Global buckling capacity of axially loaded pultruded FRP columns with doubly symmetric cross section

Seventh Asia-Pacific Conference on FRP in Structures (APFIS 2019)
Surfers Paradise, Gold Coast, Australia, 10-13 December 2019
S.T. Smith, T. Yu, D. Fernando and Z.Y. Wang (Eds.)

GLOBAL BUCKLING CAPACITY OF AXIALLY LOADED PULTRUDED FRP COLUMNS WITH DOUBLY SYMMETRIC CROSS SECTIONS

Yang Zhan[1]*, Zhangjian Wu[2], Jing Cui[3], Yaqiang Yang[4], and Benben Li[5]
[1] School of Civil Engineering and Architecture, Nanjing Institute of Technology
Nanjing 211167, China
[2] School of Mechanical, Aerospace & Civil Engineering, University of Manchester
Manchester M13 9PL, United Kingdom
[3] College of Civil engineering and Architecture, Henan University of Technology
Henan 450001, China
[4] School of Civil Engineering and Architecture, Jiangsu University of Science and Technology
Zhenjiang 212003, China
[5] College of Civil Engineering, Nanjing Tech University, Nanjing 211816, China
Email: y_zhan@126.com, jack.wu@manchester.ac.uk, jcui@haut.edu.cn, yangyq@just.edu.cn, bben369@163.com
* Corresponding Author

ABSTRACT
Accurate prediction of buckling strength is essential for the reliable, efficient, and safe design of thin-walled pultruded fiber-reinforced polymer (PFRP) columns. This paper presents the comparison of the existing six closed-form solutions based on the test database. Analysis of the experimental data from the database indicates that the Euler formula is the most unconservative of all equations (except for the equations recommedned by Strongwell Corporation) in predicting the global buckling loads of PFRP columns. The Engesser and Haringx shear correction formulae exhibit better performance than the Euler formula. The equation recommended by Fiberline Composites is observed to underestimate actual buckling capacity and is the only conservative prediction of those equations. The equations proposed by Strongwell Corporation appear to be incapable of reasonably predicting the global buckling loads of PFRP columns. The formula developed by Zhan et al. gives the most accurate predictions.

KEYWORDS
PFRP columns, global buckling capacity, closed-form equations, prediction accuracy.

INTRODUCTION

With speeding development of low carbon constructional industry, the use of pultruded fiber-reinforced polymer (PFRP) profiles and systems in civil engineering applications has been increasing apace in the past two decades (Bakis et al. 2002; Castro and De Keller 2010; Zhan et al. 2014). From a macro-mechanical view, PFRP can be considered to be linear elastic, homogeneous and orthotropic material. PFRP columns with doubly symmetric cross sections have the axes of orthotropy coinciding with the principal axes of the cross sections (Bank 2006). Because of the thin-walled sectional geometry and relatively low stiffness-to-strength ratio, PFRP members are susceptible to buckling before material strength failure, which means that the full exploitation of the material's potential may be prohibited. Therefore, rational consideration of the buckling phenomena and accurate prediction of buckling strength are essential for the reliable, efficient, and safe design of thin-walled PFRP structural elements.

For PFRP columns of sufficient slenderness that fail by global buckling, Barbero's group (Barbero 2000; Barbero and DeVivo 1999; Barbero and Raftoyiannis 1993; Barbero and Tomblin 1993; Barbero and Trovillion 1998), Hashem and Yuan (2001), and Seangatith and Sriboonlue (1999) have reported that the critical buckling load can be predicted using the classical Euler formula (Euler 1933). Currently, the classical Euler formula is adopted by the EUROCOMP Design Code Handbook (Clarke 1996), Bedford

Reinforced Plastics Inc. (2010) and Creative Pultrusions Inc. (2004). In general, PFRP members have a relatively high ratio of longitudinal elastic modulus (E_{LC}) to in-plane shear modulus (G_{LT}). Therefore, Lee and Hewson (1978) proposed that the critical buckling capacity of PFRP struts can be better estimated using the Engesser shear correction formula (Engesser 1889) considering the influence of G_{LT}. Thereafter, Zureick's group (Zureick and Scott 1997; Zureick 1998), Roberts (2002), Mottram et al. (2003), Bank's group (Bank 2006; Vanevenhoven et al. 2010) and Boscato et al. (2014) all advocated using the Engesser shear correction formula to predict the buckling capacity of PFRP members, since it has more accurate predictions. On the other hand, Barbero and DeVivo (1999) claimed that the effect of shear deformation is usually small on weak axis buckling and can be neglected accordingly. Kardomateas and Dancila (1997) reported that the Haringx shear correction formula (Haringx 1948) may always underestimate the buckling capacity of PFRP sections. Fiberline Composites (2003) and Strongwell Corporation (2013) developed their empirical equations. Meanwhile, Zhan et al. (2018) recently proposed a new closed-form equation to determine the reduction factor for global buckling of PFRP columns under axial compression, which makes the original solution recommended by Eurocode 3 (European standard 2005) easy to be used to predict the global buckling loads of doubly symmetric PFRP members.

