Experimental and numerical study of the torsional response of a modular hybrid FRP-aluminum triangular deck-truss beam

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ABSTRACT: A hybrid fiber-reinforced polymer (FRP) - aluminum modular space truss emergency bridge has been designed that consists of two triangular deck-truss beams incorporating a new structural form and advanced pultruded FRP profiles. As a fundamental investigation, this paper explores the detailed torsional behaviors of the new triangular deck-truss beam. A full-scale specimen was prepared and tested under pure torsion to evaluate the representative structural performances. A three-dimensional finite element model (FEM) was constructed and validated with experimental results showing good comparisons. Furthermore, the torsional behavior of the triangular deck-truss beam was numerically investigated by removing individual primary truss members to clearly understand the torsional mechanism. It was found that the beam exhibited a specific and unfavorable mechanical behavior prohibiting full utilization of the FRP material' potential. The external torsional moment is primarily resisted by the torsion of the longitudinal profiles and the in-plane bending of the bilateral Vierendeel trusses rather than the out-of-plane bending of the web diagonals. Possible improvement and optimization procedures are further suggested for this beam when solely used as a structure subjected to off-axis load or pure torsion.

Keywords: Emergency bridge; Modular structure; Dismountable truss; Hybrid structure; Pultruded FRP profiles; Orthotropic deck; Pure torsion test

1. Introduction

The availability and effectiveness of rapid emergency bridging systems are critical for the survival of military

personnel and those affected by natural disasters. In response to the continued desire for emergency bridges with lightweight, high strength, modular feasibility and fast construction, the applications of advanced materials, novel structural form and new technique are preferred approaches. Pultruded fiber-reinforced polymer (FRP) materials are increasingly used in the field of civil engineering as a result of their excellent properties, such as high stiffness/strength-to-weight ratio, sufficient durability and shorter installation time [1-5]. In particular, these features are ideal for new bridge constructions, such as bridge decks [6,7], footbridges [8,9], vehicular bridges [10,11] and emergency bridges [12,13]. If the pultruded FRP profiles are further implemented in favorable structural forms, e.g., planar [14,15], triangular [16,17], rectangular [18], spatial [19] and latticed trusses [20,21], the advantages of both the materials and the structures will be greatly extended [22-25]. Finally, further weight reduction and initial cost effectiveness could be achieved.

For the design of dismountable truss bridges assembled from pultruded FRP profiles, a key technique is to conceive and design appropriate connections that can exploit the advantages of high stiffness and strength [22]. To date, the usual jointing techniques for pultruded FRP profiles are bolted and bonded connections [26-28]. However, the load-bearing capacity of these basic techniques is low and they are mainly applied to planar panels rather than tubular member profile [29]. In response to this issue, several new jointing techniques were developed [22-23,30] to address the inappropriate joint designs, which contribute much to the application of FRP materials in heavy-traffic bridges [22-23,30]. A novel jointing technique termed the pre-tightened teeth connection (PTTC) was proposed [31]. This PTTC technique enables the pultruded FRP profiles to exhibit superior mechanical performance and to be easily connected with other structural members using conventional mechanical methods or welding technology.

Based on the PTTC, a new hybrid FRP-aluminum space truss emergency bridge was designed [31]. The bridge

has an ability to carry a traffic load weighing 100 kN despite weighing only approximately 1.2 tons. The bridge consists of twin trackways linked by hinged transverse braces. Each trackway is designed as a type of inverted triangular deck-truss beam incorporating a new structural form and advanced pultruded FRP profiles, and is composed of four modules jointed by male jugs and female jaws. An on-axis four-point bending loading test was previously performed on a full-scale triangular deck-truss beam to examine the flexural behavior of the entire bridge [31]. The results confirmed the feasibility of the PTTC technique and the favorable flexural properties of the proposed bridge. In fact, for this type of bridge with the structural form of a spatial truss, the torsion caused by the off-axis traffic load is usually a more critical loading condition controlling the structural responses than the on-axis load. However, there are no reports of the detailed torsional behaviors of such a complete bridge.

