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Design strategy of hybrid stay cable system using CFRP and steel materials

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Abstract. To enhance cable stiffness, this paper proposed a combined application of carbon fiber reinforced polymers (CFRP) and steel materials, resulting in a novel type of hybrid stay cable system especially for the cable-stayed bridges with main span lengths of 1400~2800 m. In this combination, CFRP materials can conserve all their advantages such as light weight and high strength; while steel materials help increase the equivalent stiffness to compensate for the low elastic modulus of CFRP materials. An increase of the equivalent stiffness of the hybrid stay cable system could be further obtained with a reasonable increase of its safety factor. Following this concept, a series of parametric studies for the hybrid stay cable system with the consideration of stiffness and cost were carried out. Three design strategies/criteria, namely, best equivalent stiffness with a given safety factor, highest ratio of equivalent stiffness to material cost with a given safety factor, and best equivalent stiffness under a given cost were proposed from the stiffness and cost viewpoints. Finally, a comprehensive design procedure following the proposed design strategies was suggested. It was shown that the proposed hybrid stay cable system could be a good alternative to the pure CFRP or traditional steel stay cables in the future applications of super long span bridges.

Keywords: hybrid stay cable system; CFRP; steel; stiffness; cost; design strategy; cable-stayed bridge; parametric study.

1. Introduction

With the increasing interest in designing cable-stayed bridges recently, bridge span lengths become longer and longer. As a result, the normally-used steel stay cables begin to negatively affect the overall structural stiffness and thus limit the further extension of bridge span lengths due to the cable sag effects, low load-carrying efficiency, as well as low equivalent stiffness (which is the axial stiffness of stay cables considering their cable sag effects, defined as $E_{eq}A$, namely equivalent elasticity modulus times cable section area, hereafter) (Ernst 1964, Gimsing 1997, Ahmadi-Kashani and Bell 1998, Nagai *et al.* 2004). In recent years, therefore, there has been increasing research interest on the application of carbon fiber reinforced polymers (CFRP) for stay cables in bridges (Meier 1987, Saadatmanesh and Ehsani 1998, Schurter and Meier 1996, Mei *et al.* 2005, Xiong *et al.* 2012). As a new material for stay

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cables, CFRP's light weight and superior strength can be utilized to improve the load-carrying efficiency of stay cables and extend the span lengths of cable-stayed bridges dramatically.

One of the important drawbacks with CFRP materials is their low elastic modulus, which can cause a significant reduction in the equivalent stiffness of stay cables and reduce the overall stiffness of cable-stayed bridges (Meier 1987, Noisternig 2000, Maeda *et al.* 2001, Zhang and Cai 2007, Xiong *et al.* 2011). Therefore, it is only beneficial when the stiffness increase due to the reduction of self-weight/cable sag effects overweighs the stiffness decrease due to the inherent low stiffness of the CFRP material. For this reason, it has been generally believed that the superior behavior of CFRP materials only can be fully utilized when applied to stay cables with super-long span lengths. Besides, the high material and manufacture costs of CFRP still remain an issue for their wide applications in bridges (Einde *et al.* 2003).

Recently, the design strategy for cable-stayed bridges with main span lengths of 1400~2800 m is becoming a very popular topic and has been widely studied by many researchers and engineers (Meier 1987, Gimsing 1994, 1997, Maeda 2001, Nagai 2004, Miao 2006). However, steel stay cables may not be suitable for such span lengths due to their low equivalent cable stiffness caused by their high-density-induced cable sag effect; meanwhile, this span length range does not warrant using full CFRP stay cables because of their low elastic modulus and high cost. To address this problem, this paper proposes a novel type of hybrid stay cable system using both CFRP and steel materials. If needed, both CFRP stay cables and steel stay cables are simultaneously installed at each location of stay cables in a cable-stayed bridge. This is to create a new structure that utilizes the advantages of each of the two constituents in order to increase the equivalent stiffness of stay cables and reduce the cost. More specifically, CFRP stay cables can conserve all the advantages of CFRP materials such as their light weight and high strength; while steel stay cables can help increase the overall equivalent stiffness to compensate for the low elastic modulus of CFRP materials. Moreover, an increase of the equivalent stiffness for the hybrid stay cable system could be further obtained with a reasonable increase of their safety factor (such as an increase of section area), which was usually set as 2.5.

In this paper, the appropriate span lengths for using pure steel or pure CFRP stay cables were firstly studied through parametric studies. The application range for hybrid stay cable system using CFRP and steel materials was then theoretically obtained. A series of parametric studies for the hybrid stay cable system with the consideration of stiffness and cost were also carried out. Three design strategies/criteria, namely, best equivalent stiffness with a given safety factor, highest ratio of equivalent stiffness to material cost with a given safety factor, and best equivalent stiffness under a given cost were proposed and discussed in details. Finally, a comprehensive design procedure following the proposed design strategies was suggested. It was shown that the proposed hybrid stay cable system could be a good alternative to the pure CFRP or pure steel stay cables in the future super long bridges.

2. Application range of hybrid stay cable system using CFRP and steel materials

In the present study, the hybrid stay cable system will be used for the transition region between the appropriate cable span lengths for pure steel and pure CFRP stay cables that will be determined next.

2.1 Criterion for determining appropriate cable span lengths

Generally speaking, all the design parameters with respect to the mechanical behaviors of stay cables

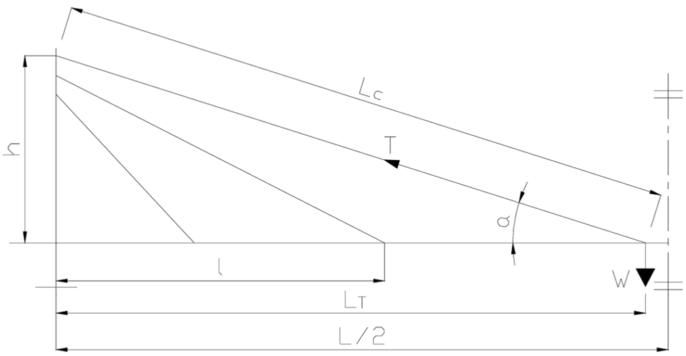


Fig. 1 Calculation model of stay cables

can be categorized into two aspects: strength and stiffness. Before studying the appropriate cable span length for each material, the controlling parameter (strength or stiffness) for the determination of appropriate cable span lengths should be firstly discussed.

To roughly examine the strength requirement, the longest stay cable (with a chord length of L_c or horizontal projected length of L_T) in a cable-stayed bridge stretched in a vertical plane as shown in Fig. 1 is considered; its cable force under self-weight and external loads can be approximately calculated using the following equation (Miao 2006)

$$T = W \cdot e\sqrt{1+\frac{1}{e^2}} \cdot \eta = \left(W_D + W_L + \frac{1}{2}W_C\right) \cdot e \cdot \nu \cdot \eta \tag{1}$$

where in Eq. (1) and Fig. 1 T = cable force of the longest stay cable; $W = W_D + W_L + W_C/2$; W_D and W_L = total dead and live loads applied on the girder between two stay cables, respectively; W_C = total self-weight of stay cables; L = main span length of cable-stayed bridges; h = pylon height above girders; L_T = horizontal projected length of the longest stay cable in cable-stayed bridges; $e = L_T/h = (L/2)/h$ (assuming $L_T = L/2$), usually equal to 2.0~2.5; η = correction coefficient, usually set as 1.1~1.15; and $\nu = \sqrt{1+1/e^2}$.

Also, we can obtain

$$W_C = A_C L_C \gamma_C \tag{2}$$

$$T = A_C \sigma_C \tag{3}$$

where A_C = cross section area of stay cables; L_C = chord length of the longest stay cable in cable-stayed bridges; γ_C = density of stay cables; and σ_C = allowable stress of stay cables.

Substituting Eqs. (2) and (3) into Eq. (1) leads to

$$A_C \sigma_C = \left(W_D + W_L + \frac{1}{2}A_C L_C \gamma_C\right) e \cdot \nu \cdot \eta \tag{4}$$

Eq. (4) can be further transformed into

$$L_T = \frac{L_C}{\nu} = \frac{\dfrac{A_C\sigma_C}{e\cdot\nu\cdot\eta} - W_D - W_L}{\dfrac{1}{2}A_C\gamma_C\nu} \tag{5}$$

For the steel case, assuming the basic design parameters as $\sigma_C = 1670/2.5 = 668$ MPa, $\gamma_C = 83.5$ kN/m^3, $W_D = 260$ kN/m, and $W_L = 85$ kN/m (AASHTO 2004), Eq. (5) can be plotted as L_T versus e in Fig. 2.

