

On the Structural Responses of Simply Supported PFRP Channel Beams under Three-point Loading

Jaksada Thumrongvut^{1*} and Sittichai Seangatith²

Abstract— In this study, the experimental results on the simply supported PFRP channel beams subjected to three-point loading are presented. The aims of this paper are to investigate the effects of the span (L) on the structural behaviors, the critical buckling loads and the modes of failure of the beams, and to compare the obtained deflections with those obtained from the Timoshenko's shear deformation beam theory equation in order to check the sufficiency of the equation. The beam specimens have the cross-sectional dimensions of $152 \times 43 \times 10$ mm with span-to-depth ratio (L/d) ranging from 13 to 33. A total of sixteen specimens were tested. Based on the experimental results, it was found that the loads versus mid-span vertical deflection relationships of the beam specimens are linear up to the failure, but the load versus mid-span lateral deflection relationships are geometrically nonlinear. The general modes of failure are the flexural-torsional buckling. Finally, the Timoshenko's shear deformation beam equation can adequately predict the vertical deflection of the beams.

Index Term— Pultruded fiber reinforced plastic, Channel profile, Flexural-torsional buckling, Simply Supported, Three-point Loading

I. INTRODUCTION

Fiber reinforced plastic (FRP) composite materials have been increasingly used in the fields of structural engineering applications over the past few decades [1]. The 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 [2]. 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 FRP composite have many advantages over the conventional civil engineering materials such as steel and reinforced concrete. These properties include a high strength-to-weight ratio, high corrosion resistance, tailoring of the material to specific applications and ease of installation [3].

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). Generally, they have the standard PFRP structural profiles similar to the structural steel, including wide-flange sections, I-sections, angles, channels and etc. However, due to relatively low stiffness of the material and thin-walled sectional geometry, the strength is not usually the governing design parameter of the PFRP structural profiles. Mostly, their design is governed by the serviceability parameters such as large deflection or buckling instability, depending on the geometry of the cross-section, the material properties, and the loading conditions [4]. In addition, the critical obstacles to their widespread applications in construction are the lack of simplified and reliable design criteria [5].

The research and development of all PFRP structures in civil engineering have progressed considerably in several countries [6]. In the past decades, several researches have been carried out on the experimental and theoretical evaluations of the flexural-torsional buckling of the PFRP structural beams. However, most of these studies have highlighted on the flexural-torsional behavior of the PFRP beams having doubly symmetric cross-sections such as wide-flange, I, and box profiles [7]-[16]. Only few research works on the mono-symmetric channel profiles were carried-out [17]. In recent years, the applications of the channel profile have been increased considerably in a variety of the secondary structures such as purlins, trusses, and bracing members because they can be easily fabricated and erected. Also, in order to create further confidence in the application of the profile, it is necessary to enhance knowledge of its structural performance, particularly the global behaviors and the global instability. This paper is intended to satisfy a portion of that need. Therefore, the objectives of this paper are to present the experimental results on the structural behaviors and mode of failure of the simply supported PFRP channel beams under three-point loading, and to compare the obtained deflections with those obtained from the Timoshenko's shear deformation beam theory equation in order to check the sufficiency of the equation.

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II. EXPERIMENTAL PROCEDURES

A. Test Specimens

The PFRP channel members used in this study were made of E-glass fiber reinforced polyester resin, and manufactured by a pultrusion process. They have the cross-sectional dimensions of $152 \times 43 \times 10$ mm with span-to-depth ratio (L/d) ranging from 13 to 33. A total of sixteen specimens were tested. Two tests were performed on each span-to-depth ratio. Details of the test profiles, dimensions, and geometric properties are presented in Table I. The specimen numbers were designated in the form of "Cd-S-L". For example, the specimen number C152-S-3.5 is the PFRP channel specimens, having depth (d) of 152 mm, S (simply supported) and span of 3.5 m, respectively.

