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Research article

Advantages of using CFRP cables in orthogonally loaded cable structures

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Abstract: Carbon Fiber Reinforced Polymer (CFRP) is an advanced composite material with advantages of high strength and light weight, giving it great potential to be a new, reliable cable material. Ideal structures for CFRP cables are orthogonally loaded cable structures, where cables are loaded orthogonally or approximately orthogonally by external loads. Using CFRP cables in such structures, e.g. cable roofs and cable facades, has advantages over traditional steel cable structures. In order to demonstrate this point, two typical orthogonally loaded cable structures, i.e. a CFRP spoked wheel cable roof and a CFRP cable net façade, were investigated in a case study. Their mechanical properties and economies are compared with that of the steel counterparts. Results show that CFRP cables can effectively improve the mechanical and economical performances of orthogonally loaded cable structures; furthermore, the advantages of applying CFRP cables for cable net facade are more obvious than that for spoked wheel cable roof.

Keywords: CFRP cable; orthogonally loaded cable structure; cable net facade; spoked wheel cable roof; advantage

1. Introduction

1.1. Carbon Fiber Reinforced Polymer (CFRP)

Carbon Fiber Reinforced Polymer (CFRP) is a non-metallic composite material with outstanding properties. As its name suggests, it is composed of carbon fibers as reinforcement embedded in a polymer matrix [1]. The mechanical properties of typical carbon fibers and polymers are listed in Table 1, compared with that of commonly used steel materials.

Table 1. Mechanical properties of carbon fibers and polymers compared with steels.

Material type		Density ρ (kg/m^3)	Tensile strength σ_u (GPa)	Elastic modulus E (GPa)	Breaking length L_b (km)
Carbon fiber [2]	Standard	1760	3.53	230	205
	High strength	1820	7.06	294	396
	High modulus	1870	3.45	441	188
Polymer [3]	Epoxy	1300	0.1	3.5	8
	Polyester	1250	0.065	2.9	5
	Vinyl ester	1280	0.088	3.2	7
Steel [4]	S355	7850	0.5	210	6
	Wire*	7850	1.77	210	23

* Round wire for full-locked coil rope, made of cold drawn non-alloy carbon steel.

Note: The breaking length L_b is a good parameter to show the high strength and light weight characteristics of certain materials, which is defined as the maximum length of a hanging bar that could suspend its own weight and can be calculated by $\sigma_u/(\rho g)$, where g is the standard gravity constant of 9,8 m/s^2.

As shown in Table 1, the tensile strengths of carbon fibers are significantly higher than that of steel materials, while their densities are much lower, which makes the breaking lengths of carbon fibers orders of magnitude longer than that of steel materials [5]. However, comparing polymers and carbon fibers, it can be found that the strengths and moduli of polymer resins are considerably smaller than that of carbon fibers. This causes CFRP to have a strong orthotropic behavior. In the fiber direction, CFRP mainly exhibits the mechanical properties of fibers, i.e. relatively high strength and high modulus; while in the direction perpendicular to the fiber axis, CFRP mainly exhibits the mechanical properties of resins, i.e. relatively low strength and low modulus. Moreover, the shear strength of CFRP is also relatively low. These above reasons make CFRP cables difficult to be anchored.

Aeronautics and astronautics industries pioneered the use of CFRP about 50 years ago, shortly after the successful manufacture of high performance carbon fibers [6]. In the field of civil engineering, the first practical utilization of CFRP is the project of strengthening the Ibach Bridge in Lucerne, Switzerland, in 1991 [7]. From then on, more and more CFRP products were used, not only in strengthening, repairing, reinforcing, pre-stressing, but also as cables in cable structures.

1.2. CFRP Cables

According to the structural form, the existing CFRP cables can be mainly classified into four types, as shown in Figure 1.

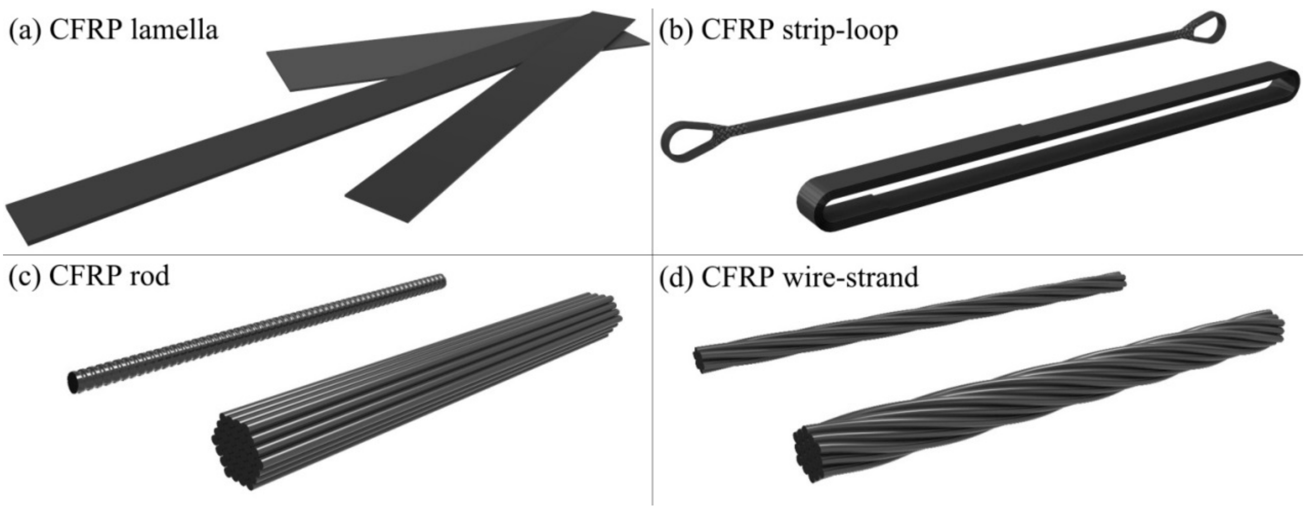


Figure 1. Four main types of CFRP cables.

Figure 1(a) shows the CFRP cable in the form of lamella, which is produced by pultrusion [8]. Figure 1(b) shows the CFRP cable in the form of strip-loop, which is fabricated by winding a continuous CFRP strip on two pins; then the strip-loop can choose to be laminated or non-laminated [9]. Figure 1(c) shows the CFRP cable in the form of rod, which is usually fabricated by pultrusion; such CFRP cable can be made up of a single rod or a rod bundle, moreover the rod can be plain round or deformed [10]. Figure 1(d) shows the CFRP cable in the form of wire rope, which is fabricated by twisting several CFRP wires into a helix; the CFRP wires used are usually produced by pull-winding [11].

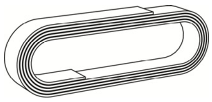
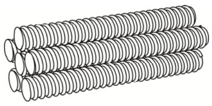
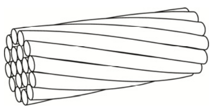
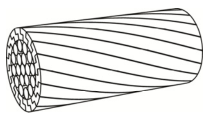
The mechanical properties along the fiber direction of CFRP, such as tensile strength σ_u and elastic modulus E, are usually approximately 60%–70% of that of carbon fibers because the fiber volume fraction is usually 60%–70%. It should also be noted that σ_u and E of CFRP cables are slightly smaller than that of corresponding CFRP, which is similar to the fact that σ_u and E of steel cables are slightly smaller than that of steel wires [5].