Fig. 2 shows the upper limitation of the design for the span lengths of stay cables (L_T) with various e and λ. This result further indicates that, based on the current design conditions (see the shaded area in Fig. 2) and strength of steel materials, from the strength viewpoint the span lengths of stay cables can safely reach 5000 m (roughly 10000 m for the main span length of cable-stayed bridges). In other words, the current allowable stress of steel materials is good for bridge span lengths in the 10000 m range, and CFRP materials with even much higher strength can extend the span length further. Therefore, if following common design methodology, the strength requirement of designing stay cables using pure steel or pure CFRP materials could be easily satisfied currently or in future.

However, besides the strength requirement, the stiffness requirement should be also satisfied in the design process. Due to the heavy self-weight of steel materials with large cable sag effects and lower elastic modulus of CFRP materials, the equivalent stiffness of super long stay cables can be apparently reduced, which results in lower overall stiffness of cable-stayed bridges. Low cable (bridge) stiffness not only decreases the load-carrying efficiency of stay cables and causes troubles in cable construction but it also produces the large deformation which can influence the driving comfort quality and bridge deck durability. Therefore, more attention to designing the stiffness of stay cables and cable-stayed bridges should be paid. In this paper, the equivalent stiffness of stay cables was regarded as a judging criterion in the following studies to determine the appropriate cable span lengths for each material. It should be noted that only the cable stiffness was considered because it can mostly determine the overall stiffness of cable-stayed bridges.

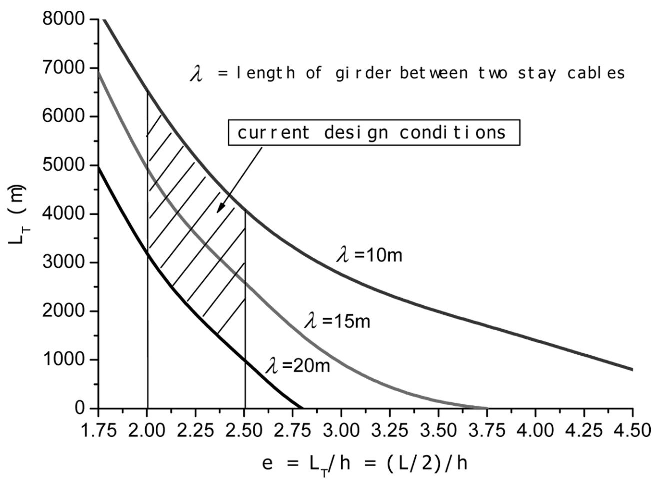


Fig. 2 Calculation results of L_T versus e

2.2 Appropriate span lengths of pure steel stay cables

As discussed earlier, the equivalent stiffness of stay cables is determined as the judging criterion in determining the appropriate span lengths. To better understand the effects of equivalent stiffness on the appropriate span lengths of pure steel stay cables, four mechanical parameters (equivalent stiffness and other three related parameters, see Table 1) were theoretically investigated through a parametric study by varying the “cable span lengths” (horizontally projected length of stay cables) from 50 to 5000 m using analytical models (see Table 2). These four mechanical parameters enable to comprehensively describe the equivalent stiffness of stay cables directly or indirectly, and all of them are the key study objectives for the span length study in the literature (Ernst 1964, O’Brien and Francis 1964, Irvine 1981, Ahmadi-Kashani and Bell 1988, Gimsing 1997, Freire *et al.* 2006). Based on the results of this parametric study the appropriate span lengths of pure steel stay cables can be recommended.

It should be noted that the geometrical configurations and physical properties of the analytical cable models were taken directly or referred partially from the preliminary designs of two steel cable-stayed bridges with 1400 m main span length each (Nagai *et al.* 2004, Miao 2006). Also, the cable force used in the analytical models was set as 5102 kN, which was a typical cable force in the two preliminary designs. In order to compare the results from the parametric study, the cable forces in all the cases were kept the same.

Table 1 Mechanical parameters and analytical solutions (Ernst 1964, Gimsing 1997)

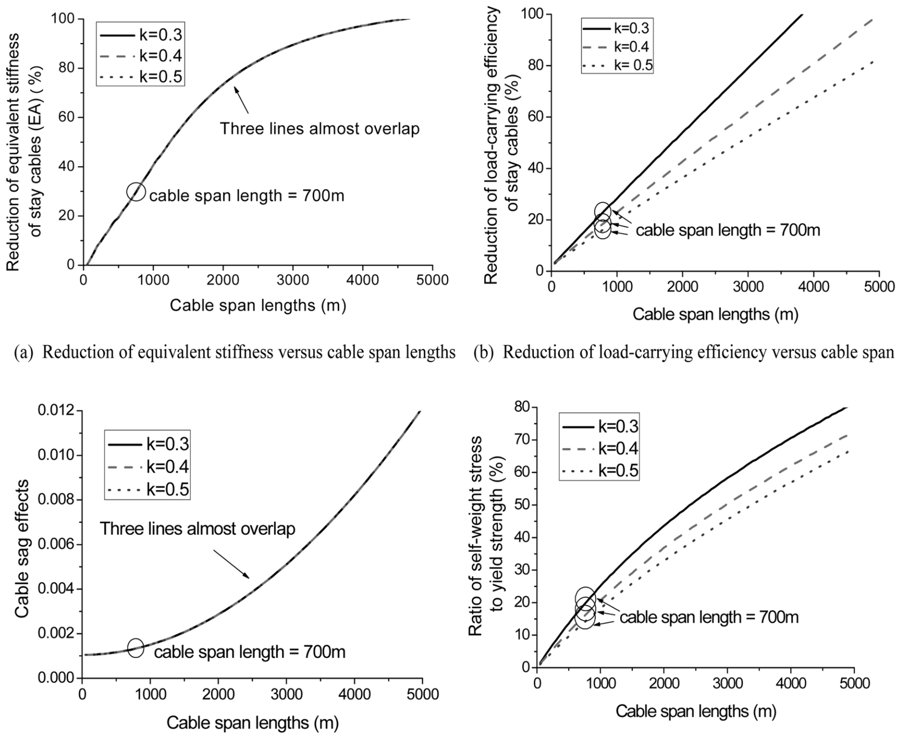
Mechanical parameters	Analytical solutions
1. Equivalent stiffness	$K_{eq} = E_{eq}A = 1/\left[\frac{1}{E} + \frac{\gamma_c^2 l^2}{24}\left(\frac{\sigma_1+\sigma_2}{\sigma_1^2\sigma_2^2}\right)\right]A \approx EA/\left[1 + \frac{\gamma_c^2 l^2}{12\sigma_1^3}E\right]$
2. Load-carrying efficiency (Real gradient of stay cables)	$V_T/H = k\left(-\frac{l}{l_{\max}} + 1\right)$
4. Cable sag effects	$\frac{\delta}{L_c} = \frac{(\sigma_2-\sigma_1)\gamma_c + \frac{1}{L_c}\left[\sigma_2^2 sh\left(\frac{\gamma_c l}{\sigma_2}\right) - \sigma_1^2 sh\left(\frac{\gamma_c l}{\sigma_1}\right)\right] - \frac{4E}{L_c}\left[\sigma_2 sh\left(\frac{q_0 l}{2\sigma_2 A}\right) - \sigma_1 sh\left(\frac{q_0 l}{2\sigma_1 A}\right)\right]}{2\gamma_c E \mathrm{ch}\left(\frac{q_0 l}{2\sigma_2 A}\right)}$
5. Self-weight stress	$\sigma_g = \frac{\gamma_c l\sqrt{1+k^2}\sqrt{1+k^2(1+l/l_{\max})^2}}{2k(1+l/l_{\max})}$

where K_{eq} = equivalent stiffness of stay cables; E_{eq} = equivalent elasticity modulus; E = elasticity modulus; A = area of the cross section of stay cables; $\gamma_c = q_0/A$ = density of stay cables; q_0 = distributed loads (uniform gravity loads) per unit length of stay cables; l = horizontally projected length of stay cables; σ_1 and σ_2 = stress of stay cable in two load conditions (usually dead load and dead + live load conditions), respectively; V_T = vertical component of the cable force in the actual curved cable; H = horizontal component of the cable force in the actual curved cable; h = vertically projected length of stay cables; $k = h/l$; $l_{\max}$ = ultimate horizontally projected length of stay cables; δ/L_c = cable sag effect; L_c = chord length of stay cables; and σ_g = self-weight stress of stay cables. The detailed derivations of these equations are not presented here and can be found in the literature (Ernst 1964, Gimsing 1997).