Actually, when each triangular deck-truss beam is treated as a longitudinal girder, this twin-trackway bridge can be regarded as a girder bridge composed of two longitudinal girders linked by rigid cross-beams. In this case, the torsional behavior of such an equivalent twin-girder bridge can be analyzed according to the modified eccentric compression method of the multi-girder bridges [32]. That is, the torsion of such a complete bridge can be decomposed into bending and torsion of its twin triangular beams [33]. Thus, an understanding of the detailed torsional response of the triangular deck-truss beam is fundamental to investigating the torsional behaviors of the entire space truss bridge. However, such a study on the triangular deck-truss beam under torsion has not yet been conducted. As a new structure, the hybrid triangular deck-truss beam is quite different in its structural configuration from conventional steel triangular tubular trusses [34-36]. It is expected, therefore, that the hybrid triangular deck-truss beam will exhibit unique torsional response, the investigation of which is necessary and meaningful.

The torsional response of the new bridge is characterized using a research program with the following two-part scope: (i) an experimental and numerical study on a triangular deck-truss beam; and (ii) an experimental and

numerical study on a complete space truss structure. The present paper focuses on stage (i), whereas stage (ii) will be addressed in forthcoming papers. In this paper, two full-scale triangular modules are mounted to a specimen and investigated through pure torsional testing and numerical analysis. The representative structural response are studied in detail. Furthermore, to clearly understand the roles of different trussed members in the torsional mechanism, a corresponding numerical analysis is conducted by removing different primary truss members. Subsequently, possible structural improvements and optimization steps for the structure in question are discussed for cases when the triangular deck-truss beam is solely used as a structure subjected to an off-axis load and torsion.

2. Description of the structure

The hybrid triangular deck-truss beam of the proposed emergency bridge [31] is mounted using four modules composed of an aluminum orthotropic deck supported by aluminum and pultruded FRP profiles. The orthotropic deck is designed to be welded into the main triangular truss to form an integral piece. The fabricated module are presented in Fig. 1. The joints of two modules are created by male jugs and female jaws with the aid of the PTTC technique [31]. As a new structure, it embodies characteristics of existing steel triangular trusses [34-37], T-type beams [38,39] and plane trusses [25], but it is not equivalent to any of these conventional structural forms. That is, the hybrid triangular deck-truss beam consists of a new structural form and advanced pultruded FRP profiles.

Each triangular module has a length of 3 m and an inverted triangular cross-section with a 1.2-m width and 0.85-m depth. In the design, aluminum alloy extrusions with different cross-sections were used for the orthotropic deck, connectors and verticals; additionally, pultruded hybrid fiber-reinforced polymer (HFRP) and glass fiber-reinforced polymer (GFRP) tubes were selected for the lower chords and the web diagonals, respectively. Here, the HFRP material is an admixture of E-glass fiber, carbon fiber and basalt fiber embedded in an isophthalic vinyl ester resin. More information about the hybrid triangular deck-truss beam is presented in [31], including the

detailed connectors, geometries and mechanical properties of the profiles used.

3. Experimental program

3.1. Specimen and test configuration

In the experiments, two pre-fabricated full-scale modules were mounted to a 6-m cantilever specimen and subjected to pure torsion. The specimen and the associate test configuration are illustrated in Fig. 2. At the fixed end, a custom-manufactured steel frame was selected to support the specimen. On the steel frame, four steel male jugs were welded to well connect the female jaws of the specimen using pins. At the free end, two reverse concentrated loads F (one pointing down and the other pointing up) provided by bob-weights were applied on the two side upper male jugs to obtain the external torsional moment. The bob-weight was composed of a hanging basket and several same steel blocks. The bob-weights were synchronously lifted by hand chain blocks with the aid of a counterforce frame constructed from a series of off-the-shelf Bailey trusses. The load arm of the external torsional moment was set at 1.2 m. Four load levels were applied ($F = 2$ kN, 3 kN, 4 kN and 5 kN). A loading and unloading process ($F = 2$ kN) was first repeated three times to minimize possible initial mounting inaccuracies and to ensure that all loading setup and instruments worked properly.

3.2. Measurement instrumentation

In the test, the specimen was equipped with electric inclinometers and an Electric Total Station (ETS) to measure the torsional angles and displacements, respectively. The corresponding instrumentation layout is shown in Fig. 3(a). In the figure, four triangular cross-sections are shown as gauged and are referred to as A-1, A-2, A-3 and A-4. The electric inclinometers were placed on the deck and along the middle main longitudinal beams. Additionally, the specimen was equipped with calibrated unidirectional strain gauges to measure the longitudinal strains. The instrumentation layout for the strain gages located on the tubular members and the orthotropic deck is

shown in Figs. 4(b) and (c), respectively. Note that all of the tubular cross-sections of the lower chords and the web diagonals are viewed from the free end to the fixed end along the specimen; the tubular cross-sections of the verticals are viewed along the tubes from points "c" to "a" and then from "a" to "b". For all of the instrumented tubular cross-sections, four strain gauges were laid equidistantly and counterclockwise. For the deck, three strain gauges were located at the upper flange, lower flange and middle position at every instrumented I cross-section of each main longitudinal beam (Z1, Z2 and Z3), and one strain gauge was mounted at the upper flange of each secondary longitudinal beam (Z4 and Z5). The strain data were synchronously recorded by four static strain indicator data acquisition systems connected to a computer. The weights of the bob-weights were recorded at each load level, avoiding the need to measure the applied concentrated loads F using a load cell or any other method.

