Design and Construction

Study on the Structural Performance of through Tied-arch Bridges with CFRP Suspenders

Weixing Cao and Xiaoqing Li *

China Design Group Co., Ltd., Nanjing 210014, Jiangsu Province, China;
* Correspondence: 71882448@qq.com

Abstract: To address the poor corrosion and fatigue resistance of the suspenders in tied arch bridges, a method using carbon fiber-reinforced polymer (CFRP) suspenders on tied arch bridges is proposed. The mechanical properties of tied arch structures and suspenders under different replacement principles are studied, and the equal area principle is selected as the material replacement method. The static responses of structures supported by CFRP suspenders and steel strand suspenders under different loads are compared and analyzed using finite element software. The differences in stress variation between the two approaches are relatively slight, and CFRP can effectively replace steel strands as the material for tied arch bridges. The load-bearing capacities of the suspenders are compared and analyzed based on the "short hanger effect". Compared with full-bridge suspender replacement, single-suspender replacement is more effective and feasible for real bridge applications. An actual engineering case using CFRP suspenders on tied arch bridges is analyzed, which provides new insights for the development of tied arch bridges.

Keywords: Tied arch bridge; CFRP suspender; finite element model; short suspender effect; actual bridge application

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1 Introduction

In recent years, tied arch bridges have seen rapid adoption in China, especially concrete-filled steel tube (CFST) arch bridges, which have become the main type of bridge in China [1]. However, over decades of service, the coupled effects of environmental erosion and load effects have gradually damaged bridge structures [2], and the degraded mechanical properties of the steel wires in suspenders is mostly due to corrosive factors in the environment and load fatigue. As a key component of a tied arch bridge, the performance of steel wires in suspenders can directly affect the overall safety of a bridge structure. Wu et al. [3] prepared 30 steel wires with 6 different corrosion levels using salt spray tests, and uniaxial tension fatigue tests showed that corrosion can significantly reduce the fatigue life of steel wire; Qiao et al. [4] conducted tension fatigue tests on 103 corroded steel wires on a half-through-tied arch bridge, and their results showed that even smaller corrosion pits could greatly reduce the fatigue life of the steel wires, significantly degrading the torsional performance. Lan et al. [5] conducted fatigue loading tests on high-strength steel wires after salt spray corrosion and established a fatigue damage evolution model for corroded steel wires; their results showed that the fatigue life of steel wires significantly decreases with an increasing degree of corrosion. The corrosion and fatigue of suspender wires was prominent. The use of anti-corrosion measures can delay damage, but the mechanical degradation of a corroded steel wire cannot be avoided, ultimately leading cable failure [6]. Research on the safety impacts of suspender fractures on arch bridge structures has gradually increased, and measures to improve structural safety have been proposed, such as strengthening the longitudinal connection of a structure and using double suspenders [7-9]. However, due to the inherent characteristics of steel, rust and fatigue in a suspender cannot be successfully eliminated, so there is an urgent need for a new material to replace steel suspenders.

Carbon fiber reinforced polymers (CFRPs) have the advantages of light weight, high strength, and corrosion and fatigue resistance [10, 11]. The use of CFRP rebar for bridge cables has been studied to improve the span and durability of bridges [12]. The use of CFRP suspenders on a bridge can fundamentally address the corrosion and fatigue of steel suspenders, thereby reducing bridge maintenance costs throughout its service life, improving bridge safety, and greatly reducing traffic closures due to cable replacement. At present, research on the use of CFRP materials for bridge structures has mostly focused on the cable systems of cable-stayed bridges and suspension bridges [13-15]. There are relatively few studies on the replacement of steel suspenders in tied arch bridges, and applications in real bridges are even rarer.

This study examined the construction of highway bridges using CFRP suspenders in China by designating the Sanduoxi Bridge in Gaoyou City—a CFST through-tied arch bridge—as the research example, using Midas Civil software to establish a finite element model (FEM) to conduct a comparative stress analysis of CFRP and conventional steel strand suspenders, investigated the effect of CFRP suspenders on the structural response of a tied arch bridge, verified the feasibility of applying CFRP suspenders in a through-tied arch bridge, and proposed an optimization scheme for applying CFRP suspenders in a real tied arch bridge.

2 CFRP Material Properties

A typical CFRP cable [16] is composed of T700 grade carbon fiber and epoxy resin matrix, with a fiber volume content of 72%. Comparisons of the mechanical and material properties of a CFRP rebar and a steel strand are shown in Figure 1 and Table 1.

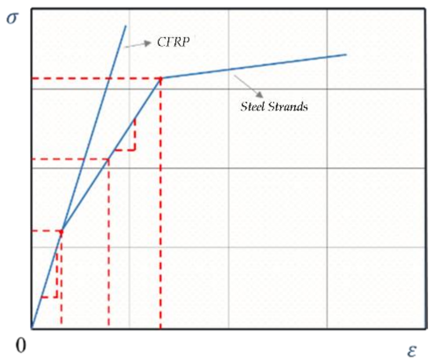

Figure 1 Comparison of the load-bearing performance of CFRP and steel strands

Table 1 Comparison of material properties of CFRP suspender and steel strand suspender

Material	Specifications	Area	Tensile Strength	Nominal breaking stress	Elastic modulus (EI)	Density	Coefficient of linear expansion
/	/	(mm²)	(MPa)	(kN)	(GPa)	(kg/m³)	(*10⁻⁶)
Steel strand	GJ15-9	1260	1860	2343.6	206	7850	12
CFRP	φ7-31	1192	2600	3100.2	165	1560	0.355

From the comparisons, the following can be found:

(1) CFRP material exhibits elastic mechanical characteristics until failure; there is no yield point, and the ultimate strain is far less than that of steel.

