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Shear Buckling of a Large Pultruded Composite I-Section under Asymmetric Loading

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***Abstract*—**An experimental and analytical research on shear buckling of a comparably large polymer composite I-section is presented. It is known that shear buckling load of a large span composite beam is difficult to determine experimentally. In order to sensitively detect shear buckling of the tested I-section, twenty strain rosettes and eight displacement sensors were applied and attached on the web and flange surfaces. The tested specimen was a pultruded composite beam made of vinylester resin, E-glass, carbon fibers and micro-fillers. Various coupon tests were performed before the shear buckling test to obtain fundamental material properties of the I-section. An asymmetric four-point bending loading scheme was utilized for the shear test. The loading scheme resulted in a high shear and almost zero moment condition at the center of the web panel. The shear buckling load was successfully determined after analyzing the obtained test data from strain rosettes and displacement sensors. An analytical approach was also performed to verify the experimental results and to support the discussed experimental program.

***Keywords*—**Strain sensor, displacement sensor, shear buckling, polymer composite I-section, asymmetric loading.

I. Introduction

SINCE the early 1990s, many researchers have studied the buckling of fiber reinforced polymer (FRP) composite members: Barbero and Raftoyiannis reported analytical and experimental approaches to buckling of pultruded FRP columns [1], [2]. Motram [3] published his study on pultruded composites' lateral-torsional buckling for the first time. Bank [4] and his colleagues published a paper describing their effective lateral buckling test method for composite beams. In 2002, Roberts [5] published that a shear deformation could significantly influence the buckling behavior of a composite I-section under any loading scheme. Shan and Qiao [6] proposed a test method and theoretical verification using energy theory for flexural torsional buckling of an open channel beam. Many other recent papers [7]–[11] have described theoretical and experimental approaches to buckling of composite members and concluded by mentioning the important effect of shear behavior on buckling. However, a full experimental approach to obtain the shear buckling load of large polymer composite I-sections has not been studied much yet. This is because a pure shear stress state is very difficult to achieve experimentally with a large span composite I-section.

In this study, a test method to detect and determine the critical shear buckling load and to observe the buckling behaviors of a comparably large pultruded composite I-section was discussed. An asymmetric shear loading scheme was proposed and utilized for the test program. In order to sensitively obtain the shear buckling load and shear behavior of the composite I-section, twenty strain rosette sensors were attached on the web surface of the I-section. The tested section was also instrumented at various locations with displacement sensors to indicate lateral and vertical displacements of the web. Finite element analysis results were compared with those from the experimental test to verify and support the discussed experimental method.

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II. Experiments

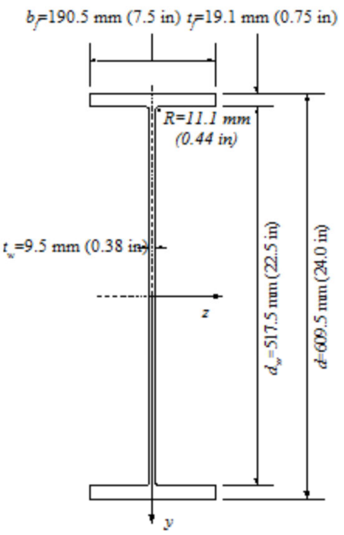

Fig. 1 The cross-sectional dimensions and reinforcing scheme of the test component.