3.3. *Experimental results*

3.3.1. *Deformation, displacement and torsion angle*

During the loading process, visual inspection revealed that the triangular deck-truss beam deformed torsionally, as shown in Fig. 4. Similar to the main and secondary longitudinal I beams of the aluminum orthotropic deck, the HFRP lower chords displayed an unambiguous torsionally deformed shape. Moreover, an apparent dislocation appeared at the upper male jaw and female jug between two modules; i.e., the central line of the female jug was no longer parallel to that of the male jaw. However, the analogous dislocation between the male jaw and female jug connecting the lower chords of the two modules was minor and can be neglected. The dislocation is attributed primarily to the interstice between the pin and pinhole combined with that between the upper male jaw and female jug. The dislocation is a particular torsional behavior characteristic to this modular structure.

Figs. 5 and 6 show the variations of the displacements of the orthotropic deck and the lower chords, respectively. It can be observed that all of the measured load-displacement curves are essentially linear, indicating

that the specimen deformed in the elastic region, as desired. Namely, the hybrid triangular deck-truss beam did not distort under the applied torsional moment. In Fig. 5, the curve of point "b" is nearly symmetrical with that of point "c" at every triangular cross-section for both the vertical and horizontal displacements; i.e., the two side longitudinal beams deformed in a compatible manner. In addition, the displacements at point "o" are approximately equal to zero (the corresponding curves are not shown). Thus, the orthotropic deck was almost rotated by the middle main longitudinal I beam. It is concluded that the torsional center of the hybrid triangular deck-truss beam without distortion was nearly collocated with that of the orthotropic deck. The aluminum orthotropic deck played a critical role in the determination of the torsional center of the hybrid structure.

In Fig. 6, the displacements of point "a" at sections A-4 and A-3 are not shown because the sight-line from ETS to notations was blocked in the test. The figure indicates that the HFRP lower chords deformed with a small vertical upward displacement, and the maximum value at A-1 was only 8.9 mm. However, the corresponding horizontal displacement reached 124.6 mm. These measurements indicate that in addition to the apparent torsional behavior (as observed in Fig. 4), the HFRP lower chords underwent a large horizontal bending deformation. The bending deformation of the HFRP lower chord was initiated by the rotation of the deck through the verticals and the web diagonals. In other words, the verticals and the web diagonals played a key role in facilitating the rigid rotation of the triangular cross-section and transferring the load from the deck to the lower chords.

Fig. 7 shows the measured relationship between the torsional moment and torsional rate (the slope is an indication of torsional stiffness). In the figure, GJ-0, GJ-1+2, GJ-1 and GJ-2 represent the segment of the specimen from section A-3 to A-2, from A-4 to A-1, from A-2 to A-1 and from A-4 to A-3, respectively; the torsional rate is obtained by dividing the torsional angles (recorded by electric inclinometers) of every segment by the corresponding segment length. It can be observed that except for the curve of GJ-0 below 3.6 kN·m, the four curves

are essentially linear and parallel. The change of the slope of GJ-0 at 3.6 kN·m is attributed primarily to the aforementioned dislocation, as illustrated in Fig. 4. At torsional loads higher than 3.6 kN·m, the dislocation disappeared and GJ-0 deformed in step with GJ-1 and GJ-2. By linear curve fitting, slopes with the following values are obtained: 5.76, 5.54, 3.95 and 4.51 kN·m²/deg for GJ-0, GJ-1+2, GJ-1 and GJ-2, respectively. The difference between GJ-1 and GJ-2 is caused primarily by the different restraining stiffness of the fixed end between the two modules. The differences between GJ-1 and GJ-1+2 and between GJ-2 and GJ-1+2 arise primarily because the torsional angle caused by the dislocation is included in the calculation of the torsional stiffness of GJ-1+2.