(2) The density of the CFRP material is approximately 1/5 that of steel, which can reduce the weight of bridges with large numbers of cables.

(3) The coefficient of linear expansion for the CFRP material is only 1/34 that of steel, which is a significant difference; when the temperature changes, the deformation of a CFRP suspender is greatly reduced.

(4) The nominal breaking stress of a CFRP suspender is 3100.2 kN, which is 1.3 times that of the steel.

CFRP material has the advantage of low density and is especially suitable for cable structures. Due to this low density, under low stress, the loss of EI caused by the self-weight of the CFRP cable is less than the sag effect of the steel cable. The effective EI of the cable is:

$$E_i = \frac{E_0}{1 + \frac{\gamma^2 l_x^2 E_0}{12\sigma^3}} \tag{1}$$

Where E_0 is the EI of the cable, γ is the density of the cable, σ is the stress of the cable, and l_x is the projected length of the cable length in the horizontal direction.

With constant stress and cable length, the effective EI increases as the material density decreases. Therefore, the application of CFRP cables can fully provide the needed material properties.

3 Project Overview

The Sanduoxi Bridge, the first CFST highway bridge with CFRP suspenders in China, is used as an example for calculation and analysis. The detailed structural dimensions are shown in Figure 2. The calculated span of the main bridge is 90 m, the rise–span ratio is 1/5, the rise height is 18 m, and the arch axis is a quadratic parabola. The overall width of the main bridge is 12.8 m, and the lateral spacing of the arch ribs is 11.4 m. The arch ribs are made of dumbbell-shaped CFSTs, the cross-section height is 2.0 m, the outer diameter of each steel tube is 0.85 m, and the steel tubes are filled with C40 self-compacting concrete (SCC). Each suspender adopts an equal-section hollow box girder, with a height of 2.0 m and width of 1.4 m. Four K-type braces are arranged laterally on the arch rib, and the K-type braces are welded by steel tubes with outer diameters of 85 cm and 50 cm. Special suspenders for GJ15-9 arch bridges are used; the spacing along the bridge direction is 5.1 m, and there are 16 pairs in the whole bridge. The bridge deck is made of a 27 cm thick solid precast slab. The lower structure adopts a pier-bearing platform–pile foundation. The cross-section of the main pier is a 1.8 m (horizontal bridge direction) × 2.2 m (along the bridge direction) chamfered rectangle; the dimensions of the bearing platform are 6.4 m (horizontal bridge direction) × 6. 4 m (along the bridge direction) × 2.5 m (height). The foundation is made of eight bored piles with a diameter of 1.5 m and a spacing of 3.9 m.

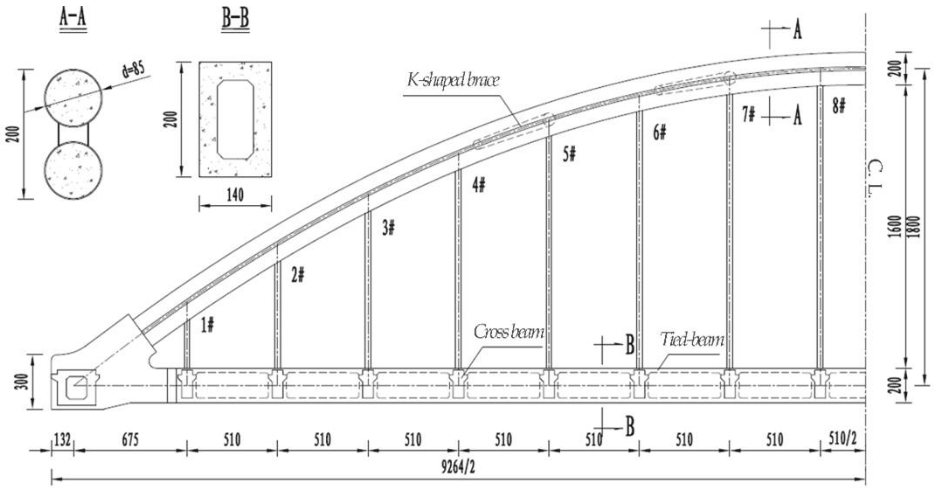

Figure2 Structural dimensions of the Sanduoxi Bridge

4 Finite Element Analysis

In this paper, Midas Civil software was used to simulate the actual construction procedure for calculation. In the model, a prestressed concrete (PSC) beam element was used to simulate suspenders, and the beam element was used to simulate arch

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ribs, longitudinal beams and beams. For the cross-section unit of the CFST arch rib, the boundary conditions before and after concrete tube filling were simulated by using a joint section during the construction phase, and a truss element was used to simulate the suspenders. The external condition of the bridge structure was static, so the external constraint was a simple support, and the connection of the suspender with tie beams and arch ribs was a rigid connection. Equivalent uniformly distributed loads were used on the bridge deck, and the loads on the bridge superstructure were symmetrically distributed. The loads in the calculation included self-weight, secondary dead load, moving load, prestress and temperature load. The full bridge was divided into a total of 540 units and 330 nodes. Figure 3 shows the calculation model. Since the suspenders of this bridge were arranged at 90°, any influence of the sag effect on the suspenders was relatively insignificant. In this paper, the difference in sag effect between the CFRP suspenders and the steel strand suspenders is not considered.