TABLE I
Geometric properties of the pultruded FRP channel specimens

Specimens	$(d \times b \times t)$ [mm]	L [m]	L/d	I_y [mm ⁴]	J [mm ⁴]	C_w [mm ⁶]	Number
C152-S-2.0	$152 \times 43 \times 10$	2.0	13.2	285281	76000	1.379×10^9	2
C152-S-2.5	$152 \times 43 \times 10$	2.5	16.4	285281	76000	1.379×10^9	2
C152-S-3.0	$152 \times 43 \times 10$	3.0	19.7	285281	76000	1.379×10^9	2
C152-S-3.5	$152 \times 43 \times 10$	3.5	23.0	285281	76000	1.379×10^9	2
C152-S-4.0	$152 \times 43 \times 10$	4.0	26.3	285281	76000	1.379×10^9	2
C152-S-4.5	$152 \times 43 \times 10$	4.5	29.6	285281	76000	1.379×10^9	2
C152-S-5.0	$152 \times 43 \times 10$	5.0	32.9	285281	76000	1.379×10^9	2

C. Test Set-up Configuration

The typical test set-up configuration and instrumentation to measure critical buckling load for the static simply supported with three-point loading test of the PFRP beam is shown in Fig. 1. To prevent beams from sudden falling off in the case of lateral buckling, the beams were restrained laterally at the support by using safety vertical rods fixed at the bottom support. This design prevents the out-of-plane twisting of the ends of the beams. At the mid-span, a bolt with M16 nut was firmly installed on the neutral axis of the cross-section, so that the concentrated vertical load can be applied passing directly through the shear center of the cross-section. The loads were initially applied by sequentially adding steel pendulums on a loading platform. The incremental loads were added until reaching the critical buckling loads and the failure of the beams. It should be noted that the critical buckling load is the values of the corresponding highest end loads at which prior to failure of the beams. Two strain gauges were installed at the top and bottom of the flange at the mid-span section, as presented in Fig. 1(a), to measure the longitudinal strain in flexural span. In addition, two 100 mm linear variable differential transducers (LVDTs) were used to measure the vertical and lateral deflection of the beams in mid-span section, as shown in Fig. 1(b). The overall deflections were automatically recorded by a MW100 YOKOGAWA data

B. Material Properties

To correlate the analytical results with the obtained test results, the values of the longitudinal modulus (E_L) and the in-plane shear modulus (G_{LT}) were determined from the tension test in accordance with ASTM D3039 and the in-plane shear coupon test in accordance with ASTM D5379, respectively. This shear coupon test is in the form of V-notched beam test with the pure shear under a four-point asymmetric bending configuration. From the coupon tests, it was found that the average values of E_L and G_{LT} were 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.

acquisition unit. Finally, the failure mechanisms were also monitored and recorded.

