Experimental Study on Lateral-Torsional Buckling of PFRP Cantilevered Channel Beams

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Abstract

This paper presents the experimental result on the structural behaviors of pultruded fiber reinforced plastic (PFRP) cantilevered channel beams. The dimensions of the beam specimens is $102 \times 29 \times 6$ mm. A total of 26 specimens were tested to investigate the effects of unbraced length of the beam on the lateral-torsional buckling behavior and the buckling moment of the beams. Then, the obtained buckling moments were compared to the critical buckling moment obtained from the modified LFRD steel design equation in order to check the adequacy of the equation. From the tests, the response curves can be generally classified into two types: short beams and slender beams, depending on the range of the linear elastic responses. The general mode of failure of the specimens is the lateral-torsional buckling. In addition, the equation can adequately predict the critical buckling moment for the slender beam. However, for the short beam, the equation overestimates the critical buckling moment.

Keywords: Pultruded fiber reinforced plastic; Lateral-torsional buckling; Channel Profile; Cantilever beam

1. INTRODUCTION

Fiber reinforced plastic (FRP) composite is a material composed of fiber reinforcement bonded to a polymer resin or matrix (e.g., polyester, vinylester and epoxy) with distinct interfaces between them (Jones 1975). In the form of FRP, the fibers and polymer resins still have their own physical and chemical properties. The fibers provide strength and stiffness, and resins provide shape and protect the fibers from damage. The usages of the FRP structural profiles have been significantly increased into the civil engineering structures over the past two decades. Among various types of manufacturing processes, the pultrusion process appears to offer the highest productivity-to-cost ratio. The FRP manufactured by this process is called pultruded fiber reinforced plastic (PFRP). In this process, the continuous glass fiber

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doi:10.1016/j.proeng.2011.07.306
fibers. The fibers provide strength and stiffness, and resins provide shape and protect the fibers from damage. The usages of the FRP structural profiles have been significantly increased into the civil engineering structures over the past two decades. Among various types of manufacturing processes, the pultrusion process appears to offer the highest productivity-to-cost ratio. The FRP manufactured by this process is becoming an attractive material choice for various modern civil engineering applications.

2. TEST SPECIMENS AND TEST SET-UP

The PFRP channel members used in this study were made of E-glass fiber-reinforced and polyester resin, and manufactured by a pultrusion process. They have one nominal sizes of $102 \times 29 \times 6$ mm. A total of 26 specimens with span-to-depth ratio ($L / d$) ranging from 5 to 40 were tested. Two tests were performed on each specimen number. Details of the test profiles, dimensions, and geometric properties are presented in Table 1. The specimen numbers were designated in the form of "C C ." For example, the specimen number C102-C-3.0 is PFRP channel specimens, having depth ($d$) = 102 mm, C (cantilever beam supported) and $L_0 = 3.0$ m, respectively.

To correlate the analytical results to the obtained test results, the values of the longitudinal tensile strength ($F_L^t$), longitudinal tensile modulus ($E_L$) and in-plane shear modulus ($G_{LT}$) were needed to be determined from the tension and in-plane shear coupon test. The mechanical properties of the PFRP material were provided by Boonsuan et al. (2009). Five tensile coupons cut from the test specimens were tested in accordance with ASTM D3039, in order to determine $F_L^t$ and $E_L$. Five shear coupons were also tested in accordance with ASTM D5379, in order to determine $G_{LT}$ . The test is in the form of V-notched beam method with the pure shear under a four-point asymmetric bending configuration. From the coupon test, it was found that the average values of $F_L^t$, $E_L$ and $G_{LT}$ were 224.03 MPa, 35.20 GPa and 2.18 GPa, respectively. In addition, the results from the distributed analysis of all the mechanical properties were in good agreement with the values of the coefficient of determination (COD) which is close to 1.0 (Boonsuan et al. 2009).
The typical test set-up of the specimen in the cantilevered configuration is shown in Figure 1. The fixed end was set up by using wood clamp. At the free end, a part of steel angle with notched groove was firmly installed so that the tip concentrated vertical load can be applied directly through the shear center of the cross-section in order to provide the flexural stress and transverse shear to the specimens. When a tip vertical load acts passing the shear center, only the bending of the beam was occurs. The loads were applied by successive adding steel plates on a loading platform. The incremental loads were added until the critical buckling loads, and the specimens were buckled. In addition, a linear variable differential transducers (LVDTs) was used to monitor overall vertical end displacement of the channel specimens.