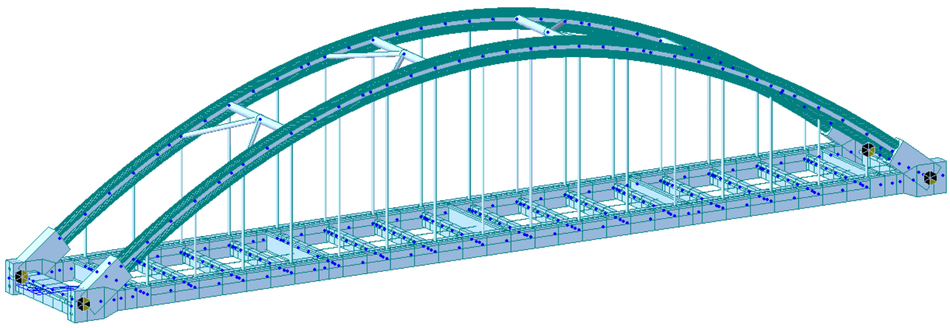


Figure 3 Finite element model

4.1 Determine the Replacement Principle

Studies have shown that when a CFRP suspender is used to replace the conventional steel strand suspender, the principles of equal strength replacement, equal stiffness replacement and equal area replacement are often used to carry out parametric replacement of the steel strand suspender. Replacing a steel strand suspender with a CFRP suspender according to different principles causes changes in the maximum load strength and stiffness of the suspender, thus causing changes in the corresponding structural response. This study used different replacement schemes, performed a force analysis of the suspender, and obtained the optimal equivalent replacement scheme while adhering to principles of safety, economy, and applicability.

The area, stiffness and strength of the steel were set to unity, and the area ratio, stiffness ratio and maximum tensile strength ratio were converted for different replacement schemes accordingly. According to the corresponding ratios, the actual strand material parameters were replaced, and the equivalent material properties of CFRP can be obtained, as summarized in Table 2.

Table 2 Comparison of material properties between a CFRP suspender and a steel strand suspender under different replacement principles

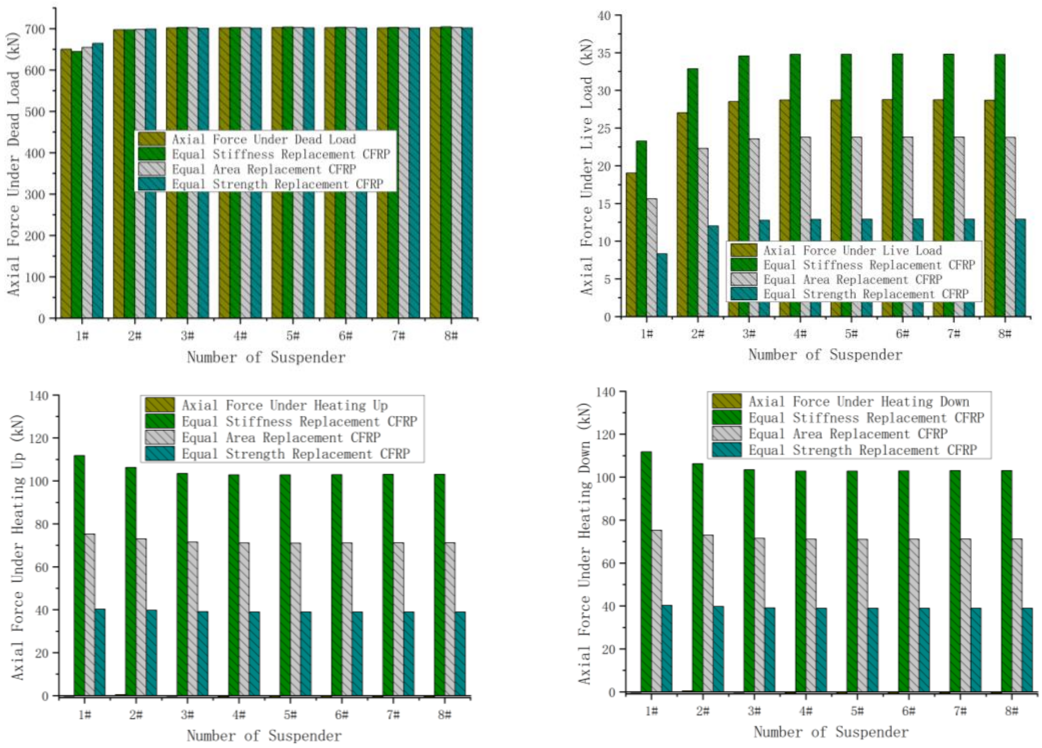
Material	Area ratio	Stiffness ratio	Maximum tension ratio	Area (mm^2)	Tensile strength (MPa)	EI (GPa)	Coefficient of linear expansion ($*10^{-6}$)	Total weight of suspender (kg)
Steel strand	1.00	1.00	1.00	1260	1860	206	12.0	4734
CFRP under equal area	1.00	0.80	1.398	1572	3246	206	0.355	1174
CFRP under equal stiffness	1.248	1.00	1.745	901	1860	118	0.355	673

Material	Area ratio	Stiff-ness ratio	Maxi-mum tension ratio		Area (mm²)	Tensile strength (MPa)	EI (GPa)	Coefficient of linear ex-pansion (*10⁻⁶)	Total weight of suspender (kg)
CFRP under equal strength	0.715	0.573	1.00	⇨	1260	2600	165	0.355	941

