Experimental investigation of bending stiffness of a novel 54m FRP space truss string bridge

Xiaoqiang Yan¹, Qilin Zhao²*, Dong Zhao³, Minyong Ke⁴, Zhigang zeng³, Dongdong Zhang¹
¹College of Field Engineering, Army Engineering University of PLA, Nanjing 210007, China
²College of Mechanical and Power Engineering, Nanjing University of Technology, Nanjing 210009, China
³Engineering Design Institute, Research Institute of CAPF, Beijing 100020, China
⁴Nanjing Hydraulic Research Institute, Nanjing 210029, China

*Corresponding author e-mail: zhaohsql919@163.com

Abstract. Composite truss has the characteristics of light weight, high strength and full play of the axial mechanical properties of the composite components, which can be applied to form long-span bridges, roof structures et al. A novel 54m space truss string bridge made of pultruded GFRP profiles is proposed in this paper based on the composite pre-tightened tooth connection. The proposed space truss string bridge was fabricated, assembled and tested statically, and the load-displacement responses were recorded. The response of the bridge evidenced a sound carrying capacity, the deformation and stiffness of the space truss string bridge meet the requirements and can be used for bridge repair in emergency situations.

1. Introduction
FRP materials have been used in civil engineering for repair or strengthening of existing structures. And recently [1], the use of such materials for main load-carrying members is increasingly promoted, especially in bridge construction. A two span all-composite bridge was introduced by Keller et al. [2], where five different pultruded GFRP profiles were employed to assemble a bridge using a truss configuration, albeit only in a planar manner. Also, pultruded GFRP profiles have been used to develop deployable bridge for military applications by R.G. Wight [3], the deployable box beam bridge was built up from hollow tube sections and plate sections, using adhesive bonding throughout. Most of these truss space structure has not the structure appeal mainly because of its low bearing capacity and small span that caused by the difficulty of jointing chord members together at nodal points.

Relevant work of joint technology has been conducted by Zhao et al. [4] [5] to explore space truss bridge structures using FRP composite materials. A novel composite pre-tightened tooth connection (PTTC) was proposed based on the composite teeth well-matched with metal teeth and interference fit technique, which can be used in space truss structures assembled with FRP tube or panel members.

The structure development works were also conducted based on the research of PPTC. In 2014, there were a 12m hybrid FRP-aluminium modular triangular truss system developed, as shown in Fig.1. Zhang et al [6] [7]. Studied its flexural properties and torsional mechanism by experiments. In 2015, a 24m
space truss bridge [8] was designed and manufactured, loading test of the bridge demonstrated that the bridge structure has a high stiffness and load carrying capacity, as shown in Fig.1. The researches of the above two bridges showed that design of this space truss bridge mainly controlled by structure stiffness.

![Figure 1. FRP structure development based on pre-tightened tooth connection](image1.jpg)

In 2017, a novel 54m hybrid FRP-aluminium space truss string bridge carrying 250kN vehicle load was designed and fabricated by Zhao et al. In this paper, the mechanical responses of the novel space truss String Bridge are investigated by loading experiment. The structure of the space truss string bridge modules, structural components and the connector is introduced first; a 54m space truss string bridge is then assembled by nine modules, and its mechanical performance is examined under static loading. Analysis of deformation and stiffness are carried out based on the experiment.

2. Description of the space truss string bridge structure
The proposed space truss string bridge is assembled by nine modular units and then reinforced with two strings, mainly used for emergency rescue work of traffic, it is designed to carry a 250kN vehicle load (maximum axle load 130kN), as showed in Fig.2. The modular unit—has a span of 6m, a top width of 3.2m, and a bottom width of 2m and a depth of 1.2m—is composed of an aluminum orthotropic deck supported by two inverted triangular trusses, which are closely connected by lateral braces. The aluminum alloy bridge deck is composed of a thin plate and a series of longitudinal and transverse beams of “I” beam. An inverted triangular truss is consisted of a lower chord, four diagonal web members and five groups of vertical components. The diagonal web members are arranged in the longitudinal plane and the vertical components are arranged in cross section, as showed in Fig.3.

![Figure 2. Schematic of the space truss string bridge](image2.jpg)
There are three main types of node connectors of the bridge structure. The joint of two module units (type A) is connected by male and female jaws with the aid of the PTTC technique, as shown in Fig. 4 (a). This node joint includes three vertical components connected with the chord PTTC, and then through male and female jaws to achieve the connection between module units. There are seven stripe-shaped teeth manufactured at the chord PTTC, the reinforced normal stress is exerted by the internal tube size interference. The node joints in inverted triangular truss (type B&C) includes three vertical components and two diagonal web members connected with chord PTTC, as shown in Fig. 4 (b). There are seven stripe-shaped teeth manufactured at the chord PTTC, the reinforced normal stress is exerted by shoving the external tube.