Table 2 Design parameters of analytical models (steel stay cables)

Design parameters	Values		
Nominal gradient of stay cables ($k = h/l$)	0.3	0.4	0.5
Cable span length (horizontal) (m)	50~5000	50~5000	50~5000
Vertical projected length of stay cables (m)	15~1500	20~2000	25~2500
Area (m^2)	0.00974		
Design stay cable force (N)	5.102E + 6		
Elasticity modulus (N/m^2)	2.00E + 11		
Density (kg/m^3)	7.85E + 03		
Yield Strength (MPa)	6.68E + 02		
Safety factor	2.50		

Figs. 3(a)~3(d) show the performance of pure steel stay cables with regard to the investigated mechanical parameters when varying the cable span lengths from 0 to 5000 m. The numbers of 0.3, 0.4, and 0.5 in the figures denote the nominal gradients of stay cables (k) for the investigated cable models. Firstly, similarity can be observed in Figs. 3(a)~3(d) that all the reductions or deteriorations of mechanical behaviors representing equivalent stiffness of stay cables become more and more obvious when the cable span length increases from 0 to 5000 m. Furthermore, from an overall observation 700 m could be a significant cable span length, after which all the investigated mechanical behaviors



(a) Reduction of equivalent stiffness versus cable span lengths (b) Reduction of load-carrying efficiency versus cable span lengths

(c) Cable sag effects versus cable span lengths (d) Self-weight stress versus cable span lengths

Fig. 3 Performance of pure steel stay cables versus cable span lengths deteriorate more rapidly and suddenly than before or already have an unacceptable reduction. More specifically, nearly 30% reduction of equivalent stiffness, 20% reduction of load-carrying efficiency, 0.0015 cable sag effects (about 40 m cable sag), and 18% as the ratio of self-weight stress to yield strength are observed at the point of 700 m in Figs. 3(a)~3(d), respectively, which are becoming unacceptable in the practical bridge engineering. Therefore, in this paper 0~700 m were determined as the appropriate span lengths of pure steel stay cables from the stiffness viewpoint, which also agrees with the span length ranges generally believed by bridge designers (Miao 2006). Additionally, 5000 m could be considered as the limit span length for pure steel stay cables because beyond 5000 m almost all the stiffness (100%) has been lost as shown in Fig. 3(a).

2.3 Appropriate span lengths of pure CFRP stay cables

Following the same methodology for pure steel stay cables discussed earlier and only with the change of design parameters (see Table 3) (ACI 2004), the stiffness-related performance of pure CFRP stay cables with regard to the investigated mechanical parameters can be also calculated through varying the cable span lengths from 0 to 30000 m, as shown in Fig. 4.

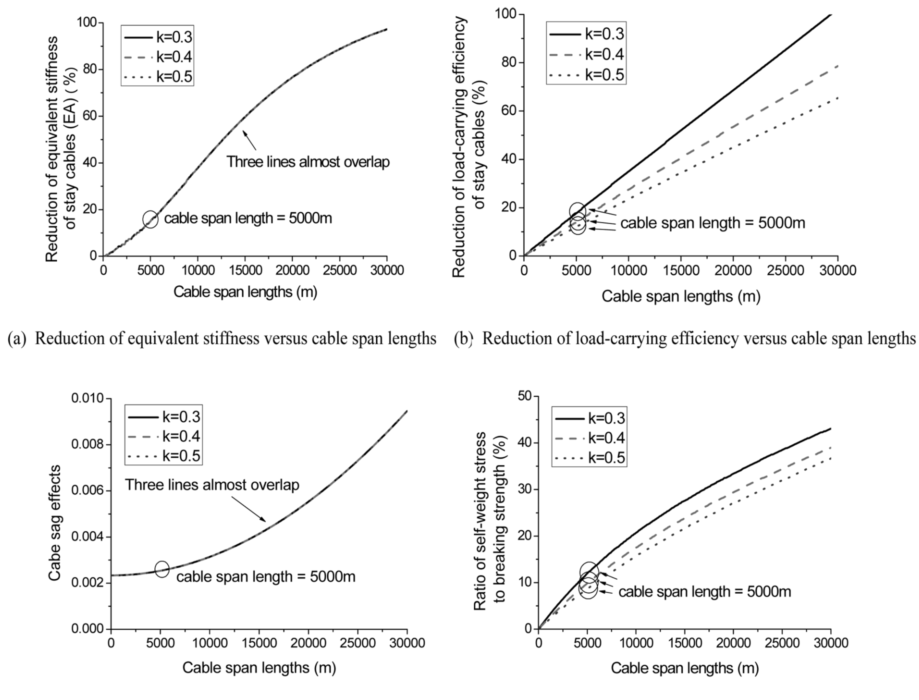
By the same analysis as previously used for pure steel stay cables, the value of 5000 m, similar to 700 m in steel case, could be another significant point in the span length study for pure CFRP stay cables. Also close to the values from steel case, nearly 20% reduction of equivalent stiffness, 18% reduction of load-carrying efficiency, 0.0028 cable sag effects (about 70 m cable sag), and 10% as the ratio of self-weight stress to breaking strength are observed at the point of 5000 m in Figs. 4(a)~4(d), respectively. Besides, by the comparison in Fig. 5, it can be also observed that pure steel stay cables show an obvious advantage in the stiffness before the cable span length reaches 1400 m; however, this advantage apparently turns into pure CFRP stay cables thereafter. In other words, 1400 m could be a start point to apply pure CFRP stay cables in cable-stayed bridges. Therefore, in this paper 1400~5000 m were determined as the appropriate span lengths of pure CFRP stay cables from a stiffness viewpoint. Additionally, 30000m could be considered as the limit span length for pure CFRP stay cables because beyond this span length almost all the stiffness has been lost.

2.4 Application range of hybrid stay cable system

The analysis conducted earlier indicated that when cable span lengths are from 0~700 m, pure steel

Table 3 Design parameters of analytical models (CFRP stay cables)

Design parameters	Values		
Nominal gradient of stay cables ($k = h/l$)	0.3	0.4	0.5
Cable span length (m)	50~25000	50~25000	50~25000
Vertically projected length of stay cables (m)	15~7500	20~10000	25~12500
Area (m^2)	0.00638		
Design stay cable (N)	5.102E + 6		
Elasticity modulus (N/m^2)	1.37E + 11		
Density (kg/m^3)	1.60E + 03		
Breaking Strength (MPa)	1.02E + 03		
Safety factor	2.50		



(a) Reduction of equivalent stiffness versus cable span lengths (b) Reduction of load-carrying efficiency versus cable span lengths

(c) Cable sag effects versus cable span lengths (d) Self-weight stress versus cable span lengths

Fig. 4 Performance of pure CFRP stay cables versus cable span lengths

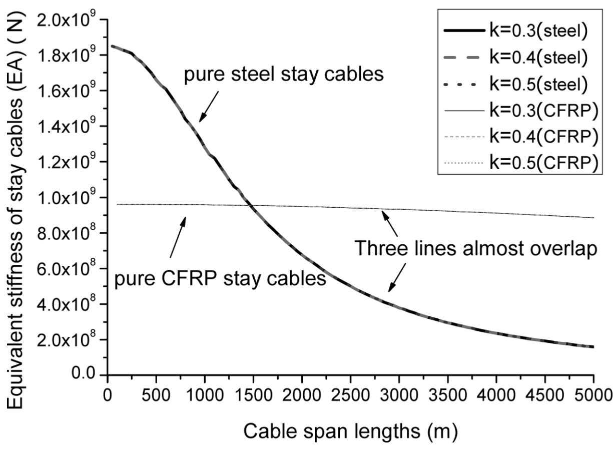


Fig. 5 Comparison for the equivalent stiffness (EA)

stay cables are more appropriate; when cable span lengths are from 1400~5000 m, pure CFRP stay cables are more appropriate; when cable span lengths are from 700~1400 m, a combined application of steel and CFRP materials (stay cables) may be more appropriate.