3.3.2. *Stresses in the tubular members*

In the test, no cracking was audible during the loading process. Fig. 8 shows the measured load-stress curves of three representative instrumented cross-sections (L1, L2 and L4) of the HFRP lower chords. The figure demonstrates that the axial stresses on the lower chord were minor and can be neglected. However, certain bending stresses existed in both the vertical plane (A-C plane) and the horizontal plane (B-D plane). The bending stresses at points B and D were much larger than those at points A and C; i.e., the lower chords primarily bore out-of-plane (horizontal-plane) bending moments rather than in-plane (vertical-plane) ones. This stress state correlates well with the corresponding deformation of the lower chords, which underwent large horizontal deformation but small vertical displacement (see Fig. 6). At the same tubular cross-section, the curves of points B and D are nearly symmetrical, as are the curves of points A and C. This finding indicates that the tubular cross-sections of the lower chords were in an almost pure bending state in both the vertical and horizontal planes. In addition, the horizontal bending stress does not gradually increase from the free end to the fixed end, indicating that the lower chord cannot be simply classified as a cantilever beam subjected to a concentrated load.

Fig. 9 shows the measured load-stress curves of the instrumented cross-sections D4 and D2 of the GFRP web

diagonals. The curves of D1 and D3/D5 are not shown because their behavior was similar to those of D2 and D4, respectively. This figure demonstrates that at the same tubular cross-section, the bending stress in the A-C plane was much smaller than that in the B-D plane; the axial stress was also much smaller and can be neglected. Similar to the lower chords, the web diagonals primarily bore an out-of-plane bending moment rather than an in-plane ones and an axial force. Moreover, the bending stress at points D and B of D4 indicates in a compression and tension state, respectively. These stress states are opposite those of D2 and D1, in which the bending stress at point D was under tension whereas point B was under compression. That is, the web diagonals with different inclination display an opposite out-of-plane bending direction. This contrast occurs primarily because the torsional angles of the triangular cross-sections increased from the fixed end to the free end along the bridge axis; under this condition, the deformation at the lower end of D4 occurred relative to that at its upper end, whereas the deformation at the lower end of D2 was relative to that at its upper end. Thus, the opposite horizontal bending moments were generated in D4 and D2 with an opposite inclination. From another point of view, if all of the triangular cross-sections were to rotate around the middle longitudinal beam with same torsional angle, all of the web diagonals would deform in-step with the same angles and the above horizontal bending moment would be equal to zero.

Fig. 10 shows the measured load-stress curves of the tubular cross-sections V1, V2 and V3 of the vertical. Because of space confinements, the curves of other tubular cross-section are not shown because they exhibited similar stress states. The figure shows that at the two end cross-sections (V1 & V3), the bending stresses at points B & D were much larger than those at points A & C, and the axial stress approached zero. However, at the middle cross-section (V2), the bending stresses at points B & D and A & C and the axial stress were nearly equal to zero. These measurements indicate that the verticals bore a regular in-plane bending state (in the diagonal plane parallel to the bridge axis). The in-plane bending stresses were caused primarily by the frame effect of the Vierendeel truss

composed of the side longitudinal I beams, the verticals and the lower chords. When the cantilever Vierendeel truss was subjected to a concentrated load (caused by the applied torsional moment) at the free end, a large bending moment distributed as a frame effect was generated.

3.3.3. Stresses in the longitudinal I beams

Fig. 11(a) presents the measured stresses in the longitudinal I beams of the orthotropic deck at 6.0 kN·m. It can be observed that the longitudinal I beams exhibited a complicated stress distribution, which was caused primarily by the spatial effect of the structure under torsion. In the two side I beams (Z1 and Z3), especially at their lower flange (shown in blue), the stresses were of a similar order of magnitude to those in the tubular members. The stresses in Z1 and Z3 were much larger than those in the middle beam Z2, which correlates well with the corresponding deformation (i.e., the vertical displacements of Z1 and Z3 were much larger than those of Z2). This difference arises primarily because the orthotropic deck rotated around the beam Z2. The results indicate that the two side main longitudinal I beams carried much more of the applied torsion moment than the middle one.

In addition, the stresses in Z1 and Z3 were much larger than those in Z4 and Z5, mainly because the secondary longitudinal I beams Z4 and Z5 were broken at the jointing segments and the fixed end, which is much different from the case of the continuous main ones Z1 and Z3. When the triangular deck-truss structure was subjected to a torsional moment, the non-restrained secondary longitudinal I beams exhibited no deformation and minimal stress was induced. Thus, compared to the secondary longitudinal I beams, the two side main longitudinal I beams played a much more critical role (in terms of vertical bending acting as a frame effect) in carrying the applied torsional moment for the spatial structure. The contribution of the secondary longitudinal I beams can be neglected.