Table 1: Geometric properties of the pultruded FRP channel specimens.

| Specimens | \((d \times b \times t)\) | \(L_h\) | \(L/d\) | \(I_y\) | \(J\) | \(C_w\) | Number |
|-----------|----------------|--------|--------|--------|------|--------|-------|
| C102-C-0.5 | 102 \times 29 \times 6 | 0.50   | 4.9    | 53996  | 11088 | 1.161E+08 | 2     |
| C102-C-0.7 | 102 \times 29 \times 6 | 0.70   | 6.9    | 53996  | 11088 | 1.161E+08 | 2     |
| C102-C-0.8 | 102 \times 29 \times 6 | 0.80   | 7.8    | 53996  | 11088 | 1.161E+08 | 2     |
| C102-C-0.9 | 102 \times 29 \times 6 | 0.90   | 8.8    | 53996  | 11088 | 1.161E+08 | 2     |
| C102-C-1.0 | 102 \times 29 \times 6 | 1.00   | 9.8    | 53996  | 11088 | 1.161E+08 | 2     |
| C102-C-1.1 | 102 \times 29 \times 6 | 1.10   | 10.8   | 53996  | 11088 | 1.161E+08 | 2     |
| C102-C-1.3 | 102 \times 29 \times 6 | 1.30   | 12.7   | 53996  | 11088 | 1.161E+08 | 2     |
| C102-C-1.5 | 102 \times 29 \times 6 | 1.50   | 14.7   | 53996  | 11088 | 1.161E+08 | 2     |
| C102-C-2.0 | 102 \times 29 \times 6 | 2.00   | 19.6   | 53996  | 11088 | 1.161E+08 | 2     |
| C102-C-2.5 | 102 \times 29 \times 6 | 2.50   | 24.5   | 53996  | 11088 | 1.161E+08 | 2     |
| C102-C-3.0 | 102 \times 29 \times 6 | 3.00   | 29.4   | 53996  | 11088 | 1.161E+08 | 2     |
| C102-C-3.5 | 102 \times 29 \times 6 | 3.50   | 34.3   | 53996  | 11088 | 1.161E+08 | 2     |
| C102-C-4.0 | 102 \times 29 \times 6 | 4.00   | 39.2   | 53996  | 11088 | 1.161E+08 | 2     |

Figure 1: Typical configuration of the test set-up.
3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1. Specimen Behaviors and Modes of Failure

The plot of the load versus the vertical tip displacement of the PFRP specimens obtained from the test is shown in Figure 2. The response curves show that the behavior of the PFRP channel specimens can be generally classified into two types: short beams and slender beams. For the short beams having the span-to-depth ratio less than 10, the curves show that the specimens have a linear elastic response up to 60-80% of the buckling load. After that, the curves are gradually becoming nonlinear, leading to the buckling failure of the beam. For the slender beams having the span-to-depth ratio larger than 10, the linear elastic response of the beams was found up to 90-95% of the buckling load. At the buckling load, all of specimens were failed in the form of twisting and large lateral displacement occurred simultaneously in the form of the lateral-torsional buckling mode of failure. No external material damage was observed. Figures 3(a) and 3(b) show the failure modes of the pultruded FRP channel beams with unbraced length \(L_0\) = 1.5 and 3.0 m, respectively.