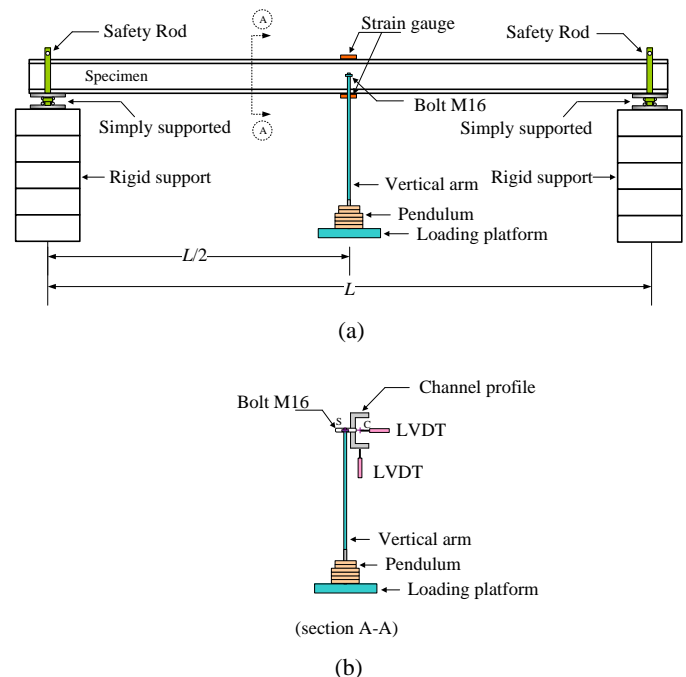
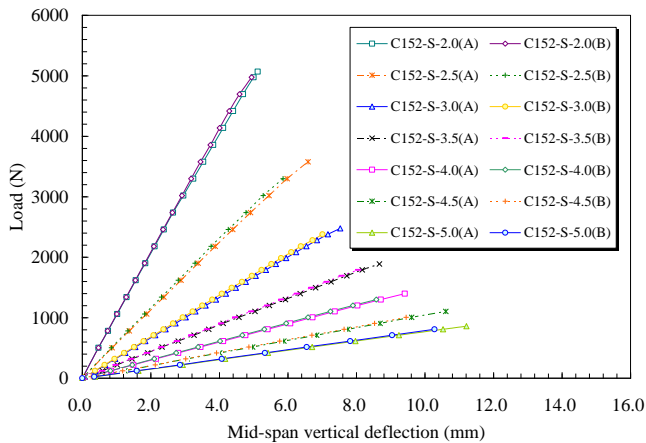


Fig. 1. Test setup (a) A schematic view and (b) Load applied through the shear center

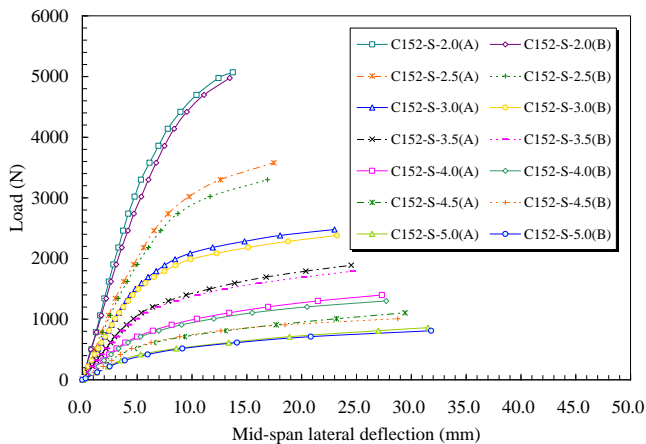
III. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. Behaviors and Modes of Failure

Fig. 2(a) and 2(b) illustrate the behaviors of the PFRP beams in terms of applied load and mid-span vertical and lateral deflection, respectively. It can be seen that the behavior of all beams has a linear elastic response up to 90-95% of the obtained critical buckling load. After that, the curves are becoming nonlinear and leading to the buckling failure of the beam. From the tests also showed that the short span beam has a slightly higher degree of nonlinear response before failure than that of the longer span beam. The distinction is due to the fact that the response of the longer span beams is less stiff than that of the shorter span beams.



(a) mid-span vertical deflection



(b) mid-span lateral deflection

Fig. 2. Load and mid-span deflection relationship of specimens

For the mid-span lateral deflection, the response curves show that the PFRP beams used in this study are in general similar to each other. The load versus mid-span lateral deflection relationships of the beam specimens are geometrically nonlinear, and the response curves exhibit gradually increasing nonlinearity toward 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 flexural-torsional buckling mode of failure. No external material damage was observed. Fig. 3 shows the typical failure modes of the pultruded beams. Fig. 4 represents the response curves between load and longitudinal strain at the top and bottom of the flange at the mid-span section. It is well known that the top and bottom strain at the same position are always in opposite. For this reason, the strains at the top of the flange are compression, while the strains at the bottom of the flange are tension. The tests also showed that both compressive and tensile strain behave linearly up to the failure. The maximum compressive and tensile strains of all beams are in the range of 500-1000 $\mu\epsilon$, and corresponding to the experimental study by Razzaq *et al.* [18].