Furthermore, at every measured I cross-section of Z1 and Z3, the stresses at the upper flange (black font), lower flange (blue font) and middle position (red font) were not equal. That is, stress arose not only from the pure

bending but also from axial forces. However, compared to the bending stresses, the axial stresses were much smaller and can be neglected. Moreover, the two beams bore a symmetrical stress state, which correlates well with the measured symmetrical vertical deformation (see Fig. 5). As illustrated in Fig. 11(b), both Z1 and Z3 bore a segmental bending stress state, which matches well with that of the verticals. This finding is attributed primarily to the aforementioned frame effect of the Vierendeel truss. For the bilateral Vierendeel trusses, the verticals can be considered to be elastic supports of the two side beams. From another point of view, if the verticals were removed from the Vierendeel trusses, the two side beams would be in a cantilever condition. However, with the verticals present, the two side beams are segmentally restrained and the stresses are redistributed.

4. Finite element analysis

4.1. Finite element modeling

From the experiments, it is concluded that the deformation of the lower chords primarily originates from the rotation of the deck through the verticals and the web diagonals; the applied torsional moment is resisted mainly by the vertical bending of the Vierendeel trusses, the out-of-plane bending of the web diagonals, the torsion of the main longitudinal I beams and the lower chords. To further understand the roles of the verticals and the web diagonals in the torsional mechanism, the structural responses were numerically investigated by removing the individual primary truss members with same type from the original structure prior to any load application. The numerical analysis was conducted using ANSYS 13.0. The finite element (FE) model of the specimen was first built and is referred to as M-1, as illustrated in Table 1. In addition, four other unique conditions were established for comparison. M-2 corresponds to the removal of all of the verticals from M-1; M-3 corresponds to the removal of all of the web diagonals from M-1; M-4 corresponds to the removal of all of the web diagonals and the four verticals (two verticals in the mid-span of every module) from M-1; and M-5 corresponds to the removal of all of

the tubular members (only deck with hinge joints) from M-1.

In the FE models, the Shell-63 element was employed to model the thin slab of the deck; the Beam-188 element was used to model the crisscrossing I beams, tubular members and connectors. The connectors were simplified as segments of the corresponding truss members. Material and geometrical non-linear effects were not considered. The generalized Hook's laws of linear elastic anisotropic and isotropic materials [40] are used as the constitutive material laws of the pultruded FRP profiles and the aluminum alloy extrusions, respectively. The engineering constants used for the generalized Hook's laws are summarized in [31]. In M-1~M-4, the appropriate displacement boundary constraint for the hinge joints was achieved by releasing a rotational DOF; in M-5, the corresponding nodes of the connectors were set as rigid to ensure convergence. In accordance with the test, four load levels were evaluated. The dead weight was not considered.

4.2. Validation of the original FE model

Fig. 12 compares the numerical torsional stiffness with experimental results for two modules of the original structure. The numerical torsional stiffness was obtained by linear fitting of the torsional moment as a function of torsional rate of M-1. It is found that the numerical linear curves lie close to the measured ones, especially for GJ-1. The torsional stiffness of GJ-1 and GJ-2 is numerically calculated to be 4.17 and 3.57 kN·m²/deg, respectively. For GJ-1 and GJ-2, the discrepancy of the torsional stiffness between numerical and experimental results is approximately 7.5% and 11.6%, respectively. It appears that, besides experimental errors, the discrepancy is caused primarily by different boundary constraints, spatial effects, and local configurations in the FE model compared to the actual specimen. Additionally, it is likely that the large numerical value of GJ-1 compared to GJ-2 arises because the restraint stiffness of GJ-1 in M-1 is larger than that of GJ-2; the aforementioned dislocation between the male jaw and female jug cannot be modeled in sufficient detail for M-1 to replace the actual condition.