As a result, a type of hybrid stay cable system was proposed in this paper. Through a rational design (see the details later), the hybrid stay cable system can be a good alternative to the traditional pure steel stay cables or pure CFRP stay cables in this concerned span length range. In other words, this span length range, i.e., 1400~2800 m for main span lengths of cable-stayed bridges or 700~1400 m for the longest cable span lengths, can be certainly regarded as the appropriate application range of the hybrid stay cable system.

3. Design strategy for hybrid stay cable system

3.1 Hybrid stay cable system

In the hybrid application, one can simultaneously install both CFRP stay cables and steel stay cables at the same location, shown in Fig. 6. By doing this, CFRP stay cables can conserve all the advantages of CFRP materials such as their light weight and high strength; while steel stay cables can increase the equivalent stiffness of stay cables and also reduce the total cost of the materials. Also, for this type of hybrid stay cable system, an increase of the equivalent stiffness could be further obtained with a reasonable increase of their safety factor, i.e., increasing the section area of stay cables. It should be noted that this increasing-safety-factor-method may not be the best option for either pure steel or pure CFRP stay cables, because it could result in a heavy self-weight or high cost, if without a combined design. If building appropriate connections between the steel stay cables and CFRP stay cables during/after construction, the hybrid stay cable can theoretically be regarded as a single cable with a composite section.

Moreover, due to the different roles played by the steel and CFRP materials, the material proportion of the hybrid stay cable system is expected to be a principal factor that will affect the stay cable behaviors and also the cost. For this reason, in the present study the ratio of the section area of CFRP stay cables to the whole cable area, i.e., $\rho = A_{CFRP}/(A_{steel} + A_{CFRP})$, was determined as the key design parameter for the hybrid stay cable system.

3.2 Analytical study for equivalent stiffness of hybrid stay cable system

Before the introduction of design strategy (design criteria), the analytical study for the equivalent stiffness of hybrid stay cable system was firstly carried out. In the present study, the equivalent stiffness

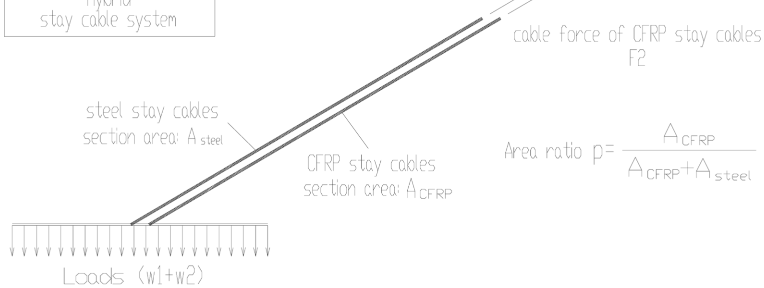


Fig. 6 Proposed hybrid stay cable system

of the hybrid stay cable system is defined as $E_{eq}A$, which is calculated from the expression 2 in Table 1, as (As stated earlier, the hybrid stay cable can theoretically be regarded as a single cable with a composite section by building appropriate connections between the steel stay cables and CFRP stay cables during/after construction)

$$K_{eq} = E_{eq}A = EA/\left[1 + \frac{\gamma_c^2 l^2}{12\sigma_1^3}E\right] \tag{6}$$

By assuming that the steel and CFRP stay cables can be pulled separately to achieve the desired force level, for the hybrid stay cable system, each section area can be designed as

$$A_{steel} = F_{steel}/\sigma_{asteel} = F_{steel}/(\sigma_{lsteel}/\eta_{steel}) \tag{7}$$

$$A_{CFRP} = F_{CFRP}/\sigma_{aCFRP} = F_{CFRP}/(\sigma_{lCFRP}/\eta_{CFRP}) \tag{8}$$

where A_{steel} and A_{CFRP} = section areas of steel and CFRP stay cables, respectively; F_{steel} and F_{CFRP} = stay cable forces of steel and CFRP stay cables, respectively; σ_{asteel} and σ_{aCFRP} = allowable stresses of steel and CFRP stay cables, respectively; σ_{lsteel} and σ_{lCFRP} = limit stresses of steel and CFRP stay cables, respectively; and η_{steel} and η_{CFRP} = safety factors of steel and CFRP stay cables, respectively.

The density of hybrid stay cable system can be written as

$$\gamma_c = \frac{\gamma_{steel}A_{steel} + \gamma_{CFRP}A_{CFRP}}{A_{steel} + A_{CFRP}} \tag{9}$$

where γ_{steel} and γ_{CFRP} = densities of steel and CFRP stay cables, respectively.

By safely assuming the deformation compatibility between steel and CFRP stay cables after they are installed, the elastic modulus of hybrid stay cable system can be given as

$$E = \frac{E_{steel}A_{steel} + E_{steel}A_{CFRP}}{A_{steel} + A_{CFRP}} \tag{10}$$

where E_{steel} and E_{CFRP} = elastic modulus of steel and CFRP stay cables, respectively.

Substituting Eqs. (9) and (10) into Eq. (6), the equivalent stiffness of hybrid stay cable system can be then described as

$$K_{eq} = E_{eq}(A_{CFRP} + A_{steel}) = \frac{(A_{CFRP} + A_{steel})}{\dfrac{A_{steel} + A_{CFRP}}{E_{steel}A_{steel} + E_{CFRP}A_{CFRP}} + \dfrac{l^2}{12\sigma_1^3}\left(\dfrac{\gamma_{steel}A_{steel} + \gamma_{CFRP}A_{CFRP}}{A_{steel} + A_{CFRP}}\right)^2} \tag{11}$$

With the definition of $\rho = A_{CFRP}/(A_{steel} + A_{CFRP})$, Eq. (11) can be further transformed into

$$K_{eq} = \frac{(A_{CFRP} + A_{steel})}{\dfrac{A_{steel} + A_{CFRP}}{E_{steel}A_{steel} + E_{CFRP}A_{CFRP}} + \dfrac{l^2}{12\sigma_1^3}\left(\dfrac{\gamma_{steel}A_{steel} + \gamma_{CFRP}A_{CFRP}}{A_{steel} + A_{CFRP}}\right)^2} \tag{12}$$

If considering the material cost, the ratio of equivalent stiffness to material cost of unit cable length can be calculated as

$$\xi = \frac{(A_{CFRP} + A_{steel})}{\frac{1}{E_{steel}(1-\rho) + E_{CFRP}\rho} + \frac{l^2}{12\sigma_1^3}(\gamma_{steel}(1-\rho) + \gamma_{CFRP}\rho)^2} / (\kappa_{CFRP}A_{CFRP}\gamma_{CFRP} + \kappa_{steel}A_{steel}\gamma_{steel}) \tag{13}$$

where ξ = ratio of equivalent stiffness to material cost of unit cable length; κ_{steel} and κ_{CFRP} = costs of unit mass for steel and CFRP stay cables with the consideration of materials and construction, respectively.

By defining $\lambda = \kappa_{CFRP}/\kappa_{steel}$, Eq. (13) can be further written as

$$\xi = \frac{1}{\frac{1}{E_{steel}(1-\rho) + E_{CFRP}\rho} + \frac{l^2}{12\sigma_1^3}(\gamma_{steel}(1-\rho) + \gamma_{steel}\rho)^2} / (\lambda\kappa_{steel}\rho\gamma_{CFRP} + \kappa_{steel}(1-\rho)\gamma_{steel}) \tag{14}$$

If the total cost for designing stay cables (including materials and construction) of unit cable length is defined as ψ, the section area of hybrid stay cable system can be designed as

$$A = \psi / (\kappa_{CFRP}\rho\gamma_{CFRP} + \kappa_{steel}(1-\rho)\gamma_{steel}) \tag{15}$$

$$A_{CFRP} = A \cdot \rho \tag{16}$$

$$A_{steel} = A \cdot (1-\rho) \tag{17}$$

Then, substituting Eqs. (16) and (17) into Eq. (12), the equivalent stiffness of hybrid stay cable system under a given (pre-set) cost ψ (or called “budget”) can be obtained.