The mechanical properties of four CFRP cables (in different forms and from different producers) and a steel full locked cable are listed in Table 2 [12–16].

The above four CFRP cables are made from standard carbon fibers (see Table 1) with approximately 60% fiber volume and have already been used in cable structures [17]. The steel full locked cable is commonly used in cable structures, such as bridges, roofs and facades. As seen from Table 2, the tensile strengths of CFRP cables are obviously higher than that of steel cable while their densities are only approximately 1/5 of steel cable's density.

In addition to the high strength and light weight, CFRP cables have better corrosion and fatigue resistance and lower thermal expansion than steel cables. Because carbon fibers have excellent creep resistance, the stress relaxation of CFRP cables is very small and hence there is no need to limit their sustained tensile stresses [2].

Table 2. Mechanical properties of CFRP cables compared with steel cable.

Name of cable	Structural form	Description	Density ρ (kg/m^3)	Tensile strength σ_u (GPa)	Elastic modulus E (GPa)
DPP CFRP lamella		Pultruded CFRP lamella	1600	2.5	140
EMPA CFRP strip-loop		Non-laminated looped CFRP thin strip	1500	2.0	120
Mitsubishi Leadline		Parallel CFRP deformed rods	1600	2.3	147
Tokyo Rope CFCC		Twisted CFRP round wires	1500	2.1	137
Steel full-locked coil rope		Twisted steel round and z-profile wires	7850	1.5	160

However, CFRP cables also have some disadvantages, such as lower elastic modulus than that of steel cables (see Table 2), relatively small ultimate strain, difficult anchoring and relatively high cost, which may have negative effects on the application of CFRP cables.

1.3. Existing CFRP Cable Structures

Studies on CFRP cable structures can be dated back to the 1980s [18]. As early as in 1987, a CFRP cable-stayed bridge with a main span of 8400 m crossing the Strait of Gibraltar was proposed [19]. However, the first practical use of CFRP cables in a real cable structure was in 1996 in the Tsukuba FRP Bridge [20]. From then to now, there have been 10 CFRP cable structures over the world, even though all of them were built more or less experimentally. The existing CFRP cable structures are listed in chronological order of completion in Figure 2 [21].

In Figure 2, No. 1 is the Tsukuba FRP Bridge (photo credit: Iwao Sasaki), which is a pedestrian cable-stayed bridge completed in 1996 and located in Tsukuba, Japan; all stay cables of this bridge are made of CFRP. No. 2 is the Stork Bridge completed in 1996 and located in Winterthur, Switzerland (photo credit: EMPA); it is a highway cable-stayed bridge with 24 stay cables and two of them are made of CFRP. No. 3 is the Neigles CFRP Footbridge (photo credit: Tokyo Rope); it is a pedestrian suspension bridge completed in 1998 and located in Fribourg, Switzerland and its two main cables are made of CFRP. No. 4 is the Herning CFRP Bridge completed in 1999 and located in Herning, Denmark (photo credit: COWI), which is a pedestrian cable-stayed bridge with all cables made of CFRP. No 5 is the Laroin CFRP Footbridge (photo credit: Freyssinet), which is a pedestrian cable-stayed bridge with 16 CFRP stay cables and 2 steel back stays; it was completed in 2002 and is located in Laroin, France. No. 6 is the Jiangsu University CFRP Footbridge completed in 2005 and located in Zhenjiang, China (photo credit: Kuihua Mei), which is a pedestrian cable-stayed bridge with all cables made of CFRP. No. 7 is the Penobscot Narrows Bridge, which is a highway cable-stayed bridge completed in 2006 and located in Penobscot, Maine, USA (photo credit: MOT); in 2007, six steel strands in the stay cables of this bridge were replaced by CFRP strands. No. 8 is the EMPA Bowstring Arch Footbridge completed in 2007 and located in Dübendorf, Switzerland (photo credit: Urs Meier); all the bowstrings of this bridge are made of CFRP. No. 9 is the TU Berlin CFRP Stress-Ribbon Footbridge completed in 2007 and located in Berlin (photo credit: Achim Bleicher); all stress-ribbons in this bridge are made of CFRP. No. 10 is the Cuenca Stress-Ribbon Footbridge completed in 2011 and located in Cuenca, Spain (photo credit: Mike Schlaich); it is a pedestrian stress-ribbon bridge with all stress-ribbons made of CFRP.

Figure 2. Existing CFRP cable structures.

As seen from the above introduction, the existing CFRP cable structures are all cable bridges. Moreover, majority of them are cable-stayed bridges. Up to now, there is not yet any CFRP cable roof or facade in the world. Furthermore, studies on CFRP cable roofs or facades are also very few [21,22,23]. This research gap is the research focus of this paper.

2. Theoretical Basis

2.1. Stiffness Composition of Cable Structures

Cable structures are tension-dominated structures. Their total structural stiffness K consists of two parts, i.e. the elastic stiffness K_E and the stress stiffness K_σ (in some literature, the stress stiffness is also called the geometric stiffness K_G [24,25]). K_E derives from the elastic modulus E of cables and exists along the cable axes; K_σ derives from the cable stress and exists not only along but also perpendicular to the cable axes. Their magnitudes and directions at the middle node of a two-link cable can be shown in Figure 3, where A denotes the cross-sectional area of cables [5].

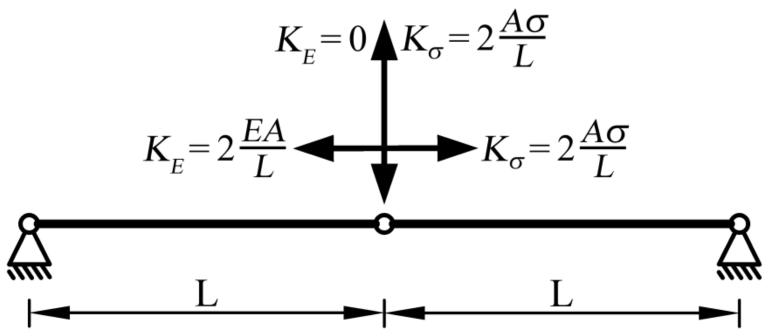


Figure 3. Magnitude and direction of K_E and K_σ.

The proportions of elastic stiffness and stress stiffness in total structural stiffness can considerably influence the structural behaviors of cable structures and thus determining their designs. This can be demonstrated by investigating a simple cable structure shown in Figure 4, which is a double-curved cable net with four cables under a vertical load at the middle point [26]. Without considering self-weight and cable sag, every cable of this cable net can be set to one cable element, whose stiffness matrices can be found in FEM literature [27,28]. In this cable net, the external load is a concentrated force acting at the Node 1 and θ is the angle between the cable axis and the external load, which is the same for all cables in this example.

