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Torsional behavior of a hybrid FRP-aluminum space truss bridge: Experimental and numerical study

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A B S T R A C T

A novel lightweight hybrid fiber-reinforced polymer (FRP) – aluminum space truss structure that consists of two triangular deck-truss beams has been designed for rapid emergency bridging system. This paper reports a large-scale pure torsion test on a cantilever full-scale specimen to evaluate the detailed linear-elastic torsional behavior and the load-carrying mechanism of the hybrid twin-trackway spatial structure. Additionally, a structural computational finite element model (FEM) was constructed and validated against the experiments. To fully understand the load-carrying mechanism obtained from the experiments, numerical analyses were performed by equivalently converting the torsion reaction of the hybrid twin-trackway structure to the bending and torsion of its twin triangular deck-truss beams. The results indicate that the experimental structure exhibits a good and specific torsional response, which can be well described by FEM. The unidirectional pultruded FRP profiles are mainly subjected to axial forces and are thus appropriate for application to this unique twin-trackway space truss, unlike in the case of the alone single-trackway triangular beam under torsion. The vertical bending of the twin triangular deck-truss beams play a key role in the behavior of load-carrying of the entire bridge, unlike in the case of the conventional torsional calculation method for the separated box beam. In the initial design, the torsional calculation of such a novel bridge can be carried out using the flexural analytical and numerical models of the triangular deck-truss beam.

1. Introduction

Fiber-reinforced polymer (FRP) materials are widely used in civil engineering as alternatives to traditional construction materials due to their excellent properties, such as high strength, light weight, sufficient durability and convenient usage [1,2]. The emerging field of engineering applications are ranging from rehabilitation of existing structural systems [3–6] to new construction with all FRP solutions [7–10] and hybrid systems [11–15]. Note that in civil infrastructure, pultruded FRP profiles that are manufactured through the highly competitive pultrusion process with sectional shapes similar to standard steel profiles are the most frequently used as load-carrying components [1,2]. These pultruded FRP profiles are characterized as exhibiting high strength in the pultrusion direction, making them promising primary load-carrying members. However, compared with steel profiles, most of the anisotropic pultruded FRP materials have lower elastic modulus and lower shear strength, which prevent full utilization of the material's potential. It seems that, however, these shortcomings can be addressed using a preferred approach by incorporating pultruded FRP profiles into trusses with excellent structural form.

Applications of FRP truss structures made from pultruded profiles have gradually developed [16–23]. These FRP truss structures are characterized by a series of interconnected rod members with a standard sectional shape located in chord members and web diagonals, where axial forces are distributed evenly in a three-dimensional manner. The load transfer for this advanced structural form is predominantly by axial forces rather than bending and shear load [24]. Thus, the pultruded FRP materials, which exhibit high longitudinal strength and low shear strength, show their best material strength and is fully utilized. Additionally, satisfactory global structural stiffness of these FRP trusses is obtained at the structural level, thereby compensating for the inherent lack of material stiffness resulting from their low elastic modulus. Namely, advances of both FRP materials and truss structures are greatly extended, and thus further weight reductions and large spans are achieved. In particular, the excellent features of these FRP trusses known for their high specific stiffness and strength are attractive in the case of emergency bridges, which primarily require being favorable properties for carrying load, being lightweight for transport

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facilities and reduced erection time [17–20].

However, joint technology is a key issue limiting the development of those trusses using pultruded FRP profiles [25]. It is difficult to conceive and design appropriate connections for the brittleness and anisotropy of assembled pultruded FRP profiles, especially the closed shape of tubular sections [24]. Over recent decades, the usual FRP connection techniques employed in deconstructable trusses are bolted and adhesive lap joints [26,27]. However, the load-carrying capacity of these basic FRP jointing techniques is low and they are mainly applied to planar panels rather than tubular members. To address the inappropriate joint designs, some new hybrid jointing techniques or solutions are developed based on the steel practice [17–20], which contribute much to the application of pultruded FRP profiles with closed-shape sections in trusses. Note that in a recent study, a novel jointing technique with high connection efficiency was proposed for pultruded FRP tubes, named as the pre-tightened teeth connection (PTTC) [28]. This connection involves a ring- or stripe-shaped tooth structure grooved at each end of FRP tube and well-matched on an external aluminum tube, and expanded by an internal aluminum external tube through interference fit. The other end of the external aluminum tube can then be easily connected with other structural members using conventional mechanical methods or welding technology. The capacity to transfer a large axial force is achieved because an interlaminlar shear stress of the FRP composite materials is higher than that of pure resin and the radial compressive stress enhances the interlamellar shear strength. This novel connection with high load-carrying capacity provides an effective jointing technique for heavily loaded FRP truss structures.

