Application And Improvement of Composite Materials in Truss Bridge Structure

Yiyi Zhang*

School of SWJTU-Leeds Joint, Southwest Jiaotong University, Chengdu, China

* Corresponding Author Email: cn20yz@leeds.ac.uk

Abstract. Composite materials are new materials with the features of light weight, high strength, high specific modulus, strong corrosion resistance, and aging resistance. The truss structure is subject to unidirectional force, which gives full play to the advantages of high strength of composite materials along the fiber direction. Therefore, composite truss structure is gradually attracted attention in engineering fields, i.e., aerospace, bridges, and construction. By analyzing the application status of composite truss bridge at home and abroad, it can be concluded that compared with traditional steel truss, composite truss bridge has advantages in flexural performance, tensile performance, stability and other mechanical properties. However, due to the stiffness control design, the strength of composite material is not fully utilized, and the structural reliability of composite truss bridge is low due to the low efficiency of structural joints. The improvement methods of these two problems are reducing the allowable deflection-span ratio of composite truss bridge design and using composite materials with greater stiffness and changing the laying Angle and laying proportion of composite materials, respectively.

Keywords: Composite materials; truss structure; composite truss bridge.

1. Introduction

Composite materials are the new materials created by using advanced material preparation technology to optimize and combine different properties of material components. With the advantages of light weight, high strength, high specific modulus, strong corrosion resistance, and aging resistance, composite materials the excellent materials for lightweight structure and long life. Besides, truss structural members are subjected to unidirectional forces. Therefore, composite truss structures have also gradually attracted attention in aerospace, bridges, construction, and other engineering fields, i.e., the external truss structure used in the support structure of the Hubble telescope optical system, and the truss/plate composite structure used in the first radar satellite body of China [1]. In terms of bridges, there are also composite truss bridges developed by the University of Patras in Greece and the Pentresina Bridge in the Swiss Alps which are representative [2].

With the gradual application of composite truss structures in the field of bridge engineering, the demand for their bearing efficiency and reliability is also gradually increasing. Therefore, this paper firstly studies the superior mechanical properties of composite truss bridges compared with traditional metal trusses by introducing the present situation of composite truss bridges. Secondly, corresponding optimization methods for the problems of connection nodes, reliability, and bearing efficiency are analyzed. Finally, the future of composite truss bridges is looked forward.

2. Application of Composite Truss Btidge

Nowadays, composite truss bridge has been widely used in bridge engineering [3]. The study of composite truss structure was earlier in foreign countries. In the late 1990s, a new type of bridge made entirely of composite materials, built in the form of truss structure, which is lighter and easier to build and install began to appear in Europe and the United States [4]. However, the development of composite multi-directional joints and all-composite truss structures in China is still in its infancy, and most complex structures are made by hand, which is expensive and of variable quality [5]. In

1982, the first fiber reinforced polymer (FRP) highway bridge - Beijing Mayen Highway Bridge was also built [4].

2.1. Application of Composite Truss Bridges Abroad

Uozumi and Kito [6] proposed a pre-compiled/RTM-formed integral Carbon fiber reinforced composites (CFRP) truss structure (as shown in Fig. 1) and tested the compression strength and bending stiffness of the truss using cantilever bending and axial compression tests on it as well as aluminum and titanium structures with the same structural form and weight. The findings indicated that the bending stiffness of a monolithic CFRP truss is 524 N/m, compared to 217 N/mm and 158 N/mm for titanium and aluminum trusses, respectively.

The University of Patras in Greece has developed lightweight bridges assembled from composite pultruded hollow square tubes with steel joints and hinges between members (as shown in Fig. 2) The bridge has a span of 11.6m, a width of 4.2m, a height of 1.2m, and a bearing capacity of up to 30 tons, while its dead weight is only 13.5 tons [5]. Therefore, its bearing capacity to self-weight ratio is much higher than other traditional materials.

Fig. 1 RTM-Formed Truss [6]

Fig. 2 Footbridge in Greece [5]

2.2. Application of Composite Truss Bridge in China

Prefabricated highway steel bridge is a kind of underbearing steel structure highway truss bridge that can be quickly assembled and disassembled. With features of easy disassembly, fast construction, reusability, modular transportation, and assembly, etc., it has been widely used in various bridge repair occasions i.e., rescue and disaster relief, traffic engineering, municipal water conservancy engineering, dangerous reinforcement, and other aspects. However, due to the excessive weight of individual components, its erection speed is slow. Therefore, a composite truss piece was developed to replace the traditional steel truss piece.