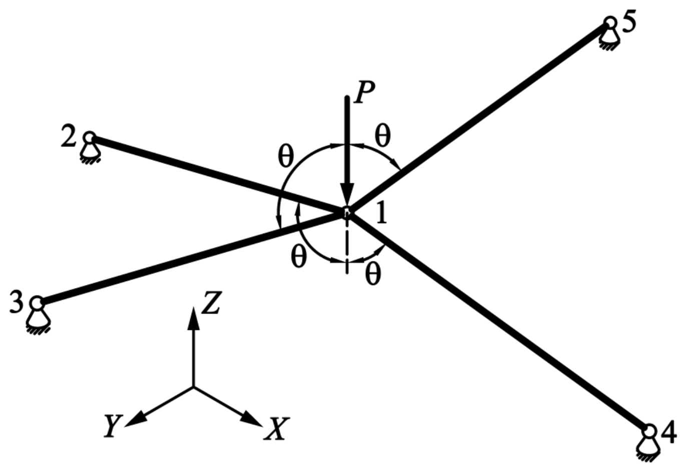


Figure 4. Double-curved cable net with four cable elements.

For the above double-curved cable net, there is only one degree of freedom, i.e. the vertical freedom at node 1. The structural stiffness of this cable net can be written as:

$$K = K_E + K_\sigma \tag{1}$$

In Eq. (1), K_E and K_σ can be expressed as:

$$K_E = 4\frac{EA}{L}\cos^2\theta \tag{2}$$

$$K_\sigma = 4\frac{\sigma A}{L} \tag{3}$$

where E is the elastic modulus of cables, A is the cable's cross-sectional area, L is the length of each cable element, σ is the initial stress of cables (i.e. σA = pre-tension force F) and θ is the angle between the external load and the cable axes.

In order to show the influence of structural geometry on the composition of structural stiffness, E, A, L, σ and external load P were set to constant and E = 160 GPa, A = 100 mm^2, L = 1 m, σ = 1 GPa (i.e. F = 100 kN) and P = 5 kN, while θ was set to varied from 90° to 0°. According to Eqs. (2) and (3), The relative sizes and values of K_E and K_σ with varying θ are compared in Figure 5.

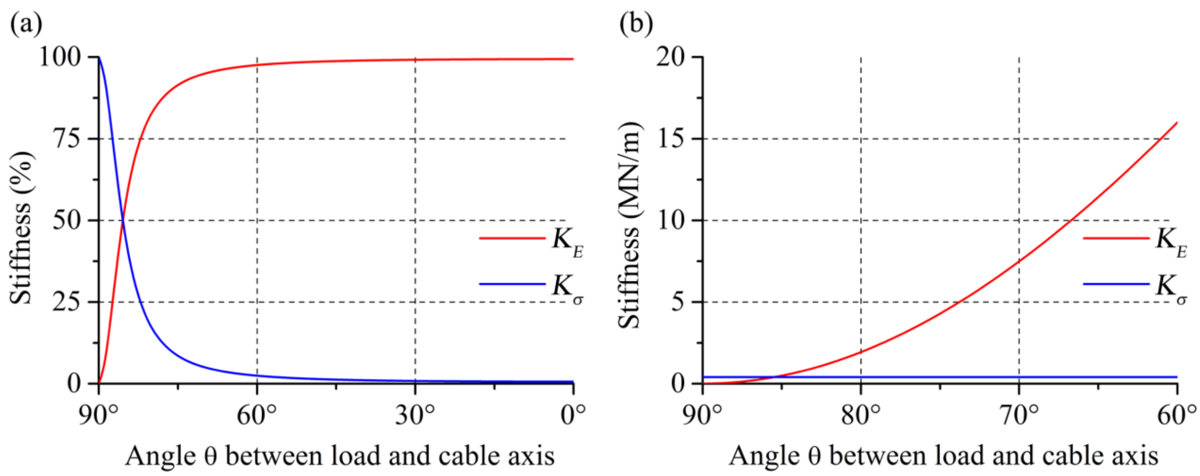


Figure 5. Comparison of K_E and K_σ with the variation of θ (a) relative size (b) value.

Figure 5(a) shows the variation of relative sizes of K_E and K_σ when θ varies from 90° to 0°, which are expressed as the percentage (%) of total structural stiffness K. As shown in this figure, the proportion of stress stiffness K_σ in the total stiffness K declines rapidly from 100% with the decrease of θ, while the proportion of elastic stiffness K_E rises rapidly from 0% as θ decreases. If θ is smaller than 60°, K will be almost entirely composed of K_E, while K_σ can be ignored. Figure 5(b) shows the variation of values of K_E and K_σ with θ varying from 90° to 60°. In this figure, K_E and K_σ are stiffness values, which are defined as the force divided by the displacement. As shown in this figure,

K_E increases from 0 quickly with the decrease of θ, while K_σ remains constant. Their sizes are equal when θ is approximately 85°.

As seen from Figure 5, when the angle θ is near 90° (i.e., the cable structure is orthogonally loaded by external loads), K_σ is greater than K_E; as θ decreases from 85°, K_E becomes much greater than K_σ, primarily because E is orders of magnitude greater than the initial stress σ. If either a smaller elastic modulus or a higher initial stress (i.e. a higher pre-tension force) were set for the cables, the lines of K_E and K_σ in Figure 5 would intersect at a smaller θ.

The above analysis indicates that the structural stiffness of orthogonally loaded cable structures is mainly composed of the stress stiffness, which is induced by the initial stress (i.e. pre-tension force) in the cables, while the structural stiffness of cable structures that are not orthogonally loaded is primarily composed of the elastic stiffness, which is induced by the elastic modulus of the cables.

2.2. Classification of Cable Structures

As seen from the previous section, if the angle θ is 90° or near 90° (i.e., the cable structure is orthogonally loaded), increasing the pre-tension force is more efficient to increase the stiffness of cable structures than increasing the elastic modulus of cables; if the angle θ is far from 90° (i.e., the cable structure is not orthogonally loaded), increasing the elastic modulus is more helpful than increasing the pre-tension force to raise the structural stiffness. Furthermore, in order to increase the pre-tension force, cables with relatively high tensile strength are needed. This indicates that in orthogonally loaded cable structures, using high tensile strength cables to increase the pre-tension force level is more helpful to reduce the deformation of structures than using high elastic modulus cables.

Consequently, it can be seen that the angle θ between the external load and the cable axis is an important parameter for cable structures and different angles make the structures have different mechanical properties.

Therefore, according to the angle θ that varies from 90° to 0°, cable structures can be classified into two categories, i.e. orthogonally loaded cable structures and other cable structures, as shown in Figure 6. The orthogonally loaded cable structure is defined as a cable structure with a majority of cables orthogonally loaded or approximately orthogonally loaded by external loads, i.e. their angle θ is 90° or near 90° [21].

Classification like in Figure 6 is significant for the design of cable structures. Orthogonally loaded cable structures (in the left one-third of Figure 6), such as cable net facade and spoked wheel cable roof, have this common aspect: the tensile strength of cables used in these structures determines not only the ultimate load bearing capacity but also the structural stiffness of cable structures. This means that if the cross-sectional area of cables is kept constant, increasing the tensile strength of cables will lead to increasing both the ultimate load bearing capacity and the structural stiffness of cable structures [5].