Although substantial studies have been performed addressing the global buckling behavior of PFRP columns under concentric compression, there is little consensus among researchers on the best calculation method for such applications. In addition, no study has been reported up to the present to evaluate the existing six solutions. In this paper, the performance of the existing six solutions is carefully analyzed, and the comparison of these solutions is performed based on the test database.

COMPARISON OF EXISTING CLOSED-FORM SOLUTIONS

A database of 120 experimental data collected from seven literatures (Cardoso et al. (2014), Hashem and Yuan (2001), Zureick and Scott (1997), Seangatith and Sriboonlue (1999), Mottram et al. (2003) Zureick and Scott (1997) and Seangatith and Sriboonlue (1999)) was created to evaluate the existing six closed-form solutions (Table 1).

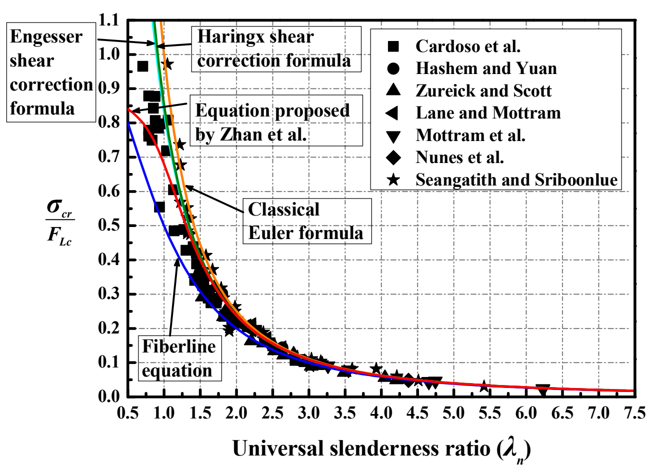

Figure 1. Comparison of the existing equations

The performance of the existing five solutions is compared in Figure 1. Design equation recommended by Strongwell Corporation cannot be plotted due to their composition. It is clear that the classical Euler formula resulted in the greatest overestimation compared with the other solutions. The Engesser and Haringx shear correction formulae generally overlapped each other and predicted marginally lower capacity than the Euler formula. The reason is that PFRP profiles have a relatively higher ratio of longitudinal elastic modulus to in-plane shear modulus (E_{LC}/G_{LT}) than that of typical isotropic materials on which the Euler formula is based. The effect of transverse shear is therefore more pronounced in PFRP materials, rendering the Euler formula non-conservative. Meanwhile, the equation recommended by Fiberline Composites was the most conservative compared to the other equations. It appears that the solution proposed by Zhan et al. could give the most accurate predictions.

The performance of these solutions was also quantified by the average absolute error (AAE) and standard deviation (SD). Specifically, the AAE and SD values of the classical Euler formula were 18.3% and 24%, respectively. The classical Euler formula overestimated the buckling capacity by 16.9%. Because the shear deformation effect is considered in the Engesser and Haringx shear correction formulae, these solutions exhibited better predictive behavior, overestimating the capacity by only 8.6% and 9.5%, respectively. Empirical design equation recommended by Strongwell Corporation significantly overestimated the experimentally observed capacity (by 119.5%) and exhibited considerable scatter in terms of the veracity of predictions with AAE = 119.5%. Such great errors demonstrate that the predictions of the equations proposed by Strongwell Corporation are unreliable, and this generic equation cannot be used for the prediction of global buckling of PFRP profiles. The equation proposed by Fiberline Composites exhibited reasonably good predictions with underestimation by 12.7%. The solution developed by Zhan et al. exhibited better results with an AAE value of approximately 9%. This solution is suitable for structural design application due to its relatively simple and familiar form and satisfactory accuracy.