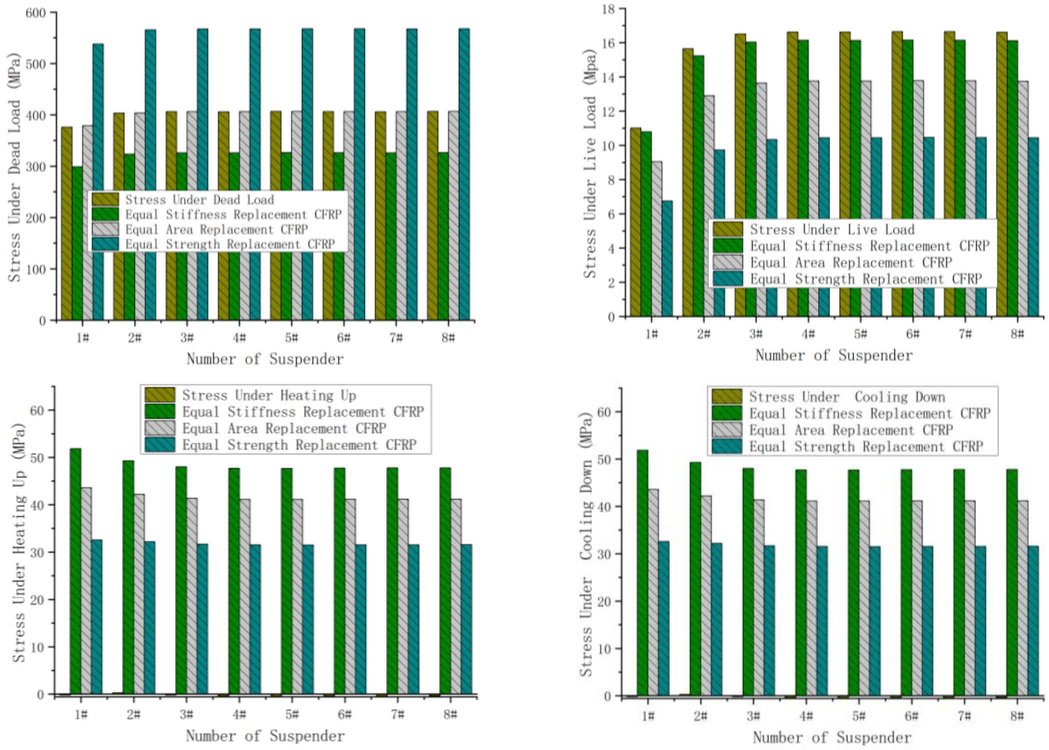
Table 2 shows that the advantages and disadvantages of the material properties that change under the different equivalent replacement schemes are relatively obvious, so it is difficult to simply determine an effective equivalent replacement scheme. Therefore, the material properties of the suspenders under the different replacement schemes were substituted into the FEM and compared. The stresses on the suspenders under different replacement schemes and loads (dead load, live load, heating up and cooling down) were compared, as shown in Figure 4. Considering the structural symmetry, only the internal forces of the half-span structure components were shown. The comparison results of the internal force, stress and displacement of the suspender are shown in Table 3, where A represents the principle of equal area, E represents the principle of equal stiffness, and f represents the principle of equal strength.

Table 3 Comparison of the internal force of the CFRP suspender and the steel strand suspender under the different replacement principles

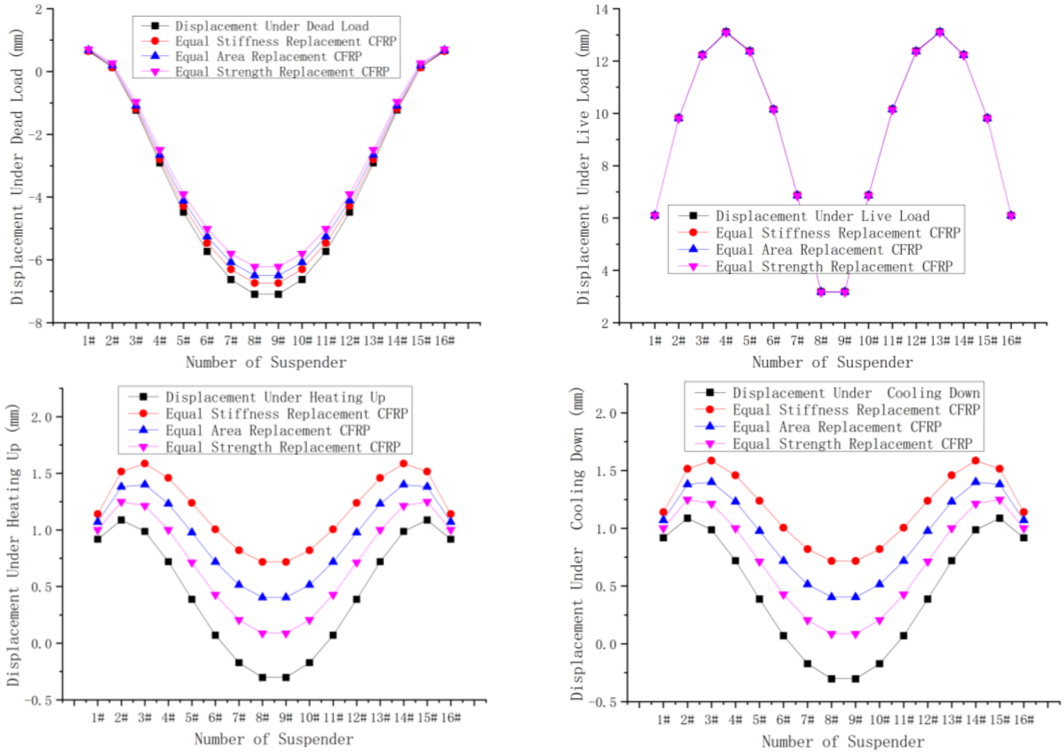
Parameters/working conditions	Axial force	Stress	Displacement
Dead load	A>E>f	A>E>f	E>A>f
Live load	A>E>f	E>A>f	A ≈ E ≈ f
Heating up	f>A>E	f>A>E	f>A>E
Cooling down	f>A>E	f>A>E	f>A>E