For the convenience of discussion, the costs per unit cable length of designing pure steel and pure CFRP stay cables with a safety factor of 2.5 are denoted as ψ_{steel} and ψ_{CFRP}, respectively, and are regarded as the basic costs. Correspondingly, any other possible costs per unit cable length with other safety factors for the hybrid section can be expressed as $\alpha\psi_{steel}$ or $\alpha\psi_{CFRP}$.

$$\psi_{steel} = F_{steel}/\sigma_{asteel} \cdot \gamma_{steel} \cdot \kappa_{steel} \tag{18}$$

$$\psi_{CFRP} = F_{CFRP}/\sigma_{aCFRP} \cdot \gamma_{CFRP} \cdot \kappa_{CFRP} \tag{19}$$

$$\alpha\psi_{steel} = \alpha \times \psi_{steel}, \quad \alpha = 1, 2, \ldots n \tag{20}$$

$$\alpha\psi_{CFRP} = \alpha \times \psi_{CFRP}, \quad \alpha = 1, 2, \ldots n \tag{21}$$

where $\alpha\psi_{steel}$ and $\alpha\psi_{CFRP}$ = α times ψ_{steel} and ψ_{CFRP}, respectively.

All the discussed parameters and expressions which describe the characteristics of the equivalent stiffness of stay cables will be used in the following studies.

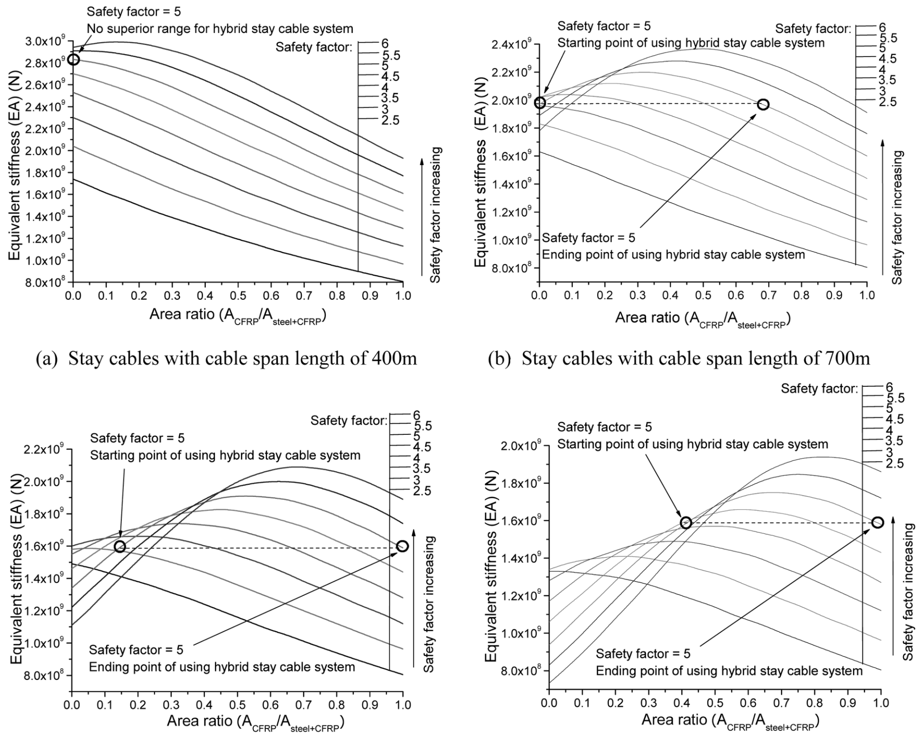
3.3 Design criteria of hybrid stay cable system

With the consideration of equivalent stiffness and cost, three design criteria for the proposed hybrid stay cable system are introduced in the following sections. Designers can choose one of these criteria in the design process, or similarly, other design criteria can be developed.

3.3.1 Design criterion 1: Best equivalent stiffness with a given safety factor

In this design criterion, the best equivalent stiffness of stay cables with a given safety factor can be pre-designed by adjusting the area ratio ρ discussed earlier. To better understand the effects of ρ on the performance of the equivalent stiffness, the equivalent stiffness of stay cables with different safety factors were theoretically investigated through a parametric study. Based on the results of the parametric study a design methodology of the hybrid stay cable system using this design criterion was recommended, which can assist engineers to perform and optimize their designs.

To cover more possible design conditions in the parametric study, four analytical models of stay cables with different horizontally projected lengths, 400 m, 700 m, 1000 m, and 1300 m, respectively, and a constant designed cable gradient 0.4, were studied mainly using Eqs. (7)~(12). The designed cable force was set as 5102 kN and kept the same in all the cases for a convenient comparison. Also, to verify the proposed methodology for stiffness improvement by increasing the safety factor, eight safety factor values were considered (2.5, 3, 3.5, 4, 4.5, 5, 5.5, and 6), though some of these safety factors are

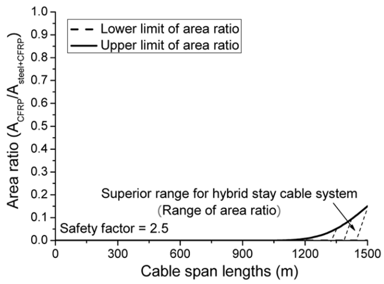


(a) Stay cables with cable span length of 400m (b) Stay cables with cable span length of 700m

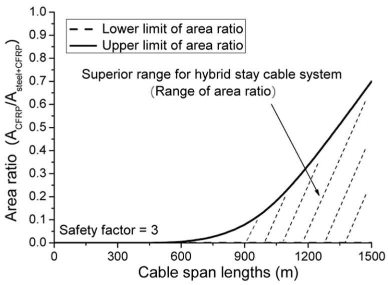
(c) Stay cables with cable span length of 1000m (d) Stay cables with cable span length of 1300m

Fig. 7 Equivalent stiffness of stay cables with different cable span lengths not practically too high. Other geometry and material properties used in the parametric study can be found in Tables 2 and 3.

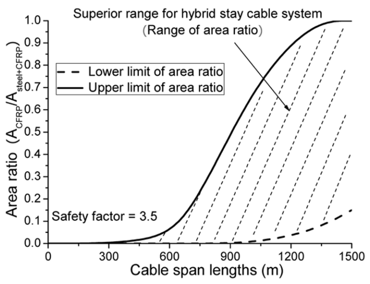
Figs. 7(a)~7(d) plot the equivalent stiffness of stay cables versus area ratio (0~1.0) obtained with different safety factors (2.5~6) and cable span lengths (400, 700, 1000, and 1300 m), separately. The effects of increasing safety factors on stiffness improvement are obviously observed from these figures. In each figure, the equivalent stiffness of stay cables at 0.0 and 1.0 area ratios represents two extreme cases, i.e., pure steel stay cables and pure CFRP stay cables, respectively. The results corresponding to the area ratios between 0.0 and 1.0 are calculated from the hybrid cases. Taking the results with a safety factor of 5 for example, the superior range of hybrid stay cable system, following the design criterion 1, is marked by a dashed line between two circles, where the equivalent stiffness is higher than that of stay cables with both pure steel ($\rho = 0$) and pure CFRP ($\rho = 1$) materials. By repeatedly doing this, all the superior ranges of hybrid stay cable system (the ranges of area ratio) with regard to different safety



