 + N_C/P_E) \quad (5)$$

In which

$$N_C = F_{LC} A_g \quad (6)$$

where P_E is given by Eq. (1).

Note that the safety factors for Eqs. (4) and (5) are not applied.

3. Construction of experimental test database

3.1. Previous databases

Due to the inherent complexity of the buckling behavior of concentrically loaded PFRP struts, test databases serve as a vital validation tool in assessing the performance of a solution. Recognition of the importance of systematically collecting existing experimental results has resulted in a number of previous attempts to develop test databases