The composite truss pieces are prefabricated with steel joints using preload tooth connection technology and then welded or bolted to the members. Besides, the overall geometry of the composite truss piece is similar to that of the traditional steel truss piece, but the weight is only 60% of the steel truss piece, which is 160kg [7].

To verify the reliability of the combined truss unit, a 12m long single-row single-layer truss bridge was erected, and the steel truss piece on one side was replaced with a composite truss piece, and then the static load test was carried out (as shown in Fig. 3) to detect the deflection change of the fiberglass composite-steel composite truss structure. The results show that although the final deflection change of the structure on the side of the composite glass fiber composite-steel composite truss is 42% larger than that of the structure on the side of the composite truss without glass fiber composite. However, it is only less than 3mm [7], which proves the stability of the mechanical properties of the composite truss structure.

Fig. 3 Static and live load loading site of composite truss piece [7]

Zhen [8] of Southeast University intends to study the tensile properties of unidirectional basalt fiber pultruded FRP materials by conducting an FRP profile tensile test, and the test results are shown in Table 1. Through Table 1 and Table 2, it can be concluded that the ultimate tensile strength of the unidirectional basalt fiber pultruded plate can reach more than 1200Mpa, while the ultimate tensile strength of the Q345 steel plate is only 470-650Mpa. It can be seen that the tensile properties of composite materials are much higher than those of traditional steel materials.

Table 1. Tensile performance data of unidirectional basalt fiber pultruded FRP profile plate [8]

Ultimate loads (kN)	Ultimate tensile strength (Mpa)	Ultimate strain ($\mu\varepsilon$)	Elastic modulus (Gpa)	Poisson's ratio
128	1212	23375	52	0.267

Table 2. Q345 steel plate data [8]

Type	Elastic modulus (Gpa)	Poisson's ratio	Density (g/cm^3)	Elongation (%)	tensile strength (Mpa)	Yield strength (Mpa)
Q345	209	0.3	7850	≥22	470-650	259-324

3. Problems of composite Truss Bridges in Engineering

3.1. Underutilization of Strength of Composite Material

Nowadays, most civil composite truss bridges use fiberglass composite materials with the same specific stiffness as steel and aluminum alloys. Table 3 shows the specific stiffness of different materials, i.e., steel, aluminum alloy, CFRP, GFRP and BFRP [9]. However, when the permitted flexural span ratio and stiffness criteria of civil bridges are met simultaneously, the strength of composite materials is not fully used. Therefore, the weight of the bridge is not greatly reduced compared with the traditional steel truss bridge, but the unit price of glass fiber composite material is 3-4 times that of traditional steel material, resulting in the initial cost of composite truss bridge being higher than that of the steel truss bridge.

Table 3. Specific stiffness of different materials [9]

Material	Steel	Aluminum alloy	CFRP	GFRP	BFRP
Specific stiffness ($10^6m^2*s^2$)	26.62	26.65	188.57	10.00	3.49

*Note: BFRP is an abbreviation for basalt fiber-reinforced composite. GFRP is an abbreviation for Glass fiber-reinforced composite.

Zhao et al. [9] counted the design parameters of three civil composite truss bridges in China. As can be seen from Table 4, due to the low elastic modulus of glass fiber composite materials, the deflection-span ratio control of civil bridges is relatively strict, about (l/600 or l/800). Therefore, under the stiffness control design, the stress state of the members is only tens of MPa, resulting in the strength of the composite material not being fully utilized. Besides, the weight of the structure has not been reduced, it is still heavy. For example, the span of the working bridge in the gate area of the bicycle rut is 36 m, the design vehicle load is 6t, and the self-weight reaches 30t [9].

To solve the problem of underutilization of composite strength, the main solution is to reduce the allowable design deflection-span ratio and use composite materials with greater stiffness, i.e., carbon fiber composites. Therefore, Zhao [10] designed the deflection-span ratio of the emergency bridge to be between l/150-l/120 and adopted carbon-glass or carbon-basalt mixed fiber composite with a specific stiffness higher than that of glass fiber composite, which significantly increased the stress of the members.