(a) Axial force of the suspender



(b) Stress in the suspender

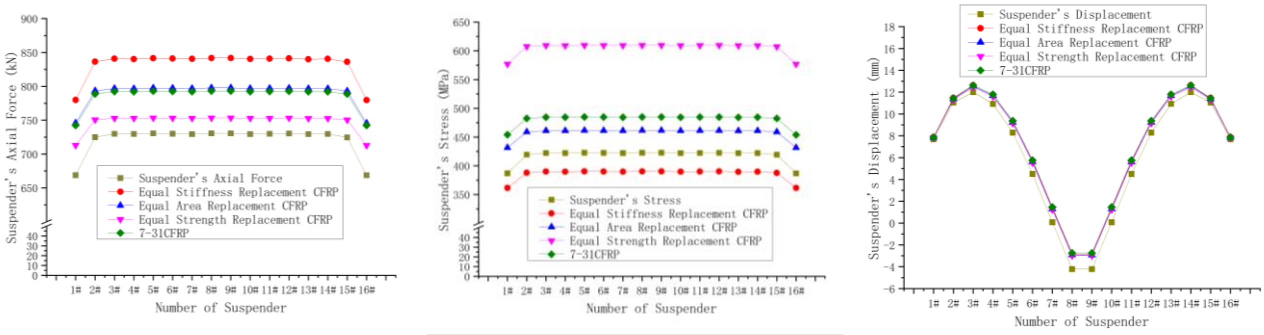


(c) Displacement of the suspender

Figure 4 Stress and displacement of the suspender under different loads (dead load, live load, heating up and cooling down)

Under different loads, the internal force responses of the suspenders with different replacement principles exhibited different degrees of superiority. Under the dead load condition, the axial force and stress of the suspender were the optimum under the equal-area principle, followed by the principle of equal stiffness. Under the live load condition, the axial force of the suspender was the optimum under the principle of equal area, followed by the principle of equal stiffness; the stress of the suspender was the optimum under the principle of equal stiffness, followed by the principle of equal area; and for the displacement of the suspender, all equivalent replacement schemes performed well. For the heating up and cooling down conditions, for the axial force, stress and displacement of the suspender, the principle of equal strength was the best, followed by the principle of equal area. Considering that the dead load and live load account for a large proportion of an actual bridge, an economic benefit analysis was conducted based on the total weight of the suspenders in Table 2, and the equal area replacement principle was determined to perform material parameter conversion between the CFRP suspenders and the steel strand suspenders in order to simulate the parameters of the suspender in the FEM.

Therefore, in this paper, a φ7-31CFRP suspender was chosen for replacement, and the relevant material parameters are shown in Table 1. The finite element analysis was performed on φ7-31CFRP, the dead load, live load and heating up conditions were investigated according to the standard load combination, and the principles of equal area, equal strength and equal stiffness were used to compare the overall load-bearing performance, as shown in Figure 5.



(a) Axial force of the suspender (b) Stress in the suspender (c) Displacement of the suspender

Figure 5 Force comparison of the φ7-31CFRP suspender in the standard load combination with different material properties

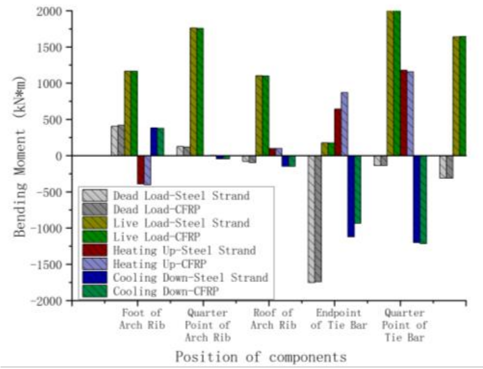
A comparison of the internal force of the suspenders with different material properties under the standard load combination showed that, compared with steel strand suspenders, the axial force of CFRP suspenders was reduced by 8.56%, the stress of the suspenders was reduced by 14.73%, and the displacement of the suspenders was reduced by 5.18%. The suspender weight was reduced by 24.2% compared to that under the principle of equal stiffness; under the standard load combination, compared to the steel strand suspender, the axial force of the CFRP suspender increased by 5.8%, the stress of the CFRP suspender increased by 24.24%, and the displacement of the CFRP suspender increased by 0.13%. The structure weight of the suspender increased by 32.3% compared to the principle of equal strength; under the standard load combination, compared to the steel strand suspender, the axial force decreased by 5.28%, the stress increased by 20.45%, and the displacement decreased by 1.25%.

The force-bearing capacity of the φ7-31CFRP suspender is significantly improved compared with that of the steel strand suspender. Compared with the equal strength principle and the equal stiffness principle, when the area of the suspender was controlled, the variation in the internal force of the suspender was slight, indicating that the principles of economy, safety, and applicability were better satisfied, so this paper selected the φ7-31CFRP suspender as a replacement.

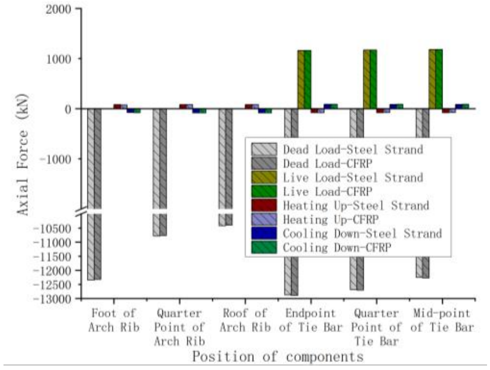
4.2 Study on the Static Performance of Tied Arch Bridges with CFRP Suspenders

Due to the large difference in the bulk density of the CFRP material and the steel strand material, the load-bearing performance of a tied arch bridge under the same structural dimensions after suspender replacement was analyzed. The analysis mainly focused on the force on the members, such as arch rib, tie bar, and suspender, and the corresponding bending moment, axial force, and displacement were compared under the dead load, live load, heating up and cooling down conditions. For the bending moment, the lower side tension is positive, and the upper side tension is negative. The axial force is positive in compression and negative in tension; the suspender force is positive in tension and negative in compression; and the displacement is negative downward and positive upward.