Fig. 13 compares the numerical stress with experimental results for several representative tubular cross-sections. Because of the similar analysis results, as described herein, the comparisons for other tubular cross-sections are not shown. The figure demonstrates that the numerical values correlate well with the measured results; the maximum discrepancy is approximately 15.6%. In addition, the numerical results show that the lower chords and the web diagonals bear primarily out-of-plane bending stress, rather than the axial stress and in-plane bending stress; the verticals bear primarily in-plane bending stress, rather than the axial stress and out-of-plane bending stress; and the web diagonals with opposite inclination bend in an opposite directions, which holds true for the two ends of the verticals. These numerical stress distributions correlate well with the measured results. Furthermore, it is confirmed from the numerical contours that the bending moment in the Vierendeel trusses exhibit a bending state with a type of frame effect (see Fig. 14a); the lower chord bears a large torsional moment (see Fig. 14b), in good agreement with the experimental deformation (see Fig. 4). Thus, it is concluded from the above comparisons that the torsional responses of the structure can be well simulated by the established FE model.

4.3. Comparison of the different FE models

For the five FE models, representative deformations were first compared, including the displacements and the torsional angles at the cantilever triangular cross-section, as summarized in Table 1. The results indicate that when all of the verticals are removed, the vertical displacements $z(a)$, $z(b)$ and $z(c)$ of M-2 are approximately 2.4 times those of M-1. The two side longitudinal I beams exhibit large horizontal displacements $y(b)$ and $y(c)$, which are approximately 5.4 and 6.1 times those of M-1, respectively. Furthermore, the orthotropic deck and the lower chords rotate with a much larger angle of 22.1° and 13.9° , respectively. The angle θ_1 is as much as 59.5% larger than θ_2 . Namely, the line a'-o' is no longer perpendicular to line b'-c', indicating that the triangular cross-section displays an apparent distortion. The large deformation discrepancy between M-2 and M-1 arises primarily because the two side

longitudinal I beams and the lower chords are no longer restrained by the verticals in M-2.

However, when all of the web diagonals are removed, the values $y(a)$, $z(b)$ and $z(c)$ of M-3 are only approximately 1.1 times those of M-1, and the values $y(b)$ and $y(c)$ are still minimal. In addition, the values θ_1 and θ_2 are similar, indicating that the deformed triangular cross-section is not distorted. The above comparison indicates that in the original structure, compared to the GFRP web diagonals, the aluminum verticals play a much more critical role in facilitating the rigid rotation of the entire triangular cross-section along with the coordinated deformation of the orthotropic deck and the lower chords.

When the two middle verticals of every module are removed from M-3, the values θ_1 and θ_2 in M-4 are still close to each other, indicating that the deformed triangular cross-section is still not distorted. However, in comparison with M-3, the values $z(b)$, $z(c)$, $y(a)$, θ_1 and θ_2 in M-4 are increased by approximately 25.7%, 29.0%, 27.7%, 28.2% and 27.9%, respectively. This change occurs primarily because when the two middle verticals are removed, the aforementioned frame effect of the bilateral Vierendeel truss is weakened. Furthermore, when all of the other verticals are removed from M-4, the deformation of the orthotropic deck in M-5 increases by a large extent with an angle (θ_1) of 29.20° . This increase is attributed to the frame effect completely disappearing under this unique condition. These results indicate that the frame effect of the bilateral Vierendeel truss has a large influence on the overall torsional deformation of the original structure.

In addition to the deformations, the consequences of removing the primary truss members on the stress state of the main longitudinal beams and the lower chords were studied. Fig. 15 shows the in-plane (vertical plane) bending stress contours in Z1~Z3 of M-2~M-4 at 6.0 kN·m; the stress contour of M-1 was presented in Fig. 11(b). Because of space confinements and the similar analysis results, the stress state in the lower chords is not shown. The figure indicates that the stress of M-3 exhibits a segmental bending state similar to that of M-1. The stress at the crossover

points of Z1&Z3 and the verticals exhibits several sudden changes caused primarily by the frame effect. The distributions of the two contours approach each other, and the maximum discrepancy of the values is approximately 10.4%. In fact, Z1~Z3 can be considered a cantilever beam restrained segmentally by the verticals in M-1 and M-3. However, the stress contour in M-2 indicates a two-region bending state and the stress at the connectors is equal to zero, which constitutes apparent difference with the behavior of M-1 and M-3. The difference occurs because in M-2, the frame effect disappears and Z1&Z3 are restrained only by the web diagonals through the main cross I beams. The values at most segments of Z1~Z3 in M-2 are larger than those of the corresponding segments in M-1 and M-3. Thus, the load transfer contributed by the web diagonals is much weaker than that of the verticals.