Consequently, in the design of orthogonally loaded cable structures, choosing cables with a higher tensile strength and the same or even lower elastic modulus like replacing steel cables with CFRP cables (see Table 2) can help reducing the cross-sectional area A of cables and hence saving the amount of cable used without decreasing either the ultimate load bearing capacity or the structural stiffness.

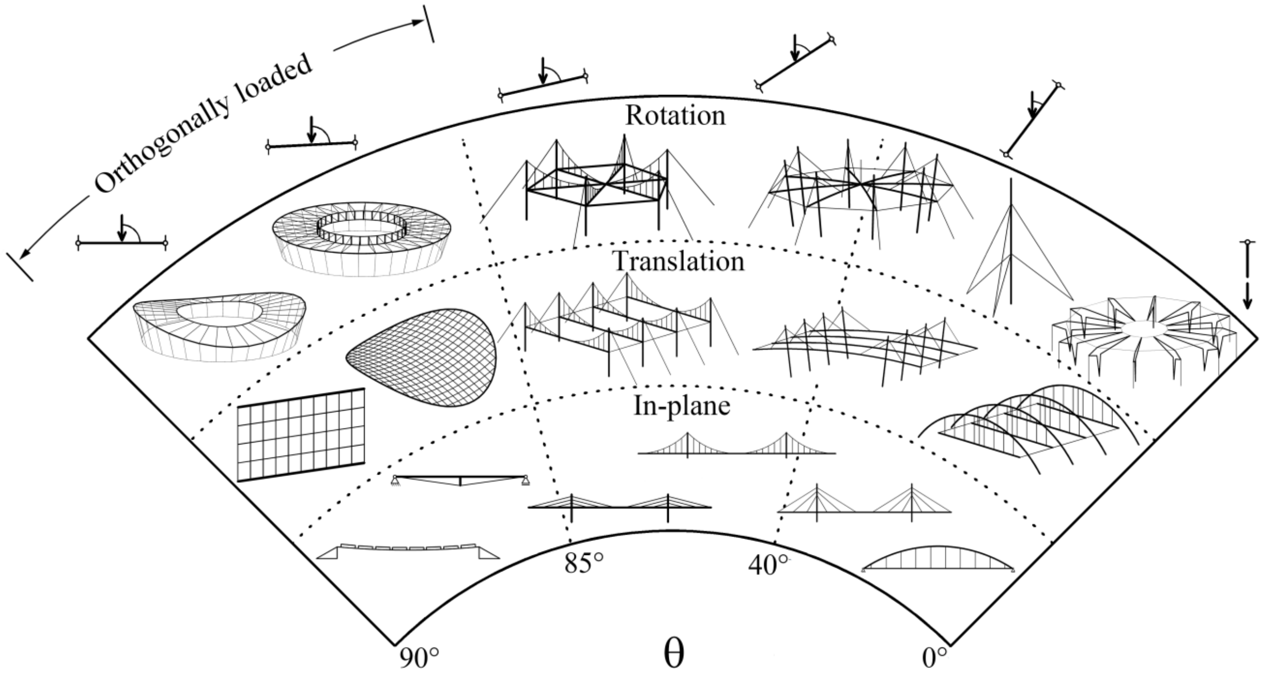


Figure 6. Classification of cable structures according to angle θ.

3. Case Study: Using CFRP Cables in Cable Net Facade and Spoked Wheel Cable Roof

Based on the aforementioned analysis, it can be found that applying CFRP cables in orthogonally loaded cable structures is a feasible way to use the advantages of CFRP cables while bypassing their disadvantages. Substituting CFRP cables for steel cables in such structures can fully exploit the relatively high tensile strength of CFRP cables and effectively avoid the unfavorable influence of their relatively low elastic modulus, thus finally improving the structural mechanical property and economic efficiency. To prove this assertion, two typical orthogonally loaded cable structures with CFRP cables, i.e. a CFRP cable net facade and a CFRP spoked wheel cable roof, were investigated in case study. Their mechanical properties and economies were compared with that of the corresponding steel cable structures. Furthermore, in order to investigate the influence of angle θ, these two CFRP orthogonally loaded cable structures were compared with each other.

3.1. Description of Investigated Structures

In this case study, a simple cable net facade and a simple spoked wheel cable roof were selected for investigation. They were analyzed in the general FEM software SOFiSTiK [29]. The cable element of SOFiSTiK (which is a straight truss but cannot take any compression force) was adopted, with a mesh size of 1.5 m. The geometric nonlinearity was considered in the calculation, which means that the situations of geometry and force would be updated in every step. Furthermore, only the cable systems were modeled, while other secondary structural members were simplified as dead load. Their geometries are shown in Figure 7 and Figure 8, respectively.

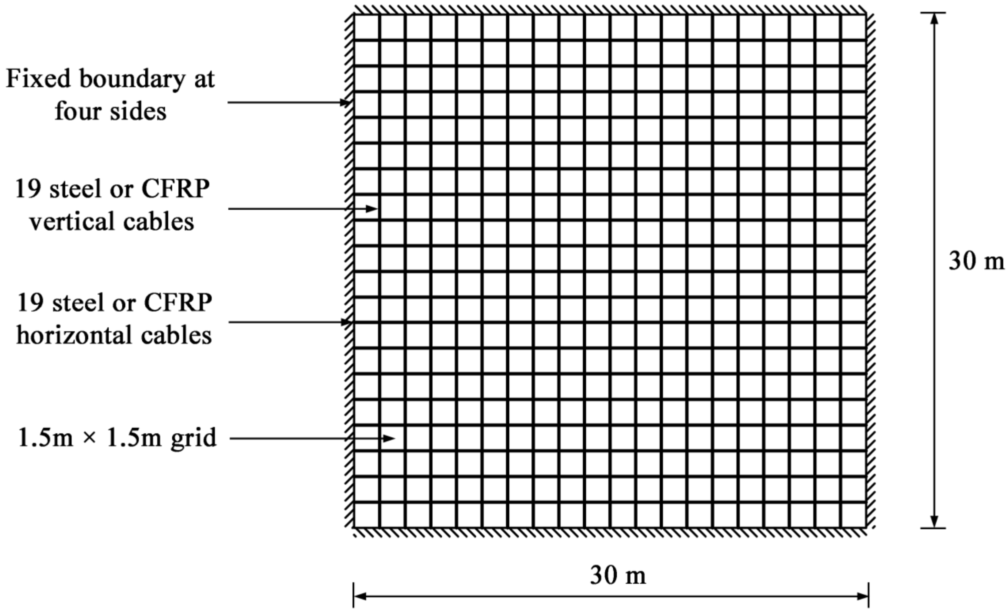


Figure 7. Geometry and boundary conditions of steel or CFRP cable net façade.

For this cable net facade, it was assumed to be located in Berlin, Germany. Based on the location, the wind load = 1.0 kN/m^2, which was set to act at the nodes and perpendicularly to the cable net plane. The dead load of the glass panels and connection members, which was set to 0.5 kN/m^2, was also assumed to act at the nodes but in the direction of gravity (i.e., along the vertical cables); the dead loads of cables were automatically calculated by the software [30,31].

