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Dynamic and fatigue performances of a large-scale space frame assembled using pultruded GFRP composites

Xiao Yang [a], Yu Bai [a,*], Fu Jia Luo [a], Xiao-Ling Zhao [a], Faxing Ding [b]

[a] Department of Civil Engineering, Monash University, Clayton, VIC 3800, Australia
[b] School of Civil Engineering, Central South University, Changsha 410075, China

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ABSTRACT

This paper describes the dynamic and fatigue performances of a large-scale space frame assembled using pultruded glass fiber reinforced polymer (GFRP) composites, with reference to pedestrian bridge application. The experimental structure was assembled by circular hollow section (CHS) GFRP members with the assistance of a novel steel connection system. The results from free vibration tests were analyzed using peak-picking (PP) and stochastic subspace identification (SSI) methods to extract modal parameters, i.e. natural frequencies, damping ratios, and mode shapes. From both experimental and validated FE analysis results, the proposed space frame structure satisfied the standard requirements for pedestrian bridge application in terms of natural frequency. The torsion mode as the first order mode shape can be avoided when the contribution of a bridge deck is considered. Furthermore, the structure was examined with 2.1 million fatigue load cycles and then statically loaded up to failure. The failure load showed no decrease when compared with that of a space frame without fatigue. The structural stiffness and strain of critical compressive members measured at 0.3 million fatigue loading intervals showed no significant variations, indicating that the applied fatigue did not degrade structural components and connections.

1. Introduction

Pultruded GFRP products share common superior properties of fiber reinforced composite materials such as high strength, light weight, and corrosion resistance [1]. They reduce raw material and manufacturing costs and introduce environmentally friendly characteristics [2]. In comparison to steel, however, pultruded GFRP materials have lower shear strength, lower elastic modulus, and poor ductility, features that separately pose concerns about full utilization of the material potential, serviceability design, and incorporation of pre-failure warnings [3–5]. To overcome these shortcomings while maintaining the advantages of pultruded GFRP, many researchers have preferred hybrid structures, in which pultruded GFRP composites cooperate with traditional construction materials such as metal materials and concrete [4–15].

It is conceivable that, if pultruded GFRP materials were applied in a space frame structure in which the members are subjected to axial load rather than shear load, satisfactory stiffness of the space frame could be achieved at the structural level rather than only at the material level, thereby compensating for the inherent lack of material stiffness. Moreover, the change of structural stiffness in a space frame as a result of the loss of axial stiffness of GFRP members in compression (due to bending or buckling) may harness its capacity of large nonlinear deformation, providing a pre-warning of failure similar to that provided by structural ductility. This would require sufficient structural redundancy to satisfy serviceability and safety and progressive failure considerations [5,16]. However, the establishment of reliable connection methods to assemble pultruded GFRP members into a space frame structure remains a challenge [17].

An innovative adhesively bonded sleeve joint proposed by Yang et al. [15] provides a solution for connecting pultruded CHS GFRP members by adhesively bonding a tubular steel connector into each end of a pultruded CHS GFRP member, thereby combining the advantages of both GFRP and steel materials and the advantages of adhesively bonded and bolted connections. In a later study [5], this joint configuration was used to prefabricate steel/GFRP hybrid structural members and then such members were interconnected via steel Octatube nodal joints by bolted connections [18], further enhancing the flexibility of spatial arrangement of members. Compared with many other hybrid space frame structures, the proposed connection system requires only simple processing techniques, without heat treatment, pressure control, cutting thread, or mold casting.

* Corresponding author. Tel.: +61 3 9905 4987.
E-mail address: yu.bai@monash.edu (Y. Bai).

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A large-scale experimental space frame structure with a span length of 8 m, width of 1.6 m, and depth of 1.13 m was designed with reference to the supporting structure of a pedestrian bridge and finally built using the proposed connection system [5]. The static performance of the large-scale space frame was examined by conducting three-point bending experiments. In the static tests, the adhesive bond between the pultruded GFRP profiles and the steel connectors behaved well – no damage of the bond line was observed before the structure lost its load-bearing capacity. The space frame also showed satisfactory static performance with reference to the requirements in relevant standards [19,20]. However, the dynamic and fatigue properties of such a space frame structure have not yet been examined, and those properties are also critical to the safe operation of a pedestrian bridge.