The tested composite girder was a 4,572 mm (15 ft.) long I-shaped section having the cross-sectional dimensions shown in Fig. 1. The web was reinforced with a total of six layers: They are two layers of E-glass rovings and three layers of randomly oriented E-glass CSM (Continuous Strand Mat). The top and bottom flanges were reinforced with eleven E-glass/carbon hybrid rovings combined with E-glass CSM layers for each; four layers of carbon roving, a layer of E-glass roving and six layers of E-glass CSM. The weight fractions of the composite constituents of the web were examined following the technique described in [12], which was based on ASTM D 2584 [13]. Regarding the weight fractions of the constituents of the flanges, the technique described in ASTM D 3171 [14] was used. Since the carbon fibers are oxidized during a burnout process, the technique outlined in [12] could not be utilized for the flange elements. Thus, digestion in nitric acid 70% solution was performed. After digestion for 168 hours (one week), the carbon and glass fibers were rinsed with acetone and water. The tensile, compressive and shear properties of the web and frange materials of the tested I-shaped section were determined according to ASTM D 3039 [15], ASTM D 3410 [16] and ASTM D 5379 [17], respectively.

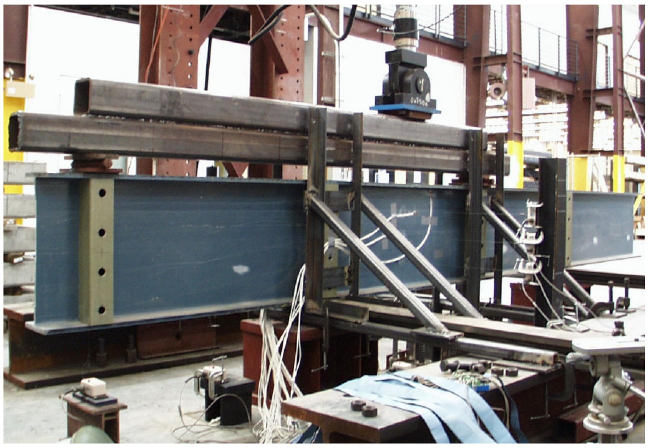

Fig. 2 Asymmetric four point loading test setup

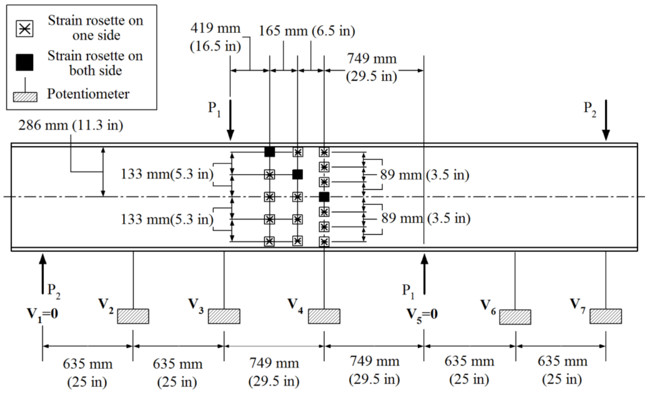

Fig. 3 Locations of strain rosettes and displacement sensors on the bottom flange

Fig. 2 shows a photograph of the test component subjected to four point asymmetric loading. Due to the asymmetric loading pattern, there is the maximum vertical shear force applied at the center of the specimen. Bending moment should be theoretically zero at the center of the beam. At the support and load application points, transverse stiffeners on both sides of the web were provided. A total of eight E-glass/vinylester tubular sections having nominal dimensions of 101.6 mm x 101.6 mm x 9.53 mm (4 in. x 4in. x .375 in.) were used as transverse stiffeners. The girder was restrained against lateral movement by means of a total of eight steel plates having dimensions of 76.2 mm x 381 mm x 12.7 mm (3 in. x 15 in. x .5 in.) and the transverse stiffeners at the support and load application points. A spreader beam was placed between the load actuator and two bearing plates to apply the asymmetric loading to the specimen. By this loading mechanism, the applied load P was divided into $0.73P$ and $0.27P$ at the shown bearing contacts.