Table1. The existing six closed-form solutions

Name	Equation
Classical Euler formula	$P_E = \pi^2 E_{LC} I_{min} / (KL_{eff})^2 = \pi^2 E_{LC} A_g / \lambda^2$
Engesser shear correction formula	$P_{Esh1} = P_E / [1 + \beta P_E / (G_{LT} A_g)]$ $P_E = \pi^2 E_{LC} I_{min} / (KL_{eff})^2 = \pi^2 E_{LC} A_g / \lambda^2$
Haringx shear correction formula	$P_{Esh2} = \left[\sqrt{1 + 4\beta P_E / (G_{LT} A_g)} - 1\right]\left[G_{LT} A_g / 2\beta\right]$ $P_E = \pi^2 E_{LC} I_{min} / (KL_{eff})^2 = \pi^2 E_{LC} A_g / \lambda^2$
Equation Recommended by Strongwell Corporation	$P_{ES} = 4.9 E_{LC} A_g / (KL_{eff}/r)^{1.7}$ (I- and W-sections) $P_{ES} = E_{LC} A_g / 56 (KL_{eff}/r)^{0.55}$ (L-section) $P_{ES} = 1.3 E_{LC} A_g / (KL_{eff}/r)^{1.3}$ (round and square tubes)
Fiberline equation	$P_{EF} = N_C / (1 + N_C / P_E)$ $N_C = F_{LC} A_g$ $P_E = \pi^2 E_{LC} I_{min} / (KL_{eff})^2 = \pi^2 E_{LC} A_g / \lambda^2$
Equation proposed by Zhan et al.	$P_Z = P_E / \left[1 + 0.04\sqrt{\beta P_E / (G_{LT} A_g)} + P_E / (2N_C)\right]$ $P_E = \pi^2 E_{LC} I_{min} / (KL_{eff})^2 = \pi^2 E_{LC} A_g / \lambda^2$ $N_C = F_{LC} A_g$

Note: A_g is gross cross section area; E_{LC} is longitudinal compressive modulus; G_{LT} is in-plane shear modulus; I_{min} is weak axis moment of inertia of section; K is end-restraint coefficient; L_{eff} is effective coefficient; r is weak axis radius of gyration of section; β is cross section shape-dependent shear coefficient; λ is slender ratio($\lambda = KL_{eff}/r$).

CONCLUSIONS

In this paper, the performance of the existing six solutions is carefully analyzed, and the comparison of these solutions is performed based on the test database. Based on the results of this investigation, the following should be emphasized:

1. The classical Euler formula is the most unconservative of all equations (except for the equations proposed by Strongwell Corporation) in predicting the global buckling loads of doubly symmetric PFRP columns.

2. The Engesser and Haringx shear correction formulae, which are improved by the additional consideration of shear, exhibit better performance than the classical Euler formula. The effects of shear can be more significant in highly orthotropic PFRP that has relatively large values of E_{LC}/G_{LT} compared to isotropic materials assumed by the Euler formulation.

3. The equation recommended Fiberline Composites is observed to underestimate actual buckling capacity and is the only conservative prediction of those equations. The manufacturer recommended equation proposed by Strongwell Corporation appears to be incapable of reasonably predicting the global buckling loads of doubly symmetric PFRP columns.
4. The closed-form solution proposed by Zhan et al. exhibits the best performance of all equations and is suitable for structural design application due to its relatively simple and familiar form and satisfactory accuracy.

ACKNOWLEDGEMENTS
This research was financially supported by the National Natural Science Foundation of China (Grant Nos: 51708259 and 51808265), the Royal Society of the UK (Grant No: R122363), the Scientific Research Foundation of Nanjing Institute of Technology and the Henan Key Scientific and Technological Project (Grant No: 2017BS021). Support from these sources is gratefully acknowledged.