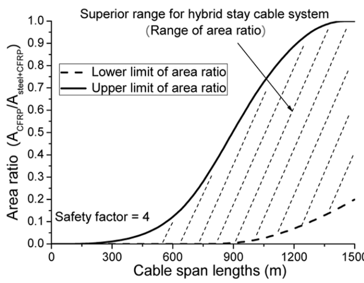
(a) Design guide with safety factor 2.5



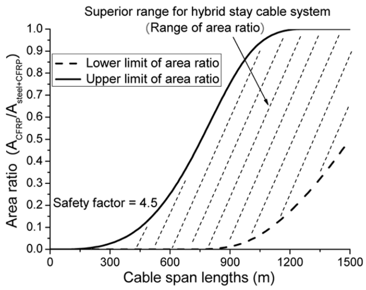
(b) Design guide with safety factor 3



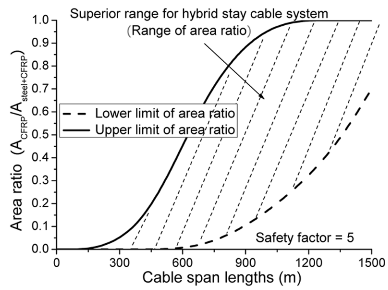
(c) Design guide with safety factor 3.5



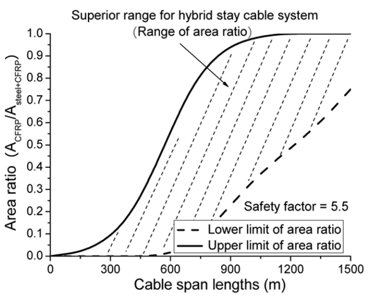
(d) Design guide with safety factor 4



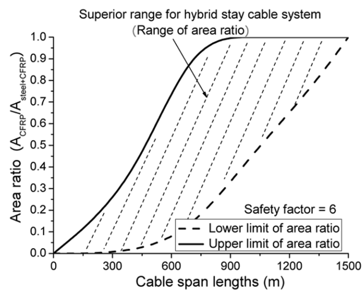
(e) Design guide with safety factor 4.5



(f) Design guide with safety factor 5



(g) Design guide with safety factor 5.5



(h) Design guide with safety factor 6

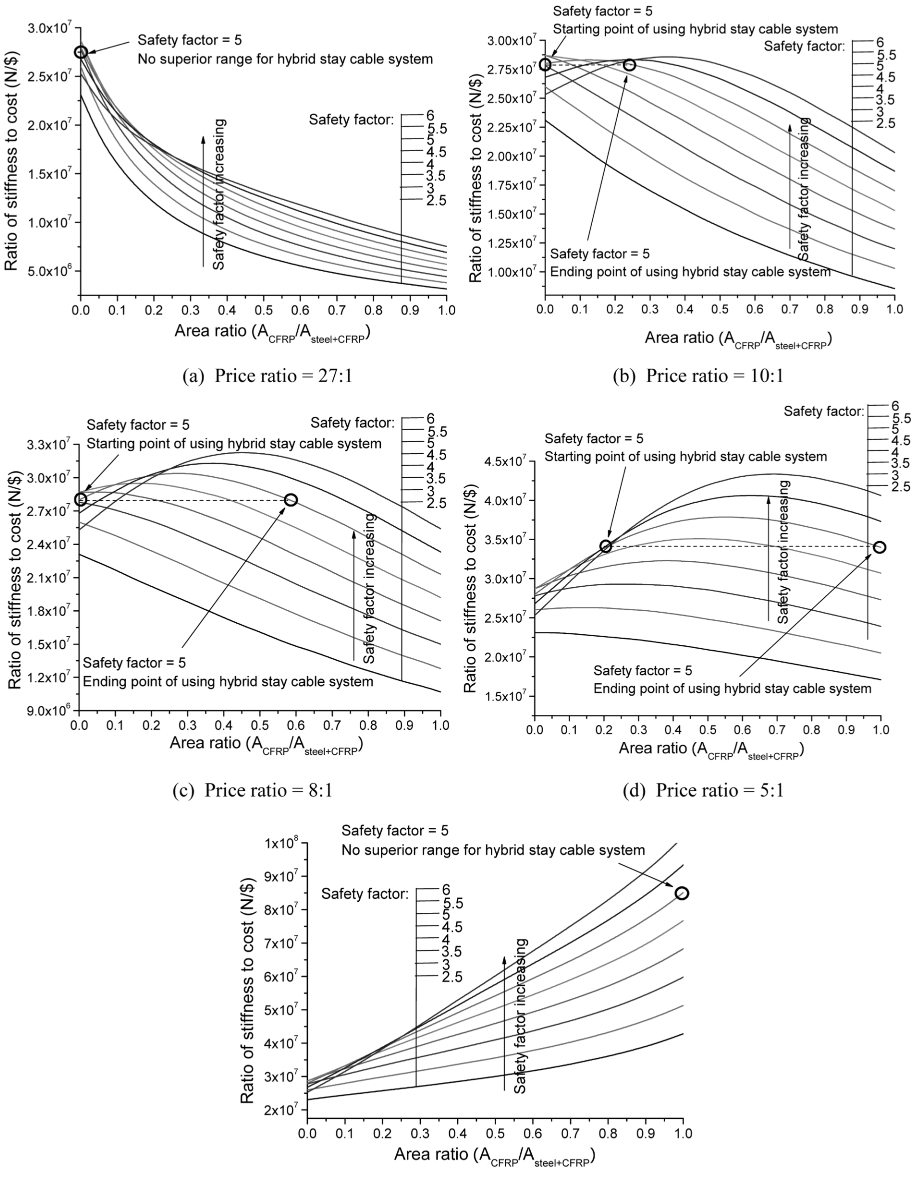
Fig. 8 Design guide for hybrid stay cable system based on design criterion 1 factors and cable span lengths can be finally obtained, which are shown in Fig. 8 as a design guide.

Based on the design guide shown in Fig. 8, the hybrid stay cable system can be easily designed using design criterion 1 as:

Step 1: Determining the cable span lengths of stay cables;

Step 2: Determining the safety factor used in the cable design;

Step 3: From the design guide shown in Fig. 8, the appropriate area ratio range for hybrid stay cable system (dashed area) can be selected based on the cable span length and safety factor used in design;



(a) Price ratio = 27:1

(b) Price ratio = 10:1

(c) Price ratio = 8:1

(d) Price ratio = 5:1

(e) Price ratio = 2:1

Fig. 9 Ratio of stiffness to cost for stay cables with 700 m span length and different price ratios furthermore, by using Fig. 7, the optimal area ratio corresponding to the highest equivalent stiffness can be obtained;

Step 4: If no appropriate area ratio can be found based on the design criterion 1, the pure steel stay cables can be selected for short cables near the pylon and the pure CFRP stay cables for long cables apart from the pylon. The reason for this arrangement was discussed earlier in section 2.

3.3.2 Design criterion 2: Highest ratio of equivalent stiffness to material cost with a given safety factor

In this design criterion, the highest ratio of equivalent stiffness to materials cost with a given safety factor can be pre-designed by adjusting the area ratio ρ with a given price ratio of CFRP stay cables to steel stay cables. Similarly with design criterion 1, to better understand the effects of ρ on this stiffness-to-cost ratio, a series of parametric studies were carried out in order to obtain a design methodology using the design criterion 2.

The analytical models and investigated safety factors for the parametric study are identical to those used in the cases of design criterion 1. However, due to the cost factor in this design criterion, different price ratios of the two materials used in the hybrid stay cable system are studied to consider future cost changes. In this study, present prices of CFRP and steel stay cables are assumed as \$77.1/kg and \$2.9/kg, respectively, resulting in a price ratio of 27:1 (Mei 2005); and more price ratios of CFRP stay cables to steel stay cables are also studied, which are 20:1, 15:1, 10:1, 8:1, 5:1, 2:1, and 1:1. Due to the page limit, only the results of 700 m (Fig. 9) and 1000 m (Fig. 10) cable span lengths with different price ratios are presented here.

Figs. 9(a)~9(e) and 10(a)~10(e) plot the ratio of equivalent stiffness to material cost versus area ratio (0~1.0) obtained with different price ratios (27:1~2:1), safety factors (2.5~6), and cable span lengths (only the 700 and 1000 m due to the page limit), separately. Good effects of increasing safety factors on stiffness improvement are also observed here. Following the method used in design criterion 1, the superior ranges of hybrid stay cable system (the ranges of area ratio) with regard to different price ratios, safety factors, and cable span lengths can be also obtained based on the design criterion 2, which are shown in Figs. 11 (price ratio = 15:1) and 12 (price ratio = 10:1) as a design guide. The results of other price ratios are not shown here due to the page limit.