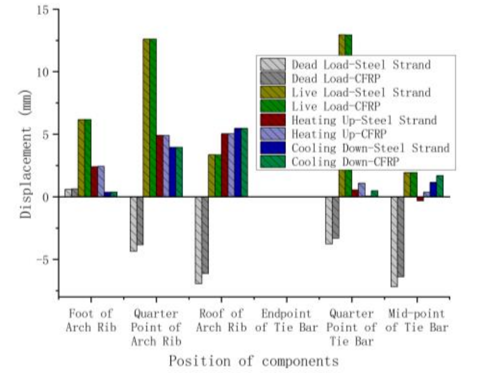
The structural responses of the arch ribs, tie bars and suspenders of the tied arch bridge under different work conditions are shown in Figure 6.



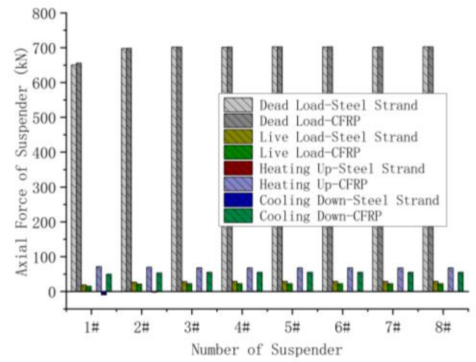
(a) Bending moment



(b) Axial force



(c) Displacement

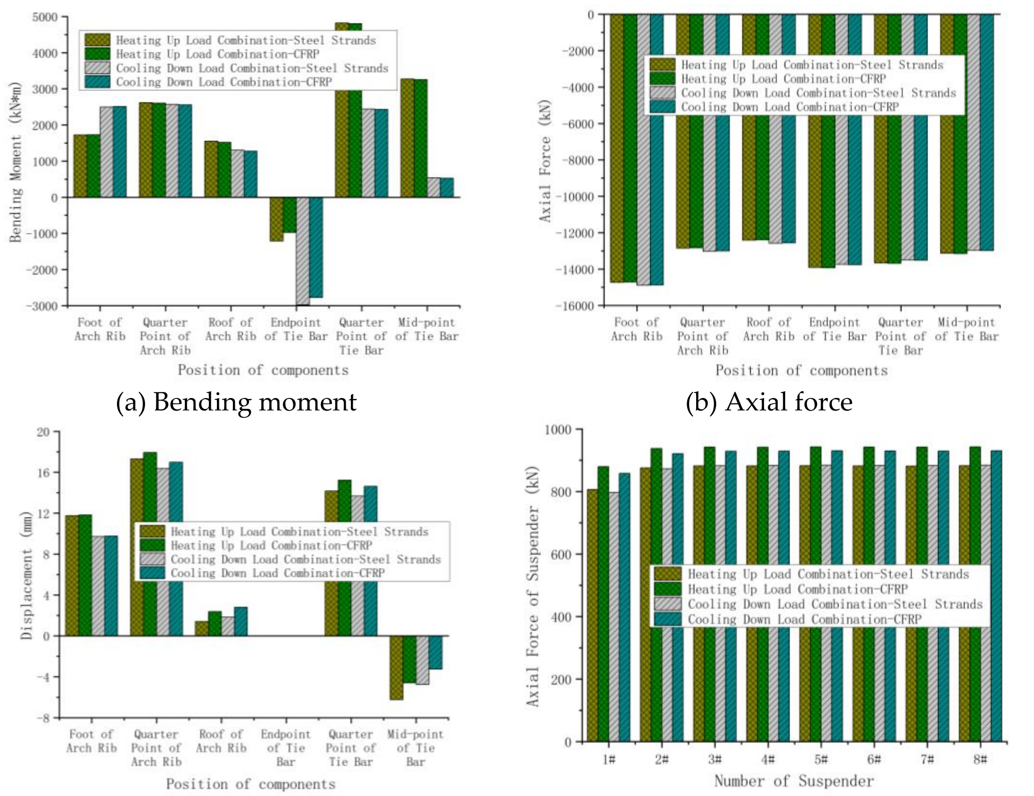


(d) Suspender force

Figure 6 Comparison of forces on different components between the CFRP suspender and steel strand suspender under different loads

When a CFRP suspender is used to replace a steel strand suspender the following are observed: (1) Under the dead load, the difference in the bending moment of the arch rib is relatively small, with a maximum difference of 16.85 kN·m; the variation in the axial force of the arch rib has no significant difference, and there is a slight difference in the displacement. The CFRP suspender shows a certain improvement on the displacement of the arch rib at the vault and the 1/4 of the arch rib; the bending moment and axial force of the tie bar show no significant change, the displacement of the lower member of the CFRP suspender is relatively slight, and the maximum difference of the mid-span position is 0.8 mm; the axial force and displacement of the CFRP suspender are smaller than those of the steel strand material; the maximum difference of the axial force of the #1 suspender is 5.81 kN, and the maximum difference of the displacement is 0.8 mm. Due to the change in the cross-sectional area, the difference in suspender stress is obvious. (2) Under a live load, the bending moment, axial force, displacement of the arch rib and tie bar and the change in the suspender material do not show significant differences, but the axial forces of the CFRP suspender and the steel strand suspender are significantly different, and the axial force of each CFRP suspender is relatively small. (3) Due to the significant difference in the coefficient of linear expansion between the CFRP material and steel strand material, the temperature effect also fully reflects the difference between the two materials. A comparison of the maximum internal force of the components under heating up and cooling down conditions shows that the axial force of the arch rib and the bending moment of the tie bar are less affected by the change in the material; the difference in the axial force of the suspender is the most significant, and the axial force of the CFRP suspender varies greatly under heating up and cooling down conditions, but the maximum axial force is only 71.57 kN; the displacement of the tie bar also shows that with the change in temperature, the variation in the CFRP suspender is more significant than that of the steel strand suspender.