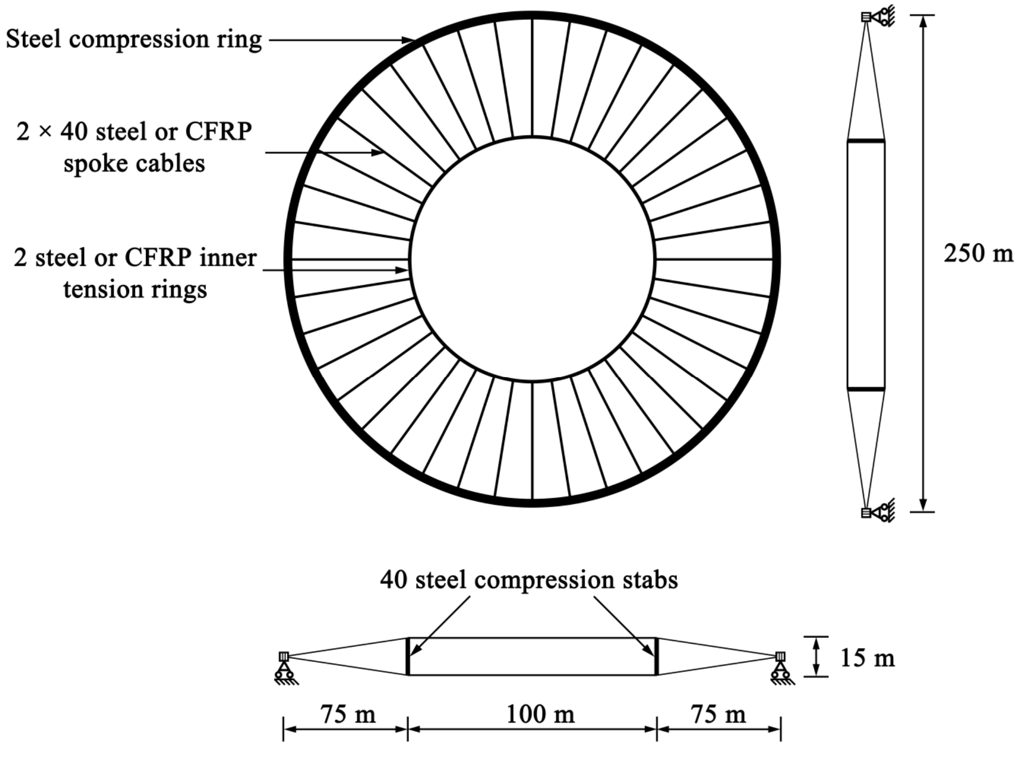


Figure 8. Geometry and boundary conditions of steel or CFRP spoked wheel cable roof.

The investigated spoked wheel cable roof consists of one compression ring and two tension rings, assumed to be located in Berlin, Germany. Based on the assumed location, the snow load = 0.68 kN/m^2, which was applied to the upper end nodes of compression stabs and in the direction of gravity; the wind load was set to 0.6 kN/m^2 and assumed to act at the same nodes as the snow load but in the reverse direction. The dead load for the membrane and its supports was set to 0.1 kN/m^2; for the catwalk and equipment along the upper inner ring was set to 3 kN/m; for every cable node was set to 10 kN; for the cables and compression stabs were automatically calculated by the software. All the above dead loads were assumed to act at the upper end nodes of compression stabs [30,31].

The cable structures were designed with the Limit States Design method provided by the Eurocode using an Ultimate Limit State (ULS) factor of 1.5 for both the wind and snow loads, as well as 1.35 for the dead loads if they were combined with the snow load [32]. A partial safety factor of 1.65 was set for the resistance of steel cables [16,33]. For comparison purposes, the partial safety factor for the CFRP cables was also set to 1.65. Furthermore, according to the design code [33] and design experience, the deflection limit in SLS for the cable net facade under the wind load was set to 600 mm, while for the spoked wheel cable roof under the wind or snow load was set to 2000 mm.

The steel cable used for these two cable structures is the full locked cable, while the CFRP cable used is a typical CFRP cable available on the market, whose properties are listed in Table 3 [16,21].

Table 3. Properties of steel cable and CFRP cable used in case study.

Cable type	Density ρ (kg/m^3)	Tensile strength σ_u (GPa)	Elastic modulus E (GPa)	Unit price (USD/kg)
Steel cable	7850	1.5	160	10
CFRP cable	1500	2	120	55

3.2. Principles of comparison and design

In this case study, the following three aspects were compared:

- Structural stiffness, expressed by the mid-span deflection in SLS.
- Amount of cable used, expressed by the cable volume.
- Economy, mainly based on the cable cost.

During the comparison, six rules were followed:

- The initial geometry, namely the geometry under the pre-tension forces and the dead loads, and the boundary condition of the steel and CFRP cable structures were kept the same.
- The external load conditions of the steel and CFRP cable structures were identical and their ultimate bearing capacities were kept the same.
- Every cable reached its ultimate tensile strength in ULS.
- If the structural stiffness was compared, the amounts of cable used in the CFRP cable structure were kept the same as that of the steel cable structure.
- If the amount of cable used was compared, the deflections of the CFRP or steel cable structure in SLS were kept the same and equal to the deflection limit.
- When the economy was compared, the cable cost was set to the primary factor. Other minor factors, such as support reaction (for the spoked wheel cable roof, force in compression ring

was taken) and cable weight, were also considered.

According to the above rules and the design code, all cable structures were designed with the same procedure, as shown in Figure 9.

As seen from Figure 9, the cross-sectional areas and pre-tension forces of cables were determined through repeated iterations to ensure the cable structures simultaneously reached their deflection limits in SLS and ultimate strength limits in ULS (i.e., were optimally designed). It should be noted that, for comparison reasons, the deflections of the CFRP cable structures could be less than or equal to the deformation limit in SLS, if the structural stiffness was compared.

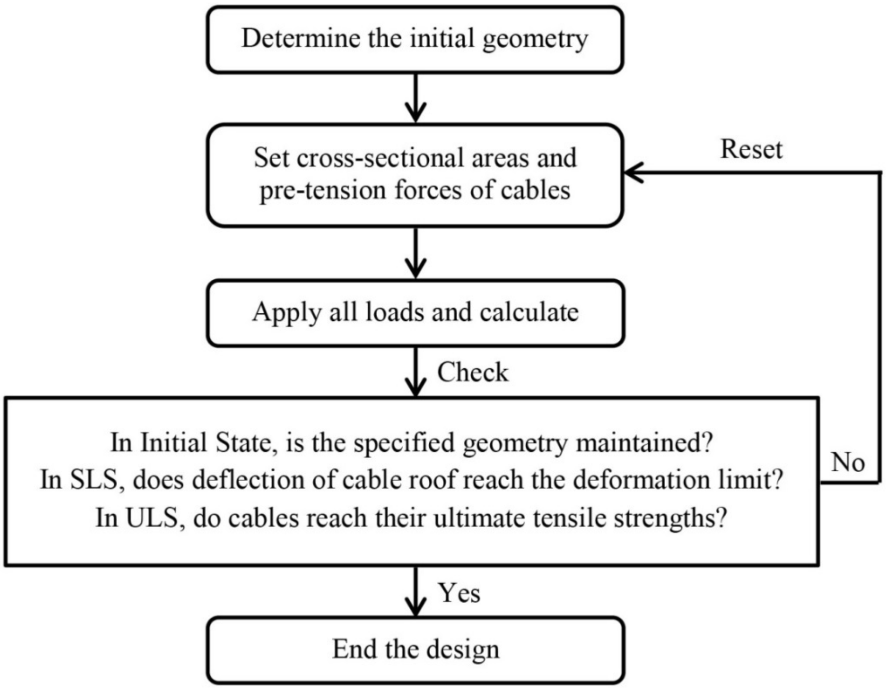


Figure 9. Design procedure of steel or CFRP cable structures.