Based on the design guide shown in Figs. 11, 12, and other figures with more different price ratios, the hybrid stay cable system can be easily designed using design criterion 2 as:

Step 1: Determining the cable span lengths of stay cables;

Step 2: Checking the recent price ratio of CFRP stay cables to steel stay cables;

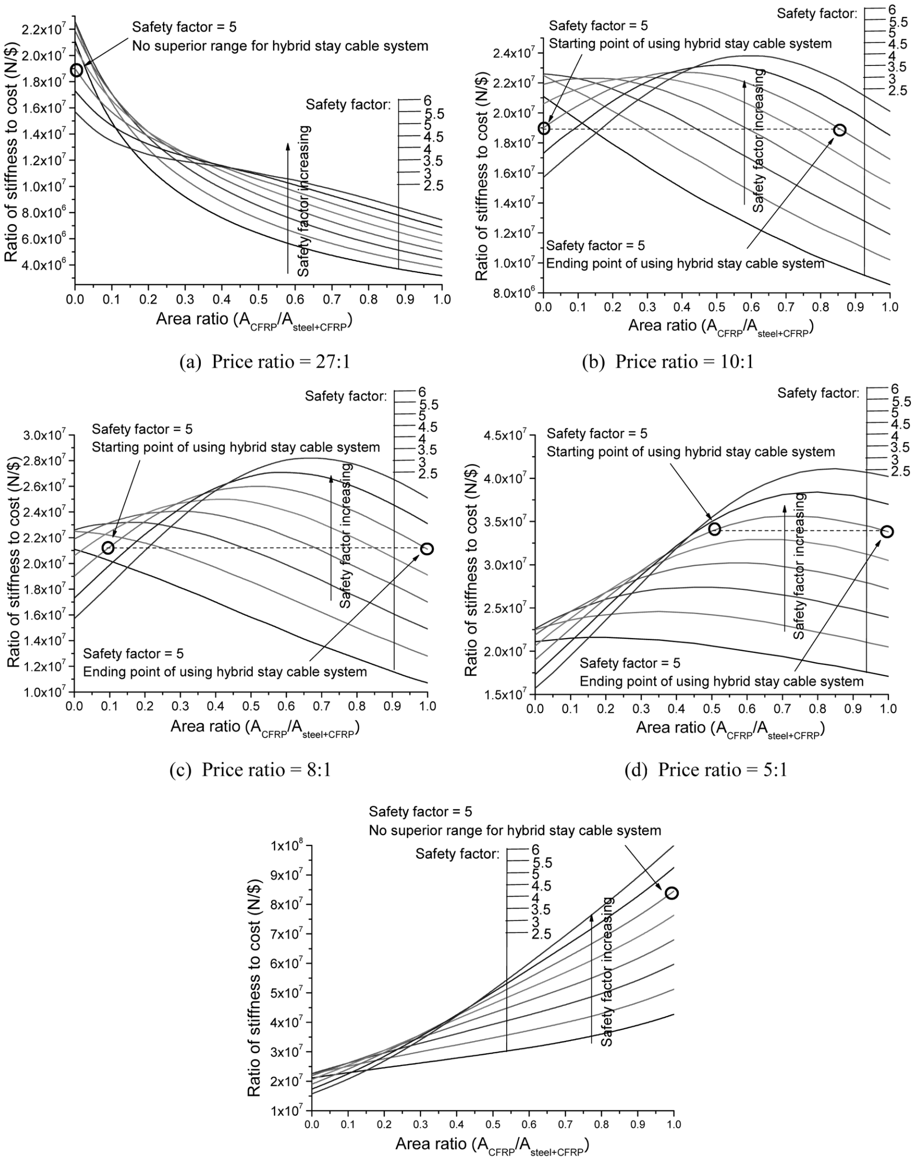
Step 3: Determining the safety factor used in the cable design;

Step 4: From the design guide shown in Figs. 11, 12, and other figures with more different price ratios, the appropriate area ratio range for hybrid stay cable system (dashed area) can be selected based on recent price ratio, cable span length, and safety factor used in design; furthermore, by using Figs. 9 and 10, the optimal area ratio corresponding to the highest equivalent stiffness to cost ratio can be obtained;

Step 5: Similar to criterion 1, if no appropriate area ratio can be found based on the design criterion 2, the pure steel stay cables can be selected for short cables near the pylon and the pure CFRP stay cables for long cables apart from the pylon.

3.3.3 Design criterion 3: Best equivalent stiffness under a given cost

In this design criterion, the best equivalent stiffness of stay cables under a given cost can be pre-



(a) Price ratio = 27:1

(b) Price ratio = 10:1

(c) Price ratio = 8:1

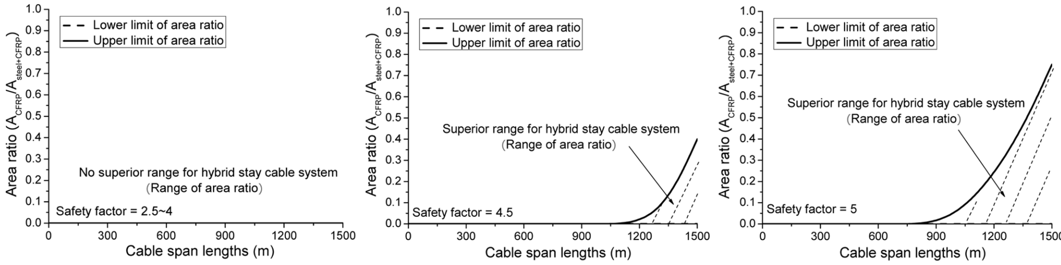
(d) Price ratio = 5:1

(e) Price ratio = 2:1

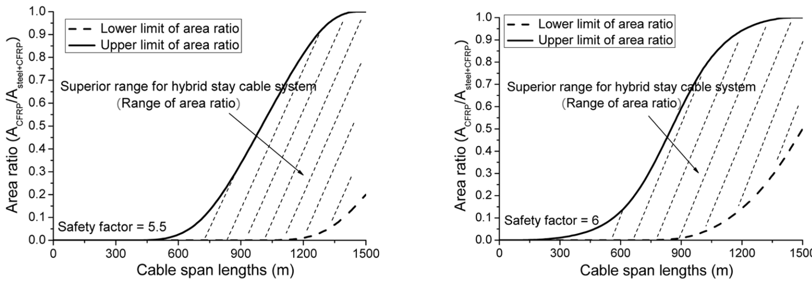
Fig. 10 Ratio of stiffness to cost for stay cables with 1000 m span length and different price ratios

designed by adjusting the area ratio ρ under a given price ratio of CFRP stay cables to steel stay cables. The safety factor value used for cables will be automatically determined when the sectional area of each stay cable is set using Eqs. (15)~(17) as well as satisfying the strength requirement. Similarly, a series of parametric studies were carried out in order to obtain a design methodology using the design criterion 3.

The analytical models and investigated price ratio for the parametric study are also identical to those used in the cases of design criteria 1 and 2. However, in addition to the developing price ratio, different

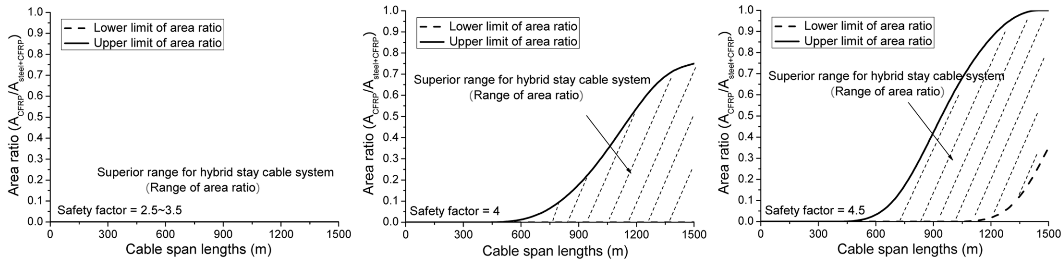


(a) Design guide with safety factor 2.5~4 (b) Design guide with safety factor 4.5 (c) Design guide with safety factor 5

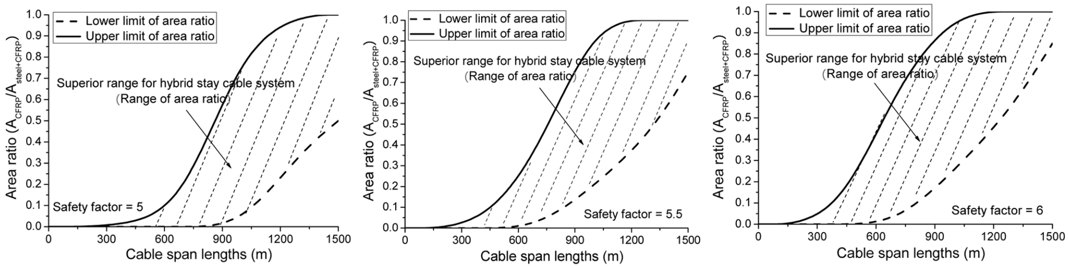


(d) Design guide with safety factor 5.5 (e) Design guide with safety factor 6

Fig. 11 Design guide for hybrid stay cable system based on design criterion 2 (price ratio = 15:1)