In summary, the structural responses of the CFRP suspender and the steel strand suspender under dead load and live load conditions vary little; the difference between the two is significant under heating up and cooling down conditions, but the internal force of the structure under heating up and cooling down conditions is much lower than that under the dead load and live load conditions. If the internal force change of the tie arch bridge under the action of temperature is considered, it is bound to be far away from the actual situation, so this paper considered the actual service status of the bridge and intended to compare and analyze the CFRP suspender under the dead load, live load, and temperature changes in accordance with the basic load combination of structural effects, that is, the combinations of permanent load design value and variable load design values in the "General Specifications for Design of Highway Bridges and Culverts" (JTG D60-2015), and the coefficients of dead load, live load and temperature are 1.2, 1.4, 1.0, respectively. The structural response of the main members of the tie arch bridge under the basic load combination of loads is shown in Figure 7.



(a) Bending moment (b) Axial force

(c) Displacement (d) Suspender force

Figure 7 Comparison of forces on different components between the CFRP suspender and steel strand suspender under different loads

Based on a basic load combination of load effects, the internal force variation of the arch rib and the tie bar is less affected by the selection of suspender material, and the load-bearing capacity of the CFRP suspender is more significant than that of the steel strand, but the safety coefficients of members are all within the requirements of the code and have improved somewhat due to the material properties.

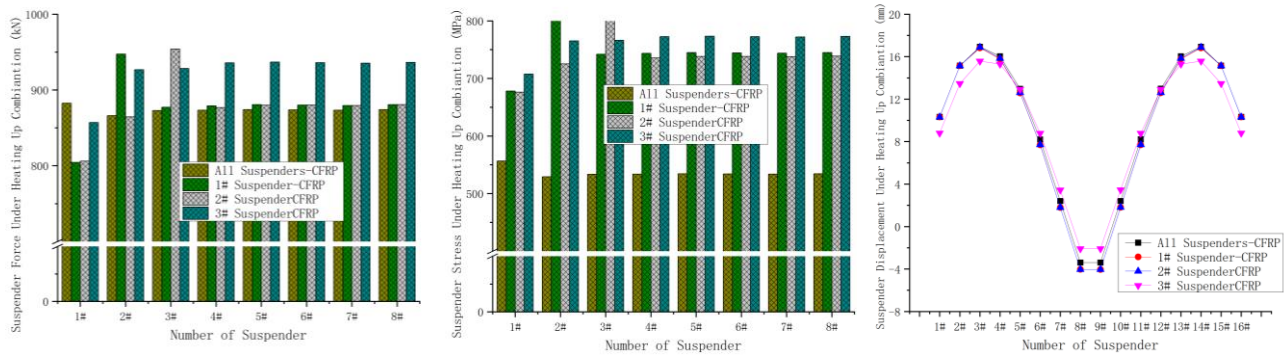
Therefore, the change in the static force of the arch bridge with CFRP suspenders is insignificant. That is, the application of the CFRP suspender to the tied arch bridge does not affect the load-bearing capacity of the structure, and some indicators of the static parameters show certain improvements when using the CFRP suspenders on the structure, such as bending moment and displacement of arch ribs under dead load, which fully demonstrates that using the CFRP material still can effectively ensure the safety of the tied arch bridge. Therefore, it can be considered that the use of φ7-31CFRP to replace all the bridge tie bars can maintain the safety and reliability of the structure under loads, can meet the structural needs of the bridge when it is in operation, and can better replace the steel strands in actual applications.

5 Structural Optimization Based on the Short Suspender Effect

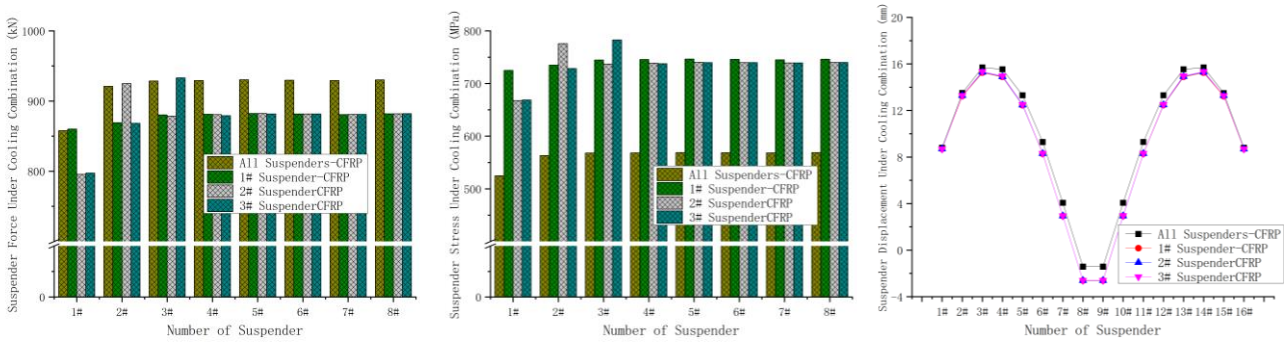
At present, the main problem that limits the wide application of CFRP material is that its cost is higher than that of traditional steel. Therefore, from an economic point of view, this paper launches a study on the replacement of some suspenders of tied arch bridges with CFRP material, aiming to find the best solution for the application of CFRP materials to tie arch bridges based on a comprehensive safety and economic point of view.