Fig. 3. Typical modes of failure

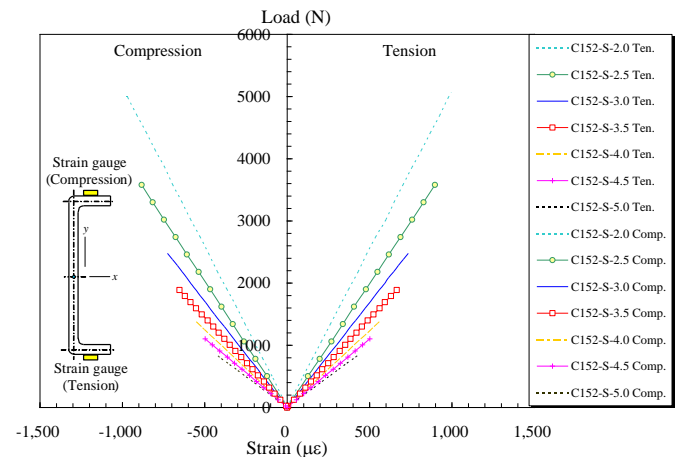


Fig. 4. Load versus longitudinal strain of specimens

Table II shows the experimentally obtained critical buckling load ($P_{cr,EXP}$) of the beams. This indicates that the critical load increases as the span of beam decreases. Also, the degree of flexural-torsional buckling of the channel beams in this study depends on the spans of the beams. With the increasing span,

the flexural-torsional buckling mode is more noticeable. In contrast, it was also found that the obtained maximum deflection ($\Delta_{ver,EXP}$) at the mid-span section increased when the span of beam increases.

B. Prediction of deflections

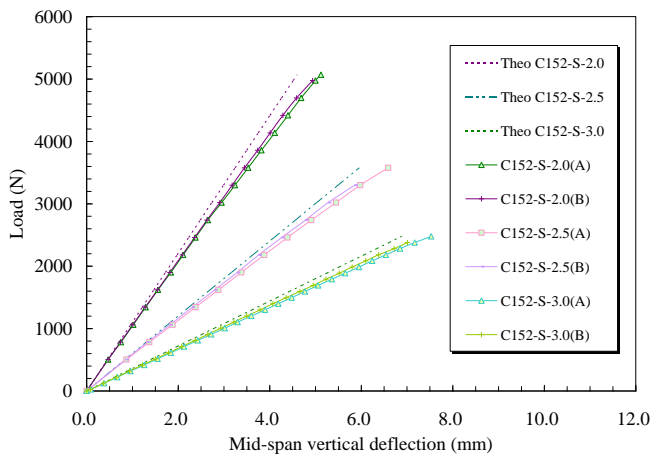
Mottram [8] emphasized that there is a possible risk in analysis and design of FRP beams without including shear deformation. Timoshenko's beam theory [19] can be used to determine the vertical deflection of pultruded beams, which takes into account shear deformation. The usages of shear deformation beam theory are especially significant in pultruded beams because of the relatively high E_L / G_{LT} ratios due to the relatively low shear modulus of pultruded materials [20]. The total beam deflection is a sum of the deflection due to bending deformation and the deflection due to shear deformation. The general expression of the vertical deflection for a three-point loading test with the load applied at mid-span is:

$$\Delta_{max} = \Delta_{flexure} + \Delta_{shear} = \frac{PL^3}{48EI} + \frac{PL}{4kGA} \quad (1)$$