The instrumentation in the girder consisted of strain rosette manufactured by Vishay (CEA-125-UR-350) and displacement sensors that were Celesco PT1A string potentiometers with up to 254 mm (10 in) measurement capacity and accuracy of 0.15% of full stroke range. Twenty strain rosette sensors were used to measure -45°, +45° and 0° directional strains as shown in Fig. 3. Seventeen strain rosettes were attached on one side of the web and the other three strain rosettes were located on the other side of the web. The identifications of the strain rosettes are shown in Fig. 4. Three locations (A-4, B-2 and C-1) were selected for back-to-back strain rosette applications to accurately determine the strains near buckling. Out-of-plane bending could also be observed by the measurement of the strains from the back-to-back rosettes at these points. Seven strain rosettes were aligned vertically on the center line A-A. Five strain rosettes were located on line B-B 165.1 mm (6.5 in) from A-A. Five strain rosettes are also located on line C-C 330.2 mm (13.0 in) from A-A.

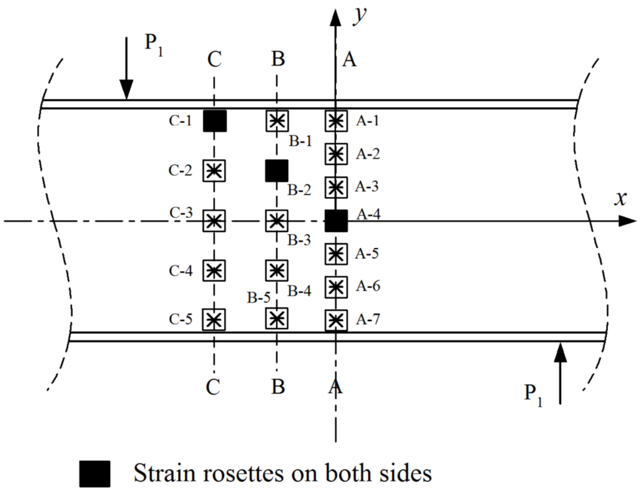

Fig. 4 The IDs of strain rosettes on the web surface

A total of eight displacement sensors were used to measure the vertical and lateral deflections of the web. Seven locations, including two supporting points, were selected to measure vertical deflections using the potentiometers. They were V_1, V_2, V_3, V_4, V_5, V_6 and V_7 as shown in Fig. 3. The vertical deflections at the supporting points (V_1 and V_5) were obviously zero. The locations of the potentiometers are also shown in Fig. 3. Three additional displacement sensors used to measure the lateral deflections along A-A. One is at A-4 the other two are at 142.9 mm (5.63") up and down.

III. Results and Discussions

Load-vertical deflection curves at five locations along the bottom of the lower flange are shown in Fig. 5. The vertical deflections were measured using displacement sensors. Fig. 6 shows the lateral web displacements measured by potentiometers at three locations of the center of the girder.