3.3. Comparison Results

Comparison results are listed as follows. First, the values of CFRP cable structures are compared with that of the steel counterparts. Then, these comparison results from CFRP cable net facade and CFRP spoked wheel cable roof are compared with each other, so as to see the influence of angle θ on the advantages of CFRP orthogonally loaded cable structures over corresponding steel cable structures. For the cable net facade, the angle θ = 90°; while for the spoked wheel cable roof, the angle θ was calculated as 86.56°, according to the cable volume weighted average. In the following histograms, red bars represent the steel cable structures, while black bars represent the CFRP ones; moreover, on the top of the bars, the corresponding values and the percentages relative to the values of steel cable structures are listed.

3.3.1. Comparison result of structural stiffness

For the comparison of structural stiffness, the result is presented in Figure 10. A greater deflection value represents a smaller structural stiffness and vice versa. It should be noted that the deflections in Figure 10(b) are the deflections of spoked wheel cable roofs due to the snow load; the deflections due to the wind load show a similar tendency.

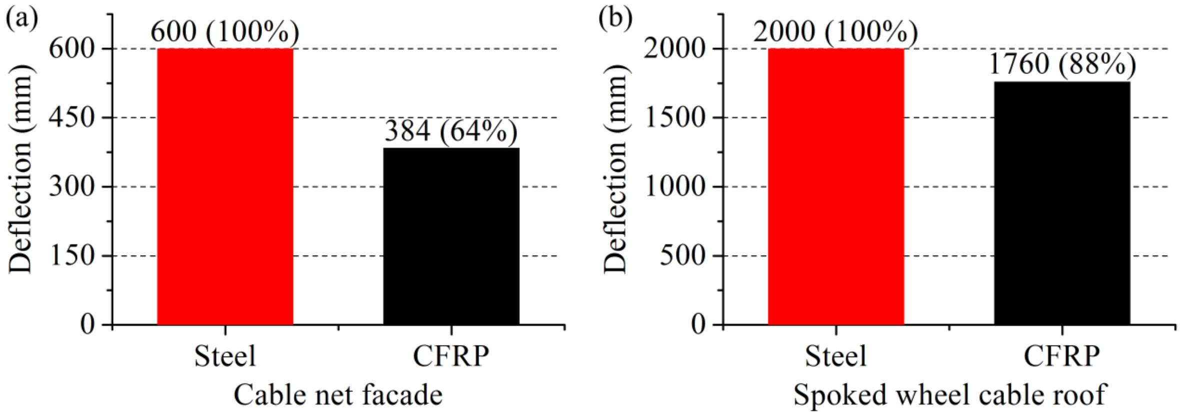


Figure 10. Comparisons of mid-span deflections (a) cable net facade (b) spoked wheel cable roof.

As seen from Figure 10, using CFRP cables in orthogonally loaded cable structures can considerably reduce the deflection and raise the structural stiffness compared to using steel cables. Furthermore, the deflection of CFRP cable net facade is 64% that of the steel counterpart, while the deflection of CFRP spoked wheel cable roof is 88% that of the steel counterpart, which indicates that, for the aspect of structural stiffness, using CFRP cables in the orthogonally loaded cable structures with a greater angle θ like the cable net facade can achieve greater advantage than using them in such cable structures with a smaller θ like the spoked wheel cable roof.

The increase of structural stiffness is a product of the increase of pre-tension force. The comparison results of the pre-tension forces in this case are shown in Figure 11. For the spoked wheel cable roof, it is the pre-tension force of lower spoke cables; other cables showed similar results.

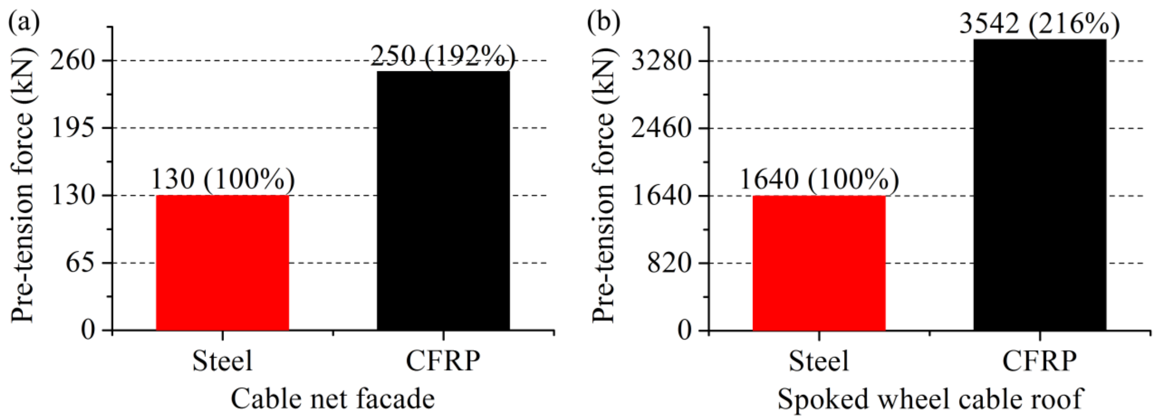


Figure 11. Comparisons of pre-tension forces when the structural stiffness is compared (a) cable net facade (b) spoked wheel cable roof.

As shown in Figure 11, the pre-tension force levels of CFRP orthogonally loaded cable structures are much higher than that of their steel counterparts. Furthermore, the increasing degree of pre-tension force in CFRP spoked wheel cable roof is greater than that in CFRP cable net facade.

3.3.2. Comparison result of amount of cable used

The comparison result of amount of cable used is shown in Figure 12.