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\text{Figure 2: Load versus vertical tip displacement of the pultruded FRP channel beams.}
\]

3.2. Critical Buckling Moment and Comparison with LRFD Approach

For the cantilevered configuration, the observed critical buckling load \(P_{cr}\) can be converting to the critical buckling moment \(M_{cr}\) by using the equation:

\[
M_{cr} = P_{cr}L_h
\]  

(1)

The averaged critical buckling moment for each pair of the specimens is considered as the experimental critical buckling moment \(M_{cr, EXP}\). Table 2 shows the experimentally obtained critical buckling moment \(M_{cr, EXP}\) of the channel specimens. It was found that the critical load increases as the unbraced length of beam decreases. With the increasing unbraced length, the lateral-torsional buckling
mode is more prominent. Thus, the degree of lateral-torsional buckling of the channel beam in this study depends on the unbraced length ($L_b$) of the beams.

Figure 3: Typical modes of failure (a) $L_b = 1.5$ m and (b) $L_b = 3.0$ m of pultruded FRP cantilever channel beams with $L/d$ ratio = 14.7 and 29.4, respectively.

To predict the elastic buckling moment of steel channel specimens, the 1999 AISC/LRFD specifications give the equation in the form of:

$$M_{cr} = C_b \frac{\pi}{L_b} \sqrt{EI_y GJ + \left(\frac{\pi E_L}{L_b}\right)^2 I_y C_w}$$

(2)

where $E$ is the modulus of elasticity, $I_y$ is the moment of inertia of the cross-sectional area about minor axis, $G$ is the shear modulus of elasticity, $J$ is the torsional constant or polar moment of inertia, $C_w$ is the warping constant and $C_b$ is a modification factor for non-uniform moment diagrams. For cantilevers or overhangs where the free end is unbraced, $C_b = 1.0$ (AISC/LRFD, 1999).

Since the PFRP material is usually considered as orthotropic homogeneous material, characterized by using two independent elastic constants: the longitudinal tensile modulus of elasticity ($E_L$) and in-plane shear modulus ($G_{LT}$). Therefore, Equation (2) should be modified by using the elastic constants instead of the isotropic modulus of elasticity ($E_L$) and shear modulus of elasticity ($G_{LT}$), respectively. Then, the modified expression for the critical buckling moment may be rewritten as:

$$M_{cr,LRFD} = C_b \frac{\pi}{L_b} \sqrt{E_L I_y G_{LT} J + \left(\frac{\pi E_L}{L_b}\right)^2 I_y C_w}$$

(3)
Table 2: Experimental critical buckling moment and comparison of the test results with LRFD approach.

| Specimens | Dimensions (d x b x t) (mm x mm x mm) | L / d | Experiment | Analytical |
|-----------|--------------------------------------|-------|------------|------------|
|           |                                      |       | Test A     | Test B     | Average    | LRFD       |
|           |                                      |       | M<sub>cr,A</sub> | M<sub>cr,B</sub> | M<sub>cr,EXP</sub> | M<sub>cr,LRFD</sub> |
|           |                                      |       | (N-m)      | (N-m)      | (N-m)      | (N-m)      |
| C102-C-0.5| 102 x 29 x 6 | 4.9   | 2317.2 | 2293.2 | 2305.2 | 3731.3 | 0.62 |
| C102-C-0.7| 102 x 29 x 6 | 6.9   | 1562.3 | 1542.7 | 1552.5 | 2019.3 | 0.77 |
| C102-C-0.8| 102 x 29 x 6 | 7.8   | 1315.4 | 1276.9 | 1296.1 | 1598.8 | 0.81 |
| C102-C-0.9| 102 x 29 x 6 | 8.8   | 1125.5 | 1116.5 | 1121.0 | 1308.9 | 0.86 |
| C102-C-1.0| 102 x 29 x 6 | 9.8   | 1006.6 | 1016.6 | 1011.6 | 1100.1 | 0.92 |
| C102-C-1.1| 102 x 29 x 6 | 10.8  | 913.0  | 935.0  | 924.0  | 944.3  | 0.98 |
| C102-C-1.3| 102 x 29 x 6 | 12.7  | 696.4  | 748.4  | 722.4  | 730.3  | 0.99 |
| C102-C-1.5| 102 x 29 x 6 | 14.7  | 627.0  | 582.0  | 604.5  | 592.5  | 1.02 |
| C102-C-2.0| 102 x 29 x 6 | 19.6  | 407.4  | 397.4  | 402.4  | 400.8  | 1.00 |
| C102-C-2.5| 102 x 29 x 6 | 24.5  | 321.8  | 308.8  | 315.3  | 303.2  | 1.04 |
| C102-C-3.0| 102 x 29 x 6 | 29.4  | 234.0  | 247.8  | 240.9  | 244.4  | 0.99 |
| C102-C-3.5| 102 x 29 x 6 | 34.3  | 218.4  | 218.8  | 218.6  | 205.1  | 1.07 |
| C102-C-4.0| 102 x 29 x 6 | 39.2  | 190.8  | 167.6  | 179.2  | 176.9  | 1.01 |