2. Background

In terms of dynamic investigations on large scale bridge structures, output-only modal identification methods based on free vibration tests have been proved efficient in large civil engineering structures [21]. For example, Cunha et al. conducted a free vibration test on a large cable-stayed bridge in Portugal (Vasco da Gama Bridge with a span of 17,300 m) by suddenly releasing a mass of 60 t suspended from one point of the deck close to the section 1/3 span. The subsequent identification of the significant modal parameters presented a very good correlation with the corresponding values provided by the finite-element model [22]. Another free vibration test performed by Magalhães et al. on the Millau Viaduct bridge, which was the tallest vehicular bridge in the world at the time with a span of 2460 m and a height of 343 m above the river level, was evidenced to be effective and accurate in identifying the modal parameters of the tested structure [23]. For large-scale FRP structures, a concrete/GFRP hybrid pedestrian bridge prototype comprising two GFRP pultruded profiles and a thin steel fiber reinforced self-compacting concrete deck was investigated experimentally and numerically by Gonilha et al. [4]. It was found through the comparison of results that the models developed using conventional numerical tools are able to predict the dynamic response of the footbridge prototype [4]. An all FRP pedestrian truss bridge was investigated by Bai and Keller [24] through free vibration tests and output-only modal identification methods. It was found that the dynamic performance of the two spans (bolted joints in one span and adhesively bonded joints in the other span) was markedly influenced by the joint types used in the truss structure [24].

Fatigue behavior is also critical to the safety of civil engineering infrastructure. Researchers have already highlighted the importance of fatigue behavior for GFRP joints. The fatigue life of single-lap and balanced double-lap joints has been investigated, comprising pultruded GFRP laminates connected through epoxy adhesive bonding [25,26], or with ordinary and blind bolts [27]. Large-scale experiments have also been conducted to simulate the effects of fatigue load caused by vehicles on road bridges composed of GFRP materials [28,29].

Unlike road bridges, the fatigue load of a pedestrian bridge does not derive from its live loads, since heavy pedestrian loads are infrequent [20]. Instead, such fatigue load is mainly brought about by natural wind load or truck-induced wind load if the pedestrian bridge is to be built across traffic lanes [30]. The natural wind load would be applied in the horizontal direction to the exposed area of all structural components. When the horizontal projected area of a space frame bridge is quite small, as in our case, the small associated natural wind load can be ignored [19]. On the other hand, truck-induced wind loads in the vertical direction, caused by the passage of trucks beneath supporting structures, cannot be ignored if the bridge deck is considered [19]. The only source of fatigue loading of the proposed reference bridge is therefore the vertical truck-induced wind load.

In this paper, free vibration tests are first conducted on the experimental space frame to investigate its dynamic responses. Two output-only modal identification methods [31], namely a peak-picking (PP) method developed in the frequency domain and a stochastic subspace identification (SSI) method developed in the time domain, are applied to analyze the data. A FE model is further developed to validate the modal identification results from free vibration tests. Furthermore, fatigue loading tests are also conducted on the experimental space frame (after dynamic testing) to investigate its fatigue performance in a three-point bending set-up.

3. Description of the space frame

A large-scale space frame was designed to use pultruded CHS GFRP profiles as its structural components with reference to a supporting frame structure for a pedestrian bridge (see Fig. 1(a)). Due to the space limitation of the testing site, the scale of the experimental space frame model was reduced in comparison to the proposed reference bridge model. One strip consisted of 5×1 grids with the resulting span length of 8 m, width of 1.6 m, and depth of 1.13 m (see the part highlighted in black in Fig. 1(a)) was taken out from the proposed reference bridge model and acted as the experimental space frame model (see Fig. 1(b)). The length between adjacent spatial node centers was 1.6 m, including additional length contributed by steel connectors and nodal joints, as shown in Fig. 1(b).

Fig. 1(c) shows the connection system used to connect the GFRP profiles. Following the advice in the manufacturer's handbook [32], a two-component epoxy adhesive (Araldite 420 A/B) [33] was applied to bond the innovative steel connectors into both ends of the pultruded CHS GFRP profiles with sufficient bond length of 120 mm [5]. Then, the pultruded CHS GFRP members with steel connectors were connected by Grade 8.8 high strength bolts to plate nodal joints known as Octatube joints [18]. The space frame was evaluated in terms of ultimate (ULS) and serviceability limit state (SLS) design criteria through static loading in [5]. The outer diameter of CHS GFRP profiles is 92 mm and the tube thickness is 8 mm, accommodating the steel tube with an outer diameter of 73 mm and a thickness of 4 mm. Relevant material properties were further listed in Table 1 as experimentally measured and introduced in [5]. It should be noted that a GFRP web-flange sandwich deck consisted of GFRP square hollow sections as the web and GFRP flat panels as the flange [34,35] can be conveniently connected to the proposed space frame. Fig. 2 demonstrates the installation of the deck system with the space frame structure, where go-through bolts or a novel type of blind bolts [34,35] can be used to join the deck and the Octatube nodal joints.

4. Experimental investigation

4.1. Dynamic test

4.1.1. Experimental set-up and scenarios

The experimental space frame was simply supported in a manner identical to that used in the static tests introduced in [5]. At one end of the experimental space frame, steel angles were welded to steel plates to serve as the support; meanwhile, steel rollers were placed under two corner nodes at the other end as illustrated in Fig. 1(b). In order to obtain the dynamic parameters of the experimental space frame, i.e. the natural frequencies, mode shapes, and damping ratios, two experimental scenarios were conducted (see Table 2). The space frame was excited by eccentric