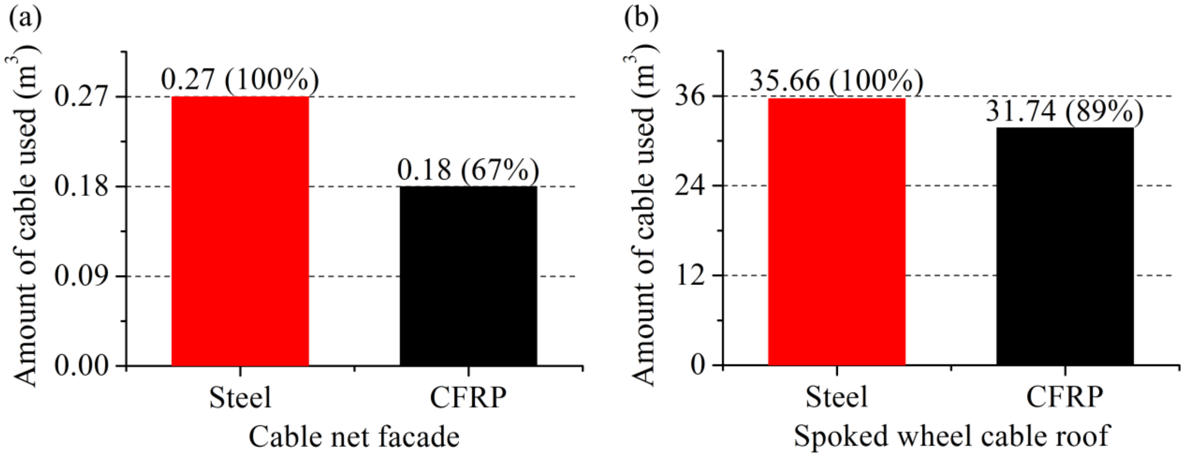


Figure 12. Comparisons of amounts of cable used (a) cable net facade (b) spoked wheel cable roof.

As seen from Figure 12, using CFRP cables in orthogonally loaded cable structures can significantly decrease the amount of cable used and thus saving the cable materials. Specifically, for the CFRP cable net facade, the reduction degree of amount of cable used is 33%; while for the CFRP spoked wheel cable roof, the reduction degree is 11%. This indicates that using CFRP cables in the cable net facade, whose angle θ is just 90°, can save more cable materials and hence achieving greater advantage than using CFRP cables in the spoked wheel cable roof, whose θ is slightly smaller than 90°.

The comparison result of pre-tension forces in this case is shown in Figure 13. It should be noted that the pre-tension forces in Figure 13 are not the same as that in Figure 11, because different design conditions were used in the comparisons of structural stiffness and the amount of cable used. Moreover, for the spoked wheel cable roof, the values of lower spoke cables are adopted in this figure; other cables had similar results.

As shown in Figure 13, the pre-tension force of CFRP cable net facade is slightly higher than that of the steel cable net facade, while the pre-tension force of CFRP spoked wheel cable roof is significantly higher than that of its steel counterpart.

The above comparisons of structural stiffness and amount of cable used confirm that the stiffness of orthogonally loaded cable structures is primarily governed by the stress stiffness K_σ (i.e., the cable's tensile strength σ_u). Using CFRP cables in such structures, whose σ_u is significantly higher than that of the steel cable, is able to increase the pre-tension force level, which can either improve the structural stiffness if the amount of cable used is maintained or reduce the amount of cable used if the structural stiffness is maintained instead.

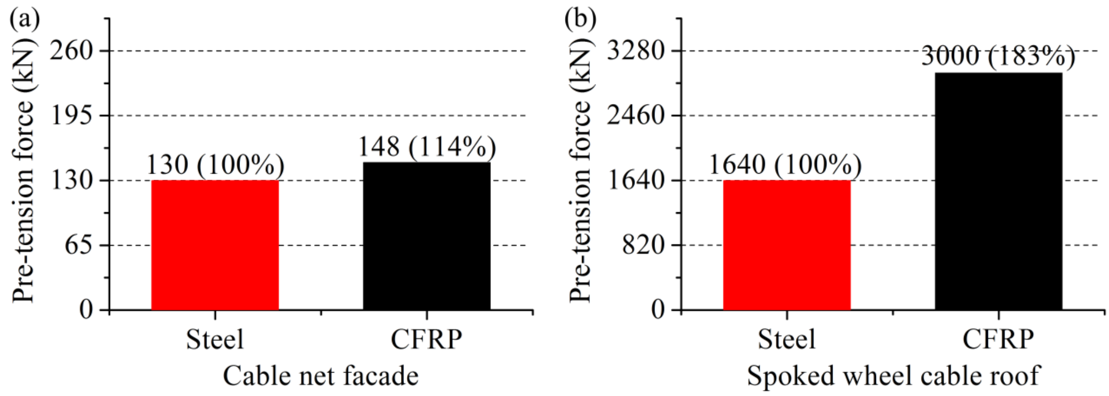


Figure 13. Comparisons of pre-tension forces when the amount of cable used is compared (a) cable net facade (b) spoked wheel cable roof.

3.3.3. Comparison result of economy

For the comparison of economy, the design condition was the same as that for the comparison of amount of cable used. First, the comparison result of one minor factor, i.e. the support reaction (for the spoked wheel cable roof, it is the force in compression ring), is illustrated (Figure 14).

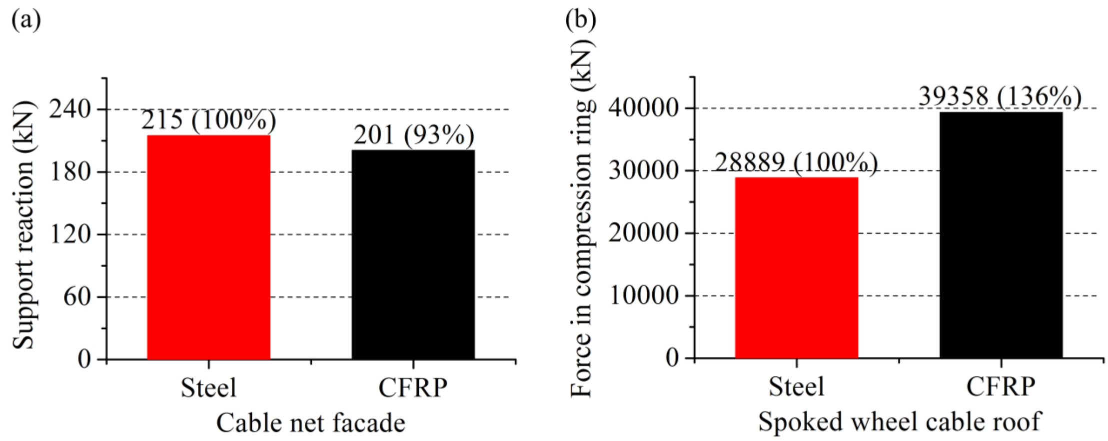


Figure 14. Comparisons of (a) support reaction of cable net facade (b) forces in compression ring of spoked wheel cable roof.

Compared to the applied pre-tension forces (Figure 13), the final support reactions or forces in compression ring in ULS are more important because they determine the design of the supports or compression rings and thus influencing the structural cost. As shown in Figure 14(a), the support reaction of CFRP cable net facade is smaller than that of its steel counterpart, which indicates that using CFRP cables in cable net facade will lead to cheaper supports than using steel cables. Furthermore, as shown in Figure 14(b), the force in compression ring of CFRP spoked wheel cable roof is 36% greater than that of steel spoked wheel cable roof.