At 4:00 am on November 7, 2001, suspenders of the Xiaonanmen Bridge on the Jinsha River in Yibin City, Sichuan Province, suddenly broke, causing bridge decks at approximately 30 m on both sides to suddenly collapse [17]. At 5:00 am on April 12, 2011, the second suspender of the main span of the Kongque River Bridge located in Xinjiang also broke due to corrosion of the load-bearing steel cables, causing the third, fourth and fifth main girders of the main span to fall into the river; 3 cars fell off the bridge, and two people being missed[18]. Coincidentally, the broken suspenders were all located in the triangular area near the connection of the arch and the bridge deck on both arch ends, and they were all the short-side suspenders in the arch bridge. Relevant studies [19, 20] have noted that under the same load, the effect of the dynamic load impact on a short suspender is much greater than that on a long suspender, sometimes even more than twice, which is unfavorable for the load-bearing performance of the short suspender. In addition, the short suspenders are located at the junction between the suspenders and the columns, and the deformation of the upper arch ribs due to temperature and force are concentrated in this area. As a result, the bridge deck is subjected to additional tension, so that the short suspenders are subjected to a larger shear deformation than the long suspenders. Moreover, the lower end of the short suspender is in a state of repeated bending, which triggers the development of microcracks and greatly reduces the fatigue resistance of the short suspender. In addition, because the short suspenders of most bridges are too short, the free length is relatively short. Under the influence of temperature change, when the bridge deck undergoes repeated vertical displacement, the short suspenders cannot swing freely, and frequently large additional stresses occur, with only the short suspender and the structure being damaged.

Therefore, this paper proposed a scheme of replacing the short suspenders of the tied arch bridge with CFRP suspenders and carried out finite element analysis. In view of the actual situation in which the short suspenders in the triangular area of the tied arch bridge are easily damaged, only suspenders #1, #2 and #3 were replaced with CFRP suspenders, and results were compared to those with all suspenders replaced by CFRP suspenders. The differences in the axial forces, stresses and displacements of the suspender under dead load, live load, heating up and cooling down combination were analyzed, as shown in Figure 8.



(a) Heating combination



(b) Cooling combination

Figure 8 Response on the suspender members under different load combinations.

Figure 8 shows that under the same load, the axial force and stress of the suspender have similar patterns. Under dead load, when a single CFRP suspender is used to replace a steel strand suspender, the stresses of the suspenders are very similar and are slightly higher than the stresses of the suspenders with all suspenders replaced by CFRP suspenders; under live load, the stresses of the CFRP suspenders are significantly lower than those of steel strand suspenders and slightly higher than those in the case of all suspenders replaced by CFRP suspenders; under the temperature changes, the CFRP suspenders are significantly affected.

Under dead load, the displacements of the suspenders when only one CFRP suspender is used are almost the same and larger than those in the case of all suspenders replaced by CFRP suspenders. Under live load, the displacements of the suspenders when only one CFRP suspender is used are the same as those in the case of all suspenders replaced by CFRP suspenders. Under the influence of temperature rise and fall, the displacements of the suspenders are larger than those in the case of all suspenders replaced by CFRP suspenders, but the difference between working conditions is small.

In summary, there is little difference between the full-bridge suspender replacement scheme and the single-suspender replacement scheme, and the economic and safety benefits of the single-suspender replacement scheme are more significant. The arch bridges under the side suspender replacement scheme and the side + secondary side suspender replacement scheme all show consistent structural responses under dead load, live load and temperature load conditions; the force and deformation of each suspender are basically reasonable, and both schemes can be adopted. Among them, the side + secondary side suspender replacement scheme can be given priority because it can better utilize the material characteristics of CFRP. Therefore, based on the vulnerability of the triangular area of the short suspender and the comprehensive cost and safety considerations, it is recommended to only replace suspender #2, which is the optimal single-suspender replacement scheme in actual bridge construction.

6 Conclusions

Based on a comparison of the material parameters and mechanical parameters of CFRP and steel strand materials, a scheme of applying CFRP suspenders to a tied arch bridge is proposed. The replacement principle of the material parameters is analyzed, and after comprehensively evaluating structural safety and economic applicability, the equal area principle is determined as the optimal equivalent replacement principle.

Based on the FEM structural response after material replacement, the load-bearing performances of the arch bridge under different conditions, such as dead load, live load and temperature, are compared, and the CFRP suspenders have little impact on the structure and could ensure the safe use of the structure while meeting the standards.

To address the problem of short suspenders in tied arch bridges, a scheme of partial replacement of the steel suspenders in tied arch bridges is proposed. Finite element analysis verifies that the difference in the load-bearing capacity of the suspenders between the schemes of overall replacement and partial replacement is relatively small, so it is recommended to only replace suspender #2, which is the optimal single-suspender replacement scheme in actual bridge construction.

In this paper, the application scheme of a real bridge is determined through finite element analysis. The actual load-bearing capacity of the structure is still not clear. The degree of corrosion for each girder is not high, and the nonlinear mapping characteristics between the degree of corrosion and the degree of structural damage are not obvious. In future work, the method proposed in this paper can be further improved by validating and revising the finite element analysis using the structural response data of a real bridge.

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Data Availability Statement: The data that support the findings of this study are available from the corresponding author, Li, upon reasonable request.

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AUTHOR BIOGRAPHIES

	**Weixing Cao** M.E. Senior Engineer, China Design Group Co., Ltd. Research Direction: Design of Long-span Bridge Structures. Email: 54537341@qq.com		**Xiaoqing Li** M.E. Engineer, China Design Group Co., Ltd. Research Direction: Design of Long-span Bridge Structures. Email: 71882448@qq.com