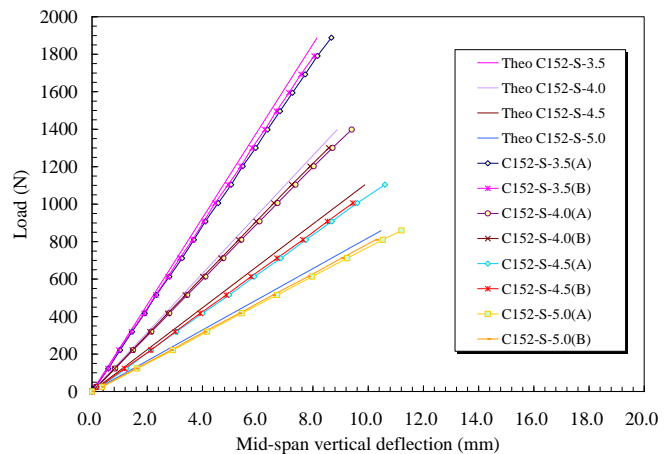
in which EI is the flexural rigidity, kGA is the transverse shear rigidity. For homogeneous pultruded beam, having the same properties in the flanges and webs of the profile, the transverse shear rigidity can be approximated by the in-plane shear modulus multiplied by the area of the web ($kGA \approx G_{LT}A_w$) [20], [21]. Table II also presents the obtained vertical deflection compared with those predicted by equation (1). From the analytical results, the $\Delta_{ver,EXP} / \Delta_{ver,Theo}$ ratios are in the range of 1.05 to 1.10, this indicating that the experimental results are in good agreement with the predicted results. In addition, the effect of shear deformation increases when the span of beam decreases. Based on the results of this study, Fig. 5 shows the plots between the test results with the predicted results from the Timoshenko's beam theory equation in order to check the adequacy of the equation. It can be seen that the theoretical equation can be used to adequately predict the vertical deflection of the specimens.

TABLE II
Experimental critical buckling load and deflection of the PFRP beams

Specimens number	L/d	Experimental				Analytical (1)	
		Test A	Test B	Average	Average	Timshenko	$\frac{\Delta_{ver,EXP}}{\Delta_{ver,Theo}}$
		$P_{cr,A}$ [N]	$P_{cr,B}$ [N]	$P_{cr,EXP}$ [N]	$\Delta_{ver,EXP}$ [mm]	$\Delta_{ver,Theo}$ [mm]	$\frac{\Delta_{ver,EXP}}{\Delta_{ver,Theo}}$
C152-S-2.0	13.2	5069	4976	5023	5.03	4.56	1.10
C152-S-2.5	16.4	3578	3298	3438	6.23	5.73	1.09
C152-S-3.0	19.7	2477	2379	2428	7.27	6.75	1.08
C152-S-3.5	23.0	1889	1790	1839	8.36	7.95	1.05
C152-S-4.0	26.3	1398	1300	1349	9.00	8.57	1.05
C152-S-4.5	29.6	1104	1006	1055	10.03	9.45	1.06
C152-S-5.0	32.9	859	809	834	10.75	10.18	1.06



(a) specimens with span of 2.0 to 3.0 m



(b) specimens with span of 3.5 to 5.0 m

Fig. 5. Load versus deflection curves obtained from the experiment and theoretical calculation

IV. CONCLUSION

Based upon the results, the following conclusions can be drawn:

- 1) The relationship between the load and mid-span vertical deflection of the PFRP channel beams are almost linear up to the failure. In contrast, the load versus mid-span lateral deflection relationships are geometric nonlinear response and the response curves exhibit gradually increasing nonlinearity toward the buckling failure of the beam. All of specimens were failed in the form of twisting and large lateral displacement occurred simultaneously in the form of the flexural-torsional buckling.
- 2) Based on the experimental results, the responses between the load and longitudinal strain at the top and bottom of the flange at the mid-span section are linear up to the failure, and the critical buckling load increases as the span-to-depth ratios of beam decreases.
- 3) By comparing the obtained vertical deflection with those predicted by the Timoshenko's shear deformation beam equation, it was found that they are in good agreement. It is concluded that the shear deformation beam theory is especially important in pultruded beams, which is of key importance for the serviceability design.

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