Then, the comparison result of another minor factor, i.e. the cable weight, is illustrated (Figure 15). It was calculated by multiplying the amount of cable used (Figure 12) with the corresponding cable density (see Table 3).

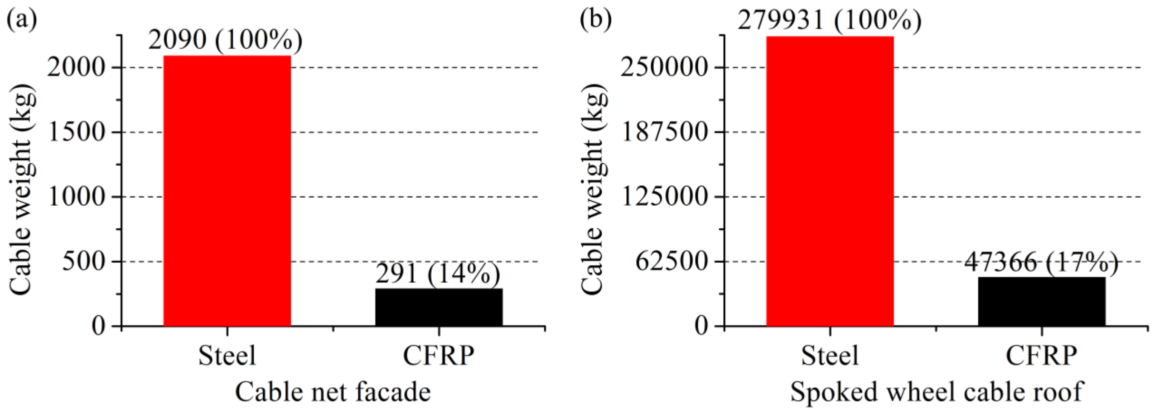


Figure 15. Comparisons of cable weights (a) cable net facade (b) spoked wheel cable roof.

As seen from Figure 15, the cable weights of CFRP orthogonally loaded cable structures are considerably smaller than that of their steel counterparts, which can lead to lower cost of installation. This is not only because using CFRP cables can reduce the amount of cable used in such structures but also because the density of CFRP cable is much smaller than that of steel cable. Furthermore, the cable weight reduction degree of CFRP cable net facade is 3% greater than that of CFRP spoked wheel cable roof, which indicates that using CFRP cables in cable net facade can more significantly reduce the weight of cable system.

Multiplying the cable weights (Figure 15) with the corresponding unit prices of cables (see Table 3), the cable costs of investigated cable structures, which can most significantly influence the economy, were obtained and compared with each other. The result is shown in Figure 16.

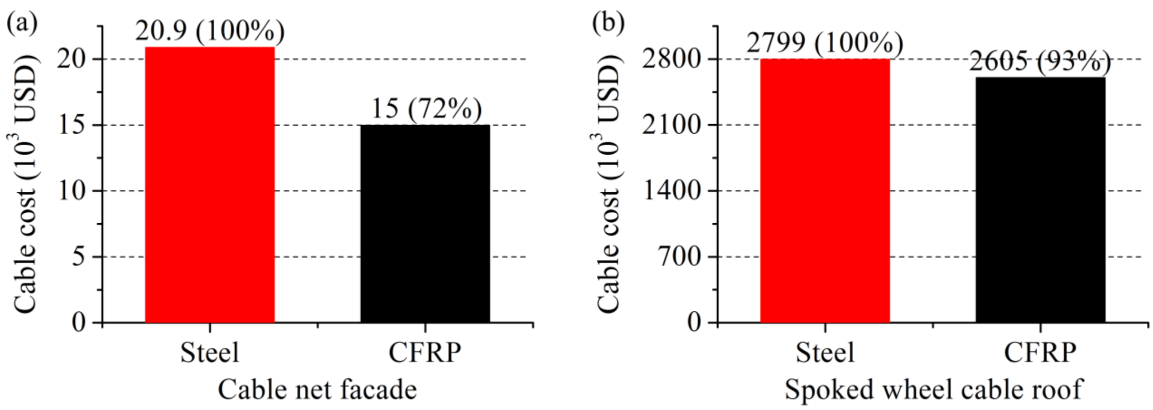


Figure 16. Comparisons of cable costs (a) cable net facade (b) spoked wheel cable roof.

As seen from Figure 16, both the CFRP cable net facade and the CFRP spoked wheel cable roof have lower cable cost than their steel counterparts, though the unit price of CFRP cables is considerably higher than that of steel cables. This is mainly because using CFRP cables in orthogonally loaded cable structures can reduce the amount of cable used and thus achieving significantly lower cable weight than the corresponding steel cable structures. Moreover, the cable cost reduction degree of the CFRP cable net facade is 21% higher than that of the CFRP spoked wheel cable roof, which indicates that using CFRP cables in cable net facade can save more cable cost than using them in spoked wheel cable roof.

In summary, according to the above analysis, it can be found that using CFRP cables in the cable net facade, which makes the cable cost, the cable weight and the support reaction become lower, can obviously achieve economic efficiency compared to using steel cables; using CFRP cables in the spoked wheel cable roof can also improve the economic efficiency compared with using steel cables, primarily because this can reduce the cable cost and the cable weight. Furthermore, the improvement degree of economic efficiency of CFRP cable net facade is greater than that of CFRP spoked wheel cable roof.

4. Conclusion

In this paper, a new application field of CFRP is proposed and studied, that is, using CFRP cables in orthogonally loaded cable structures. For this type of cable structures, whose angle θ is just or close to 90°, the structural stiffness primarily comprises of the stress stiffness, which is controlled by the tensile strength of cables. This signifies that using CFRP cables, whose tensile strength is higher than that of steel cables, in orthogonally loaded cable structures can improve the structural mechanical and economical performances.

To demonstrate this point, two typical orthogonally loaded cable structures, i.e. a cable net facade and a spoked wheel cable roof, were selected and studied. The mechanical properties and economies of these two structures with CFRP cables were compared to that of counterpart steel cable structures. The influence of the angle θ on the advantages of CFRP orthogonally loaded cable structures was also investigated through comparing these two CFRP cable structures with each other. Key conclusions drawn from this research are:

- Compared to steel cables, using CFRP cables in orthogonally loaded cable structures can significantly raise the structural stiffness if the amount of cable used is maintained; using CFRP cables can also considerably reduce the amount of cable used if the structural stiffness is maintained instead.
- Compared to the spoked wheel cable roof, using CFRP cables in the cable net facade can either increase more structural stiffness or save more cable material, because the angle θ of cable net facade is closer to 90° than that of spoked wheel cable roof.
- Although the unit price of CFRP cables is much higher than that of steel cables, CFRP orthogonally loaded cable structures can still achieve lower cable costs than the steel cable structures used for comparison and thus leading to better economy, primarily because the material savings successfully offset the adverse effect of the high unit price of CFRP cables.
- Moreover, the improvement degree of economic efficiency of the CFRP cable net facade is greater than that of the CFRP spoked wheel cable roof, which shows that applying CFRP cables for the orthogonally loaded cable structure with a greater θ is more advantageous than applying them for the cable structure with a smaller θ.

Conflict of Interest

The authors declare no conflict of interest.

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