At truss members connected to aluminium alloy decks, a slightly complicated transfer joint pedestal with aid of bolt was used to realize the effective connection between steel gusset plates and aluminium alloy deck.

3. Experimental Investigation of the space truss string bridge

3.1. Materials
To examine the design and understand the actual behavior of the space truss string bridge, all the components were fabricated and developed. Three kinds of materials were used in the fabrication of the space truss string bridge, namely aluminum alloy, GFRP and DB685 steel. The bridge decks were made of aluminum alloy, including longitudinal and transverse beams and panels. The lower chord of the side bridge modular units and all internal tubes of pre-tightened tooth connection joints were also made of...
aluminum alloys. DB685 steel is mainly used to manufacture gusset plates and all external tubes of pre-tightened tooth connection joints. Three types of pultruded GFRP sections were employed—a radius of 44 to 52 circular tube was used to fabricate the lower chord, a radius of 46 to 52 circular tube was employed for the diagonal web members and a radius of 24 to 30 circular tube was applied to the vertical components. Typical coupon properties for structural shapes show a weight fraction of 80% for glass fibers. Characterization of the material properties was achieved by cutting out coupons from GFRP profiles with a water jet cutter, and then testing them in relevant accordance, and the results were summarized in Table.1.

| Material                       | Modulus (GPa) | Poisson ratio | Strength (MPa) |
|--------------------------------|--------------|--------------|---------------|
| Pultruded GFRP a (weight fraction of 80%) | E₁=52, E₂=E₃=10.2, G₁₂=G₁₃=5.7, G₂₃=4.8 | ν₁₂=ν₁₃=0.26, ν₂₃=0.20 | X₁=1130, X₃=895; Y₁=45, Y₃=98; Z₁=45, Z₃=98; Sₓᵧ=76; Sᵧz=60; Sₓz=76 |
| Steel DB685                    | 200          | 0.3          | Tension: 548; Compression: 548 |
| Aluminum alloys 7005           | 71           | 0.33         | Tension: 405; Compression: 385 |

3.2. Assembly and span of the space truss string bridge

The structure unit is manufactured in factory, weigh it when it leaves factory that was 1320kg. It can be transported and deployed by using universal transport cars and light cranes, shown as Fig.5 (a). The experiment was carried out on the factory floor with light gantry cranes and light cranes available. First of all, nine modular units were assembled on the ground into a 54m space truss beam with the help of light cranes, only modular units placed in the middle and pins installed need to be done by manually, as shown in Fig.5 (b). Then, use the gantry cranes to lift the space truss beam to a certain height to install the strings, at the same time, use a crane to lift the middle of the space truss beam to eliminate self-weight deflection for tensioning the strings, as shown in Fig.5(c). Finally, the assembled space truss string bridge is hoisted onto the temporary abutments and simply supported on bearings, shown as Fig.6.

![Figure 5. Assembly and span the space truss string bridge](image5)

![Figure 6. the spaned and supported space truss string bridge](image6)
3.3. Test Setup and Instrumentation

After the completion of the span setup, the loading experiment was carried out. The space truss string bridge was simply supported on bearings under the four connectors of lower chord, and bearings could provide lateral constraints, as shown in Fig.7. It should be noted that the actual boundary condition of the space truss string bridge may be different and complex because of the location of the bridge structure and the rigidity of the supporting structure.

The load was applied by mass blocks and transferred to the bridge structure through four sleepers on the decks (see Fig. 8). And the mass blocks loads were exerted by classification, the next level of load was applied after the deformation measurement. During testing, the applied load was recorded, and the vertical deflection was measured manually by a total station instrument, as shown in Fig6 (d). The horizontal displacement was not measured. The static test on the bridge structure was therefore conducted based on a simple setup, and the objectives of this work are to demonstrate the design concept and the feasibility of structural assembly, examine loading performance in such a setup.

Before the test carrying out, a 20kN pre-loading test was conducted to eliminate gaps caused by manufacturing.

![Figure 7. Loading test setup](image1)

![Figure 8. loading configuration](image2)

3.4. Results and Discussion

Fig.9 (a) shows the relationship between the applied load and measured vertical deflection from the test. A linear elastic behavior was found from the commencement of loading until about 170 kN of the applied load was reached, and the corresponding bending stiffness was calculated from the slope as 550.025 kN/m. When the applied load was above 170 kN, the load-displacement curve also exhibited a slight broken behavior, and the vertical deflection increased more rapidly, a slightly lower bending stiffness was also identified, the corresponding slope of the load displacement curve being about 479.578 kN/m.