Table 4. Design parameters of three civil composite truss bridges in China [9]

Bridge name	Span	Hight	Width	Design loads	Deflection-span ratio		Maximum member stress (MPa)	
	(m)	(m)	(m)	(kN*m-2)	Design values	Allowed values	Tensile stress	Compressive stress
Mao Yisheng Public Welfare Bridge	20	3.75	2	5	l/2148	l/600	10.50	11.11
BFRP-UHPC combination bridge	7	1.25	1.9	200	l/2287	l/800	28.44	15.15
Gate area working bridge	36	4	3.6	5	l/989	l/600	45.30	37.30

*Note: UHPC is the abbreviation of ultra-high-performance concrete

3.2. Needs to Improve the Reliability of the Structure

Although FRP composite materials have substantial advantages over traditional materials in terms of lightweight and durability in truss bridge structures, joints will often be destroyed before members because of the low joint connection efficiency (20%–30%) [11]. For example, for the FRP truss bridge designed by Professor Wan Shui, the connection efficiency of bolts is only 25% even if the plus or minus 45° layup is added [10]. For composite pultruded profile members dominated by unidirectional fibers, the bolt connection efficiency is even lower, in addition, the joint connection is prone to brittle failure forms. However, because the brittle joints and brittle members cannot redistribute the internal forces of the steel truss, their structural reliability is lower [9].

To solve the problem of joint efficiency of composite trusses, Liu et al. studied the influence of the laying angle and laying ratio of basalt composite materials on the tensile properties of bolt joints and components [11]. Six laying schemes were designed, respectively. In scheme 1, 6 layers are laid at 0°. Scheme 2 is 3 layers at 0°, 1 layer at 45° and 2 layers at 0°. Scheme 3 places 1 layer at 0°, 1 layer at 45°, two layers at 0°, 1 layer at -45°, and 1 layer at 0°. Scheme 4 places 1 layer at 0°, 1 layer at 45°, 1 layer at 0°, 1 layer at -45°, 1 layer at 0°, and 1 layer at 45°. Besides, scheme 5 places 3 layer at 0°, 1 layer at 90°, and 2 layers at 0°. For scheme 6, it places 1 layer at 0°, 1 layer at 45°, 1 layer at 90°, 1 layer at 0°, 1 layer at -45°, and 1 layer at 0°.

As a result, the tensile test and joint performance test of the six schemes are carried out respectively. According to load-displacement Fig. 4, multi-axial layering can reduce the tensile properties of components, but the final failure displacement does not increase significantly. In addition, as shown in Fig. 5, the increase in multi-angle layering can lead to the reduction of the tensile properties of components.

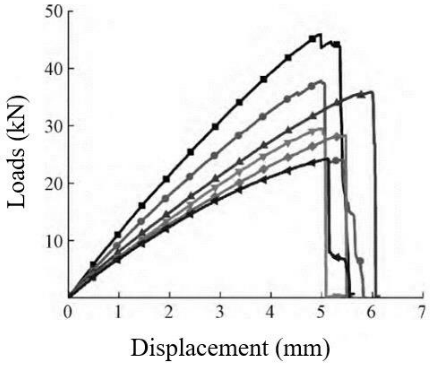

Fig.4 The tensile load-displacement curve of components [10]

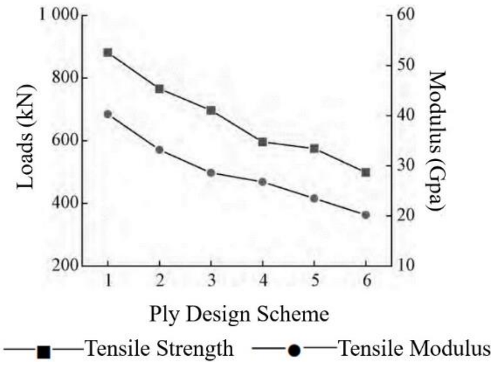

Fig. 5 Influence of different ply designs on the tensile properties of components [11]

Fig. 6 shows the nodal load-displacement diagram of different laying designs. As shown in the figure, the addition of 45° and 90° ply can change the failure mode of the joint, from the original brittle failure to extrusion failure, which improves the bearing capacity of the joint.