REFERENCES
Bakis, C.E., Bank, L.C. and Brown, V.L. et al. (2002) "Fiber-reinforced polymer composites for construction—state-of-the-art review", Journal of Composites for Construction, ASCE, Vol. 6, No. 2, pp. 73–87.
Bank, L.C. (2006) Composites for Construction: Structural Design with FRP Materials. Hoboken, NJ: John Wiley & Sons.
Barbero, E. and Tomblin, J. (1993) "Euler buckling of thin-walled composite columns", Thin-Walled Structures, Vol. 17, pp. 237–258.
Barbero, E.J. (2000) "Prediction of buckling-mode interaction in composite columns", Mechanics of Composite Materials and Structures, Vol. 7, pp. 269–284.
Barbero, E.J. and DeVivo, L. (1999) "Beam-column design equations for wide-flange pultruded structural shapes", Journal of Composites for Construction, ASCE, Vol. 3, No. 4, pp. 185–191.
Barbero, E.J, and Raftoyiannis, I.G. (1993) "Euler buckling of pultruted composite columns", Composite Structures, Vol. 24, No. 2, pp. 139–147.
Barbero, E.J. and Trovillion, J. (1998) "Prediction and measurement of the post-critical behavior of fiber-reinforced composite columns", Composites Science and Technology, Vol. 58, No. 8, pp. 1335–1341.
Bedford Reinforced Plastics, Inc. (2010) Bedford design guide. Bedford, PA: Bedford Reinforced Plastics, Inc.
Boscato, G., Casalegno, C. and Russo, S. et al. (2014) "Buckling of built-up columns of pultruded fiber-reinforced polymer C-sections. Journal of Composites for Construction, Vol. 18, 04013050.
Cardoso, D.C.T., Harries, K.A. and Batista, E.M. (2014) "Compressive strength equation for GFRP square tube columns", *Composites Part B: Engineering*, Vol. 59, pp. 1–11.
Castro, J. and De Keller, T. (2010) "Design of robust and ductile FRP structures incorporating ductile adhesive joints", Composites Part B: Engineering, Vol. 41, No. 2, pp. 148–156.
Clarke, J.L. (1996) Structural Design of Polymer Composites: EUROCOMP Design Code and Handbook. London: Taylor & Francis.
Creative Pultrusions, Inc. (2004) The Pultex Pultrusion Global Design Manual of Standard and Custom Fiber Reinforced Polymer Structural Profiles. Bedford, PA: Creative Pultrusions, Inc.
European Standard, EuroCode 3. (2005) Design of Steel Structures Part1-1: General rules and rules for buildings, EN 1993-1-1, 2005.
Engesser, F. (1889) "U¨ber die Knickfestigkeit gerader Sta¨be", Zeitschrift Fu¨r Architektur Und Ingenieurwesen, Vol. 35, No. 4, pp. 455–462 (in German).
Euler, L. (1933) De Curvis Elasticis, Vol. 20, No. 58. Bruges (English Translation of the Book Methodus Inveniendi Lineas Curvas Maximi Minimive Proprietate Gaudentes, 1744, Lausanne).
Fiberline Composites. (2003) Fiberline Design Manual. Middelfart: Fiberline Composites A/S.
Haringx, J.A. (1948) "On highly compressible helical springs and rubber rods, and their application for vibration-free mountings", I. Phillips Research Reports 3, Eindhoven, pp. 401–449.
Hashem, Z.A. and Yuan, R.L. (2001) "Short vs. long column behavior of pultruded glass-fiber reinforced polymer composites", Construction and Building Materials, Vol. 15, No. 8, pp. 369–378.

Kardomateas, G.A. and Dancila, D.S. (1997) "Buckling of moderately thick orthotropic columns: comparison of an elasticity solution with the Euler and Engesser/Haringx/Timoshenko formulae", International Journal of Solids and Structures, Vol. 34, No. 3, pp. 341–357.

Lee, D.J. and Hewson, P.J. (1978) The use of fibre-reinforced plastics in thin-walled structures. In: Richards TH and Stanley P (eds) Stability Problems in Engineering Structures and Components. New York: Elsevier, pp. 23–55.

Mottram, J.T., Brown, N.D. and Anderson, D. (2003) "Physical testing for concentrically loaded columns of pultruded glass fibre reinforced plastic profile", Proceedings of the Institution of Civil Engineers: Structures and Buildings, Vol. 156, No. 2, pp. 205–219.

Roberts, T.M. (2002) "Influence of shear deformation on buckling of pultruded fiber reinforced plastic profiles", Journal of Composites for Construction, ASCE, Vol. 6, No. 4, pp. 241–248.

Seangatith, S. and Sriboonlue, W. (1999) "Axially loaded glass-fiber reinforced plastic composite columns. In: Proceedings of 7th East Asia-Pacific conference on structural engineering and construction (EASEC-7), 25 February, 1999, Kochi, Japan, pp. 1307–1312.

Strongwell Corporation. (2013) Strongwell Design Manual. Bristol, VA: Strongwell Corporation.

Vanevenhoven, L.M., Shield, C.K. and Bank, L.C. (2010) "LRFD factors for pultruded wide-flange columns", Journal of Structural Engineering, ASCE, Vol. 136, No. 5, pp. 554–564.

Zhan, Y., Wu, G. and Harries, Kent A. (2018) "Determination of critical load for global flexural buckling in concentrically loaded pultruded FRP structural struts", Engineering Structures, Vol. 158, pp. 1–12.

Zhan, Y., Wu, G. and Yang, L.S. (2014) "Experimental investigation of the behavior of a lattice steel column repaired with pultruded GFRP profiles", Journal of Performance of Constructed Facilities, ASCE, Vol. 29, 04014094.

Zureick, A. (1998) "FRP pultruded structural shapes", Progress in Structural Engineering and Materials, Vol. 1, No. 2, pp. 143–149.

Zureick, A. and Scott, D. (1997) "Short-term behavior and design of fiber-reinforced polymeric slender members under axial compression", Journal of Composites for Construction, ASCE, Vol. 1, pp. 140–149.