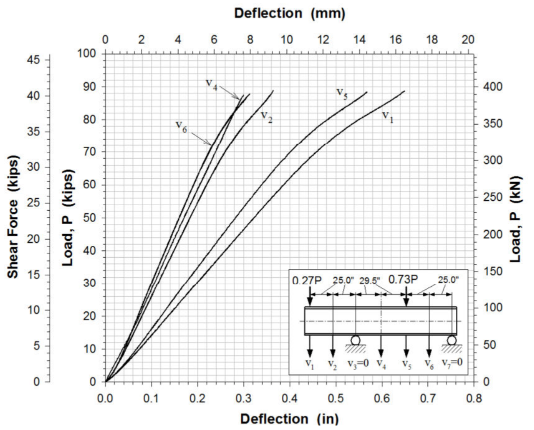

Fig. 5 Measured bottom flange vertical displacements

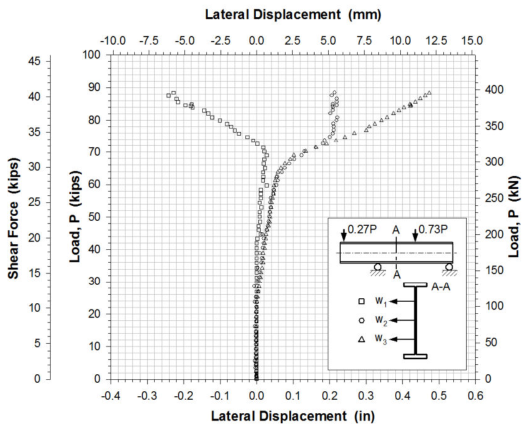

Fig. 6 Web out-of-plane displacements at section A-A

Figs. 7 and 8 show the shear strains in the *x*-*y* plane γ_{xy}, the difference in the shear strain values obtained from the back-to-back gages $(\gamma_{xy})_1$ and $(\gamma_{xy})_2$, and the average value of the shear strain γ_{xy} at locations A-4 and B-2, respectively. All figures show clearly that prior to buckling the load-strain behavior were close to linear.

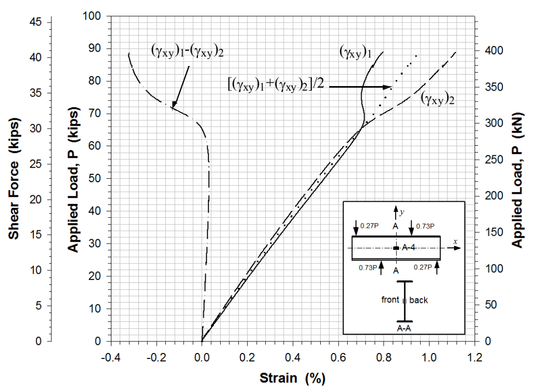

Fig. 7 Load-shear strain at location A-4

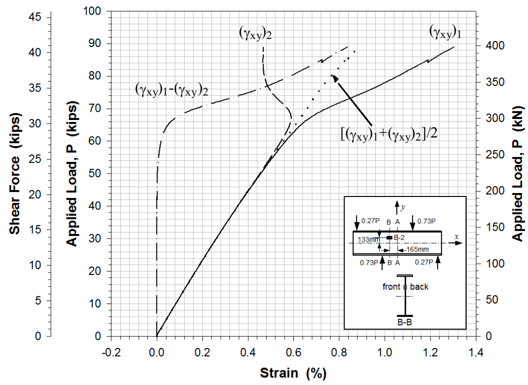

Fig. 8 Load-shear strain at location B-2

The experimental buckling load was estimated from the load-lateral displacement curves obtained from the displacement sensors (Fig. 6) and from the load-strain relation curves determined by the data points of strain rosettes (Figs. 7 and 8). It was determined by taking the intersection point of the tangent drawn to a curve before and after buckling as outlined by [18]. This method is a well-known method called Bifurcation method. It is based on the phenomenon that the web surface should be sharply deformed at the moment of buckling. The critical load was determined by applying projection of the intersection onto the load-displacement and load-strain curves. Any analytical equation was not used to determine a shear buckling load in this study. The evaluation results for the experimental buckling load by the data curves in Figs. 6-8 were very consistent. The determined shear buckling load was 295 kN (66.3 kips).

IV. Conclusions

In this study, the buckling of a pultruded polymer composite I-shaped section under shear loading was investigated experimentally. Based on the results, the following conclusions were derived:

(1) The presented shear buckling test method using an asymmetric loading scheme effectively generated a shear loading condition and a pure shear region on the web of the tested I-section.
(2) The corresponding displacements and shear strains were successfully obtained from the displacement and strain sensors, and they were used to observe the shear buckling behaviors of tested composite I-section.
(3) In order to determine shear buckling load experimentally, a classical approach presented by Hoff, et al. was used. The results of shear buckling loads from load-lateral displacements relations, and load-shear strain at three different locations were very close.
(4) The critical shear buckling load experimentally obtained was 295 kN (66.3 kips).
(5) In order to verify the experimental results, a finite element analysis was performed. The obtained shear buckling load was 292 kN (65.6 kips). The analysis results support the validity of the presented experimental approach.

ACKNOWLEDGMENT

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