In M-4, the stress contour indicates a segmental bending state with fewer sudden changes than that of M-3. Because of the removal of the two middle verticals, the sudden changes at the corresponding crossover points disappear. The maximum discrepancy between M-3 and M-4 is approximately 38.9%. In M-5, because the longitudinal I beams are no longer restrained by the verticals, the stress distribution greatly approaches that of a cantilever beam. Under this condition, the load subjected to the deck is no longer transferred to the lower chords. These numerical results confirm further that compared to the web diagonals, the verticals play a much more critical role (in terms of the frame effect) in transferring the load from the orthotropic deck to the lower chords.

Altogether, the torsional mechanism can be further understood as follows. When subjected to pure torsion, the deformation of the lower chords primarily originates from the rotation of the orthotropic deck through the verticals and the web diagonals. The distribution of the torsional load on the longitudinal members, the in-plane bending of the bilateral Vierendeel trusses and the out-of-plane bending of the web diagonals contributes considerably to the maintenance of the external torsional moment. Compared to the web diagonals, the verticals play a much more critical role in transferring the load from the deck to the lower chords, as well as facilitating the rigid rotation of the

entire triangular cross-section of the hybrid structure.

5. Discussion

It can be concluded from the experimental and numerical results that the hybrid triangular deck-truss beam exhibits specific structural responses under the pure torsion condition. Reflecting the overall torsional behavior of the rigid triangular cross-section, the HFRP lower chords and the corresponding pre-tightened teeth connectors themselves display large torsional and bending deformations. Compared to conventional planar trusses [14,15,25] and steel triangular trusses [34-37], the bilateral Vierendeel trusses of this hybrid triangular deck-truss beam have a smaller flexibility factor, leading to a poorer overall torsional stiffness.

In addition, the hybrid structure exhibits a complicated stress state, especially in the FRP tubular profiles. Large bending and shear stresses are induced in the FRP members, which hinders application of the advantages of the unidirectional pultruded FRP materials. The HFRP lower chords primarily bear an out-of-plane bending moment and torque; the GFRP web diagonals primarily bear an out-of-plane bending moment; and the verticals primarily bear an in-plane bending moment. This stress state does not match that of the initial design, in which these member profiles are only subjected to axial forces; i.e., they are designed for a pure tension-compression state. In fact, if isotropic aluminum is used for the lower chords, the bending and torsional problem does not need to be highlighted. However, it should be given significant consideration in the case of anisotropic composite materials because the interlaminar shear stress of the extrusion-type FRP profiles is low. When subjected to certain bending and shear stresses, these FRP profiles will bear a complicated and deleterious stress state, which may cause damage to the composites. The same analysis results can be applied to the pre-tightened teeth connectors for FRP tubes.

Thus, the triangular deck-truss beam cannot be solely used as a structure subjected to off-axis load and torsion. If it is used alone in further engineering applications, certain necessary structural improvements are needed. For

example, the local structures at the two ends of the verticals and the web diagonals (which bear large bending moment) need to be strengthened to obtain a reliable connection, e.g., by adding triangular plates (similar to that of the vertical plane, see Fig. 1) with reliable welding. Moreover, these FRP tubes cannot be simply designed as pure tension-compression members, and the axial force, bending moment, shear force and torque should be included in the initial design to enable a larger bearing capacity and enable better structural properties.

Furthermore, to obtain a larger torsional stiffness of the entire structure and to improve the stress states of the FRP members, the original structure in question should be re-designed. First, the secondary longitudinal I beams of the orthotropic deck between two adjacent modules should be connected by male jugs and female jaws. This change is recommended because when the secondary longitudinal beams between two adjacent modules are connected, their bending and torsion participate in carrying the external torsional moment. Second, the bilateral Vierendeel trusses of the original structure should be changed to a conventional planar truss (e.g., a Warren truss, Pratt truss or Howe truss [15]). In this way, the flexibility factor of the two side trusses is enlarged and their in-plane vertical bending carries much more of the external torsional moment. Third, the structural form of the original lower chord with a single FRP tube can be replaced by a form of planar truss [15]. This modification will increase the horizontal bending stiffness and torsional stiffness of the lower chords and thus increase the overall torsional stiffness of the structure; furthermore, the bending moment of the original lower chord with its single tube will be converted into axial forces in the trussed members of the replaced planar truss. These improvements are significant to this type of hybrid structure, especially for those with large spans. The detailed structural improvement and optimization procedures will be implemented in further studies, in which the hybrid triangular deck-truss beam will be used solely as a structure subjected to off-axis load and torsion.