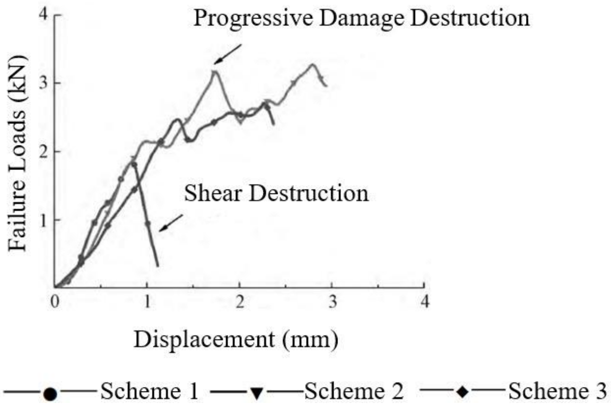

Fig. 6 Bolt joint load-displacement curve [11]

The bearing capacity of joints significantly grew with the inclusion of multi-axial lay-up, but the growth rate was also gradually reducing. The growth amounts of schemes 2, 3, 4, and 5 compared to scheme 1 were 48.6%, 84.6%, 111.7%, and 115.9%, respectively. However, the modulus of its components is gradually decreasing. Therefore, considering the performance of joints and components, there is an optimal ratio of ply design between unidirectional ply and multi-axial ply. Liu et al. believed that ± 45°-layer ratio should be greater than 20% to obtain a certain ductility of extrusion failure, and the proportion of 0° layer should not exceed 60% to ensure the stiffness of structural components [10]. Besides, the proportion of the 90° layer should not be more than 20% because of its destruction-delaying effect, and the specific proportion should be adjusted according to the performance of joints and components.

4. Conclusion

The composite truss bridge perfectly combines the characteristics of composite materials with the force characteristics of the structure, satisfies the full utilization of composite materials, and realizes the advantages of lightweight and high strength. However, there are still some problems in the engineering field of composite truss bridge. Firstly, most of the existing civil composite truss bridges adopt stiffness control design, resulting in small stress on the members, and fail to fully exert the excellent tensile and compressive properties of the composite materials, resulting in heavy structure and high bridge construction costs. As a result, a crucial aspect of composite truss bridge development now centers on how to increase their stiffness. In addition, for the truss bridge with high member stress states, its members and joints are prone to brittle failure, and the structural reliability needs to be further improved. Therefore, how to design and connect the composite joints is still one of the difficulties of composite truss structure in bridge field.

References

[1] Zhang Linghui, Li Jiashen, Jia Qiji, Xia Yingwei, Yin Yongxia, Tu Bin. Research progress of composite truss structure for spacecraft. Fiber Composites, 2013, 30(04): 62-68.

[2] Keller Thomas. Overview of Fibre-Reinforced Polymers in Bridge Construction. Structural Engineering International, 2002, (12): 66 - 70.

[3] Yu Bai. Thomas Keller. Modal parameter identification for a GFRP pedestrian bridge. Composite Structures, 2008, (82): 90~100.

[4] Sun Huiming, Fang Hai, Xu Yiyang, Liu Weiqing. Experimental study on static load performance of composite pultruded profile truss bridge. Industrial Construction, 2014, 44(S1): 896-900.

[5] Kuang Boyang, Zhao Qilin, Chen Li. Research progress of composite truss structures. Proceedings of the 9th National Academic Exchange Conference on FRP Application in Construction Engineering, 2015: 125-134.

[6] Uozumi T, Kito A. Carbon fibre-reinforced plastic truss structures for satellite using braiding/resin transfer moulding process. Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications. 2007, 221(2): -101.

[7] Zhao Qilin, Liu Pengfei, Xu Longxing, Li Fei, Chen Haosen, Xu Kang. Long-term Mechanical Properties of glass fiber composite and steel composite truss Structure. Proceedings of the 8th National Academic Exchange Conference on FRP Application in Construction Engineering, 2013: 215-219.

[8] Jiang Zhen. Research on Mechanical Properties of BFRP Truss Bridge with Integrated Design. Southeast University, 2020.

[9] Zhao Qilin, Gao Jiangang, Tao Jie, Gao Yifeng, Yan Xiaoqiang. Discussion on some Key Problems of Composite truss Bridge. Journal of Nanjing University of Technology (Natural Science Edition), 2017, 39(05): 146-152.

[10] Zhao Qilin, Gao Jiangang, Pan Darong, Li Fei, Zhang Dongdong, Chen Li. Discussion on Design and Calculation Status and Problems of Composite metal-composite truss bridge. Building Structure, 2017, 47(S1): 824-828.

[11] Liu Lulu, Wang Xin, Wu Zhishen. Study on Joint Performance of Fiber Reinforced Composite Truss Structure Based on component-Node Integration. Industrial Architecture, 2019, 49(09): 109-112+172.