Based on the novel PTTC technique, a new hybrid FRP-aluminum space truss structure was proposed for an emergency vehicular bridge carrying a four-wheel truck weighing 100 kN [28]. The bridge was designed as a single-span one-lane bridge, which corresponds to a twin-trackways traffic load and has a typical span of 12 m. The single-trackway beam comprises four triangular deck-truss modules and enables a new structural form, which is made from an aluminum orthotropic deck supported by pultruded FRP tubes. For practical purposes, the flexural performance of the complete bridge under on-axis traffic loads in the travel direction has been experimentally and numerically studied [28]. However, the detailed torsional behavior of the complete twin-trackway structure has not yet been examined. In fact, the one-lane bridge may also bear off-axis loads because that the wheel transverse spacing (1.8 m) is less than the deck width of bridge (3.0 m). As a recognized most critical load case for emergency bridges, the off-axis loads will lead to a certain torsional moment in the structure. The mechanical behavior under this unsymmetrical loading will definitely influence the load distribution among truss girders to be considered in the design of any bridge. So research on the torsional behavior of the new structure is desired. Note that, instead of directly subjecting the off-axis traffic loads to a complete bridge, an usual experimental method for examining the torsional behavior of a complete bridge is subjected a pure torsion test to a cantilever segment.

For investigation on torsional behavior of the hybrid twin-trackway space truss structure, it is worthy mentioning that its structural form is partially similar to that of some separated steel bridges [29–31]. However, the corresponding research results of these steel bridges subjected to torsion, if any, cannot be applied to the new hybrid twin-trackway space truss structure because of their dissimilarities in terms of detailed structural form, local configuration and used material. Actually, the available information on the torsional behavior and the load-carrying mechanism of these steel bridges are very limited. Therefore, it is expected that the modular hybrid twin-trackway space truss bridge will exhibit unique torsional response and load-carrying mechanism. Additionally, it should be noted that experimental studies on large-scale space truss structures made from FRP composites are still very limited [24], especially for the torsional behavior. Thus, investigation on the torsional behavior of the novel large-scale hybrid space truss structure is necessary and meaningful.

The research program on the torsional behavior of the new bridge is characterized with a two-part scope: (i) an experimental and numerical study on a single-trackway triangular deck-truss beam subjected to pure torsion; and (ii) an experimental and numerical research on a complete twin-trackway space truss structure subjected to pure torsion. The present paper focuses on stage (ii), whereas stage (i) has been conducted in a previous work [32]. In the present study, the primary objective is to examine the detailed torsional response in the elastic range and to explore the corresponding load-carrying mechanism for this unique large-scale bridge structure. Four full-scale triangular modules were linked up to build up a cantilever experimental structure that could be subjected to a pure torsion test. The representative mechanical performances were recorded and studied, including the load-displacement response of the structure and the load-strain response at the concerned members; the load transfer performance was then experimentally explored. Additionally, numerical analysis based on finite element model (FEM) was performed and validated against the corresponding experimental behavior. The validation of the load-carrying mechanism determined from the experimental results was also numerically performed by a decomposition and reconstruction process. Finally, recommendations on the structural design and calculation of this unique structure were proposed. The present research contributes a valuable approach to design of this type of bridge.

2. Description of the structure

The novel hybrid FRP-aluminum space truss bridge was developed in 2012 [28]. It enables a modular system, which corresponds to a twin-trackway traffic load carrying a four-wheel truck weighting 100 kN, but itself weighs only approximately 1200 kg. Fig. 1 shows a modular twin-trackway unit with a length of 3.0 m, a width of 3.0 m and a depth of 0.85 m. As shown, the modular twin-trackway unit is composed of two inverted single-trackway triangular deck-truss beams linked up by

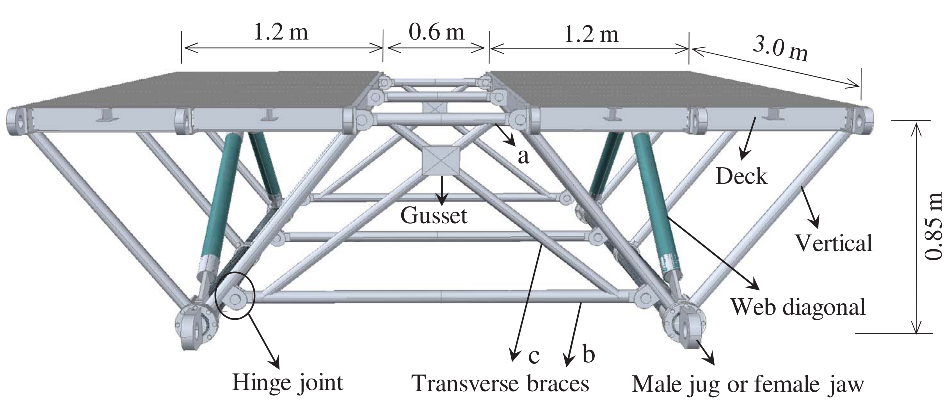

Fig. 1. A modular unit of the hybrid twin-trackway space truss bridge.