6. Conclusions

In this paper, both experimental and numerical research studies were conducted to investigate the torsional response of the modular FRP-aluminum triangular deck-truss beam. The following conclusions pertain specifically to this new hybrid structure:

(1) Under the elastic pure-torsion condition, the hybrid structure exhibited specific structural responses. Reflecting the overall torsional behavior of the rigid triangular cross-section, the tubular lower chords and the main longitudinal I beams themselves displayed large torsional and bending deformations. The torsional center of the hybrid triangular deck-truss beam was essentially collocated with the center of the aluminum orthotropic deck. The deformation of the lower chords was initiated by the rotation of the orthotropic deck through the verticals and the web diagonals. Compared to the web diagonals, the verticals played a much more critical role in facilitating the rigid rotation of the triangular cross-section. The torsional stiffness of the fixed and free modules was experimentally found to be approximately 4.51 and 3.95 kN·m²/deg, respectively.

(2) The hybrid structure exhibited a complicated stress state in the trussed members, especially the pultruded FRP tubes. The HFRP lower chords themselves were subjected primarily to a large torque and out-of-plane bending moment; the GFRP web diagonals bore primarily a large out-of-plane bending moment. Because of the frame effect of the bilateral Vierendeel trusses subjected to an in-plane load, the two side main longitudinal I beams and the tubular lower chords were exposed to segmental vertical and horizontal bending stress states along the bridge axis, respectively; additionally, the verticals underwent regular bending from the large moment at their two ends. This bending stress state of the bilateral Vierendeel trusses was similar to that of an identical Vierendeel truss subjected solely to a cantilever concentrated force. The complicated stress state did not match that of the initial design, in which the tubular profiles were designed as tension-compression members subjected to axial force only.

(3) The applied torsional moment of the hybrid structure was primarily resisted by the following factors: the

in-plane vertical bending of the bilateral Vierendeel trusses, the out-of-plane horizontal bending of the GFRP web diagonals, and the torsion of the HFRP lower chords and the aluminum main longitudinal I beams. Compared to the GFRP web diagonals, the aluminum verticals played a much more critical role in transferring the load from the orthotropic deck to the lower chords. The frame effects of the bilateral Vierendeel trusses and the torsion of the lower chord should be given ample consideration in the load transfer mechanism for this spatial structure.

(4) The hybrid structure exhibited a poor torsional stiffness. Moreover, the pultruded FRP members and the pre-tightened teeth connectors themselves displayed large torsional and bending deformations combined with a complicated stress state, which limited the advantages of the unidirectional pultruded FRP materials. Thus, if this new hybrid triangular deck-truss beam is further used alone as a structure subjected to an off-axis load with a large torsional moment, the original structure in question should be strengthened or re-designed and structural improvements are necessary. These detailed structural improvements and optimization procedures will be implemented in future studies.

Acknowledgments

The research work reported in this paper is supported by the National Science Foundation of China under Grant Nos. 51408606 and 11372355, the Major State Basic Research Development Program of China (973 Program) under Grant No. 2012CB026202 and the National Science and Technology Support Program of China under Grant No. 2014BAB15B.

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Table list:

Table 1 Comparison of the displacements and torsional angles at the cantilever triangular cross-section among the five FE models.

Table 1 Comparison of the displacements and torsional angles at the cantilever triangular cross-section among the five FEMs.											
Numerical results	Vertical displacements / mm				Horizontal displacements / mm				Torsional angles / Deg.		Schematics of the deformed triangular cross-section
	z(a)	z(b)	z(c)	z(o)	y(a)	y(b)	y(c)	y(o)	θ_1	θ_2	
M-1	7.2	92.2	-99.6	-3.7	-135.3	8.1	-7.3	0.4	9.20	9.19
M-2	16.6	217.2	-234.6	-8.7	-204.4	43.5	-44.7	-0.6	22.12	13.87	
M-3	9.0	102.8	-112.3	-4.7	-151.8	10.1	-9.3	0.4	10.33	10.31	
M-4	14.7	129.2	-144.9	-7.8	-193.8	16.0	-15.7	0.2	13.20	13.19	
M-5	0	282.6	-302.8	-10.1	0	74.5	-77.7	-1.6	29.20	—	
Schematics of the five different FEMs
	M-1	M-2	M-3	M-4	M-5						
FEMs	Original model of specimen	Removal of all the verticals from M-1	Removal of all the web diagonals from M-1	Removal of middle verticals of each unit from M-3	Removal of all the web diagonals and verticals from M-1						

Figure list:

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(a)

(b)

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(a)

(b)

(c)

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(b)

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(a)

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(a)

(b)

(c)

(d)

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