Table 2 presents the obtained critical buckling moment compared with those predicted (M<sub>cr,LRFD</sub>) by equation (3). The M<sub>cr,EXP</sub> / M<sub>cr,LRFD</sub> ratios are also presented to show the correlation between the experimental results and the predicted results. Based on the analytical results, the M<sub>cr,EXP</sub> / M<sub>cr,LRFD</sub> ratios are in the range of 0.62 to 1.07. For L / d > 10, the M<sub>cr,EXP</sub> / M<sub>cr,LRFD</sub> ratios show the values close to unity, indicating that the experimental results are in good agreement with the predicted results and corresponding to the experimental study by Turvey (1996). The deviation from unity may be primarily due to the unavoidable initial crookedness of the specimens. On the other hand, for L / d < 10, the M<sub>cr,EXP</sub> / M<sub>cr,LRFD</sub> ratios are in the range of 0.62 to 0.92, indicating that the modified LRFD design equation overestimates the buckling moment of the PFRP channel specimens by approximately 10-40%, depending on the span-to-depth ratio. This is due to the fact that the short beam has higher degree of nonlinear response than the slender beam, which can be seen in Figure 2.

Figure 4 shows the plots between the test results with the predicted results from the modified LRFD design equation in order to check the adequacy of the equation. It can be seen that the modified equation can not by accurately used to predict the critical buckling moment of the PFRP specimens when the short beam with the span-to-depth ratio less than 10 and more development is needed.

4. CONCLUSIONS

Based upon the results of this study, the following conclusions can be drawn:
1. The behavior of the PFRP channel beams subjected to tip concentrated load applied passes the shear center of the cross-section can be generally classified into two types: short beams and slender beams. The short beams have linear elastic response in the range of 60-80% of the buckling load while the slender beams have linear elastic response in the range of 90-95% of the buckling load. All of the specimens were failed in the form of twisting and large lateral displacement occurred simultaneously in the form of the lateral-torsional buckling mode of failure.

2. Based on the test results, the critical buckling moment increases as the span-to-depth ratios of beam decreases. By comparing the obtained critical buckling moment with those predicted by the modified LRFD steel design equation, it was found that they are in good agreement when the span-to-depth ratio exceeds 10. However, for the span-to-depth ratio less than 10, the predicted critical buckling moment overestimate the test results in the range of 10-40% and more development is needed.

![Figure 4: Critical buckling moment versus L/d ratio.](image)

**ACKNOWLEDGMENTS**

The authors gratefully acknowledge all the supports of Suranaree University of Technology for this study, which is a part of the research project “The Development of Design Equation for Pultruded-Fiber Reinforced Plastic Having C-Section under Compression and Flexure”.

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