Such a difference in stiffness may be mainly attributed to the nonlinear elastic behavior of aluminium alloy of some bridge decks, rather than failure behaviour of the bridge structure. This opinion can be further validated in the following unloading experiment.

The maximum applied load was 230 kN, and there were no cracking noises and visible failure behaviors occurred during the loading process, the measured maximum vertical displacement...
(433.75mm) is less than the admissible deflection limit (450mm). After measuring the last applying load, all mass blocks were unloaded, and there was a residual deformation of 48.43mm measured. The residual deformation was disappeared completely after one-night (10 hours) standing. That the phenomenon of the recovery of deformation validated the above viewpoint, and this time course was called aging.

A symmetrical deformation shapes of the space truss string bridge under the hierarchical load were found, as shown in Fig.9 (b). It shows it shows a sound structural integrity performance and comfort of driving.

4. Conclusion
A novel 54m FRP space truss string bridge was introduced, which is composed of nine modular units and a group of reinforced strings. The modular units and structure components were fabricated and assembled into a 54m space truss string bridge. Then, the structure performance of the space truss string bridge was obtained by experiments. The following conclusions were drawn.

1) Based on the lightweight pultruded FRP and aluminium alloy, and the effective composite pre-tightened tooth connection, a novel 54m FRP space truss string bridge was designed and fabricated. The modular unit has a light weight of only approximately 1.3 tons, which can be transported and deployed by using universal transport cars and light cranes. The assembled space truss string bridge weighted approximately 13.6 tons, it can be lifted with a 25T light crane. Thus, the ratio of load to weight is 1.9, which reflects the characteristics of lightweight and high strength of composite materials.

2) The experimental study showed the feasibility of the space truss sting bridge structure design and assembly, the measured maximum vertical displacement (433.75mm) is less than the admissible deflection limit (450mm).

3) The bridge structure displayed an elastic behavior under the design load according the experiment. A linear elastic behavior was found from the commencement of loading until about 170 kN of the applied load was reached, the corresponding bending stiffness was calculated as 550.025 kN/m. A nonlinear elastic behavior was found when the applied load was above 170 kN, the load-displacement curve exhibited a slight breaking behavior, a slightly lower bending stiffness was also identified, which was 479.578 kN/m. After dumping load and a certain time later, the deformation and stiffness of the space truss string bridge can fully recover.

4) The space truss string bridge has a symmetrical deformation shapes under steps load, the bridge featured a sound structural flexural behavior and driving comfort.
Acknowledgments
The research presented in this paper is supported by the National Key R&D Plan of China under Grant No. 2017YFC0405103, National Natural Science Foundation of China (51708552), Natural Science Foundations of Jiangsu Province (BK20170752) and the Young Elite Scientist Sponsorship (17-JCJQ-QT-020).

The authors wish to acknowledge their team members for their assistance in conducting the experiments. Thanks are also given to anonymous reviewers for their helpful suggestions on the quality improvement.

References
[1] Gand AK, Chan TM, Mottram JT. Civil and structural engineering applications, recent trends, research and developments on pultruded fiber reinforced polymer closed sections: a review. Front Struct Civ Eng 2013; 7 (3): 227 - 44.
[2] Keller T. Recent all-composite and hybrid fiber-reinforced polymer bridges and buildings [J]. Progress in Structural Engineering & Materials, 2010, 3 (2): 132 - 140.
[3] Wight R G, Erki M A, Shyu C T, et al. Development of FRP Short-Span Deployable Bridge-Experimental Results [J]. Journal of Bridge Engineering, 2006, 11 (4): 489 - 498.
[4] Zhao Q, Chen H and Li F. Composite tube connection technology. Patent zl.201020157303.1, China, 2010.
[5] Gao Y, Li F, Zhao Q, et al. Failure modes and failure mechanisms of single tooth bound to composite pre-tightened tooth connection [J]. Journal of Reinforced Plastics & Composites, 2017, 37 (4): 073168441774120.
[6] Zhang D, Zhao Q, Huang Y, et al. Flexural properties of a lightweight hybrid FRP-aluminum modular space truss bridge system[J]. Composite Structures, 2014, 108 (1): 600 - 615.
[7] Zhang D, Huang Y, Zhao Q, et al. Structural Performance of a Hybrid FRP-Aluminum Modular Triangular Truss System Subjected to Various Loading Conditions [J]. The scientific world journal, 2014, 2014 (5): 615927.
[8] Zhang, D.D. (2016). "Load-carrying properties and calculation methods of a novel hybrid FRP-metal space truss bridge." DSc Thesis, PLA Univ. of Sci. & Tech.