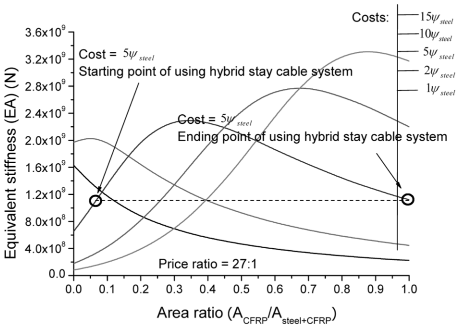
(a) Design guide with safety factor 2.5~3.5 (b) Design guide with safety factor 4 (c) Design guide with safety factor 4.5



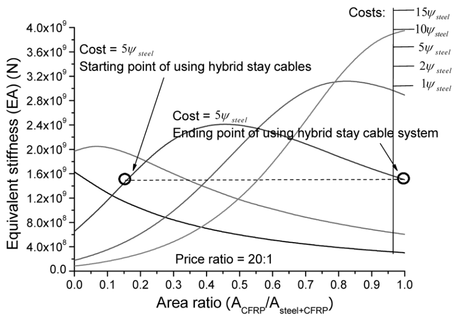
(a) Design guide with safety factor 5 (b) Design guide with safety factor 5.5 (c) Design guide with safety factor 6

Fig. 12 Design guide for hybrid stay cable system based on design criterion 2 (price ratio = 10:1)

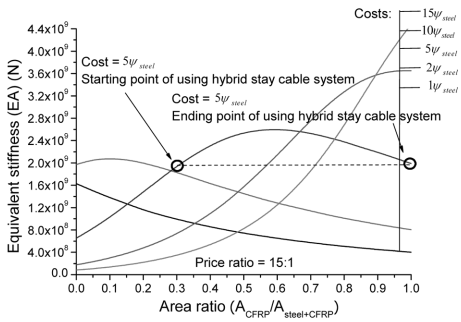
given costs ($\alpha\psi_{Steel}$ and $\alpha\psi_{CFRP}$, using Eqs. (18)~(21) to define them) prepared for the hybrid stay cable system should be also considered, which are $1\psi_{steel}$, $2\psi_{steel}$, $5\psi_{steel}$, $10\psi_{steel}$, $15\psi_{steel}$, $1\psi_{CFRP}$, $2\psi_{CFRP}$, $5\psi_{CFRP}$, $10\psi_{CFRP}$, and $15\psi_{CFRP}$. Due to the page limit, only the results of 700 m (Fig. 13) and 1000 m



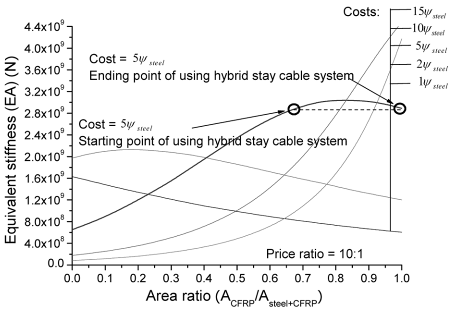
(a) Price ratio = 27:1



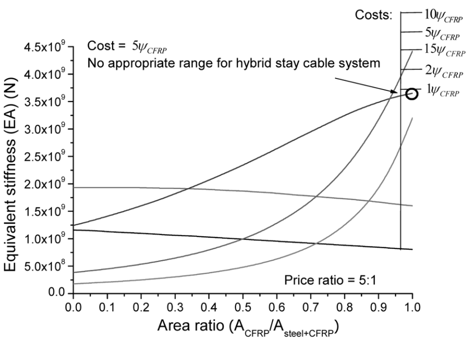
(b) Price ratio = 20:1



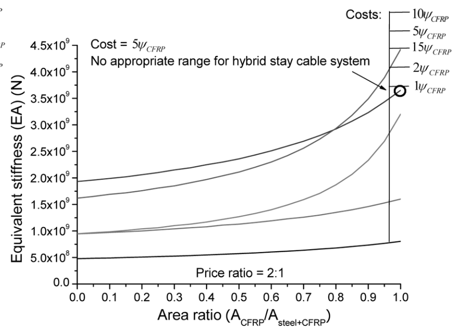
(c) Price ratio = 15:1



(d) Price ratio = 10:1



(e) Price ratio = 5:1

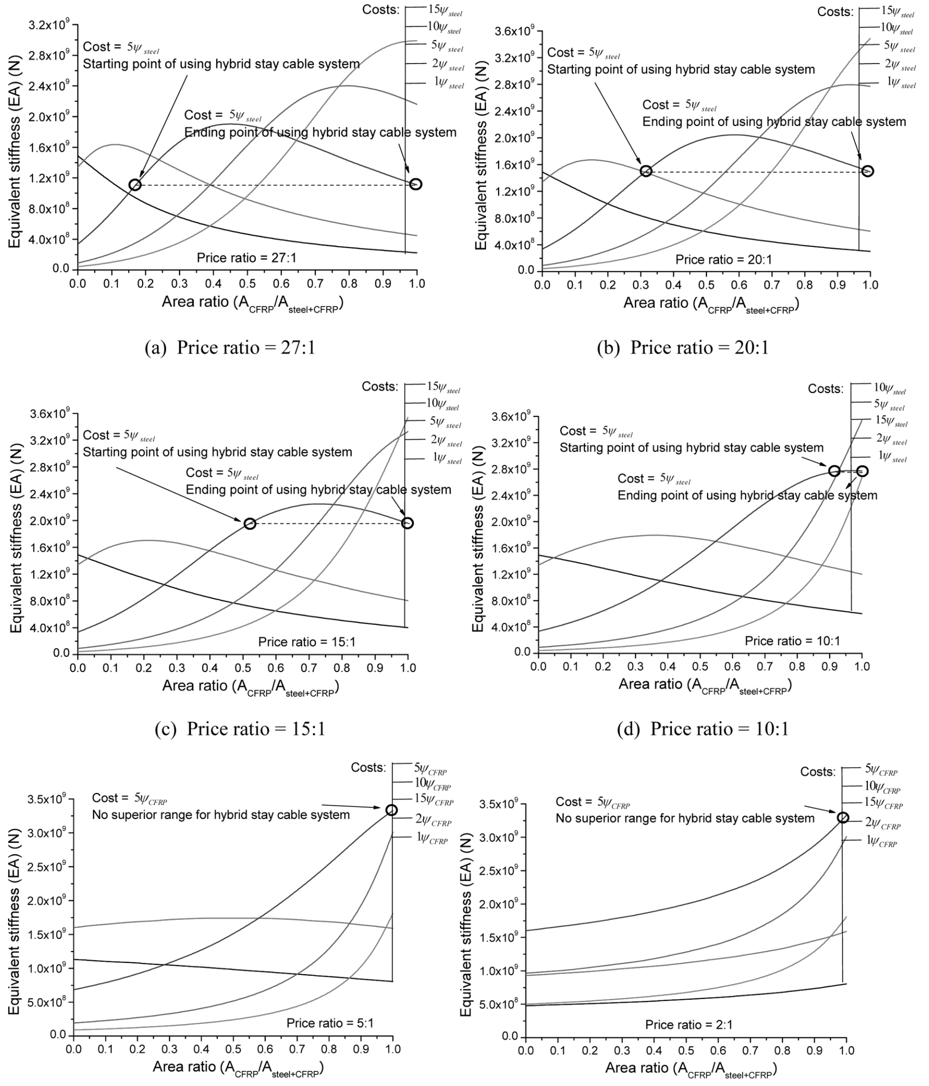


(f) Price ratio = 2:1

Fig. 13 Equivalent stiffness of stay cables with 700 m span length and different price ratios

(Fig. 14) cable span lengths with different price ratios are presented here.

Figs. 13(a)~13(f) and 14(a)~14(f) plot the equivalent stiffness of stay cables versus area ratio (0~1.0) obtained with different given costs ($1\,\psi_{steel}$~$15\,\psi_{steel}$ and $1\,\psi_{CFRP}$~$15\,\psi_{CFRP}$), price ratios (27:1~2:1), and cable span lengths (only the 700 and 1000 m due to the page limit). The reason to switch ψ_{steel} to ψ_{CFRP} for the cases of 5:1 and 2:1 price ratios is that in these cases the cost to build CFRP stay cables has been similar with or even less than that of steel stay cables. Similar to the previous criteria, the dashed line between two circles in each figure is also taken as an example to show the superior ranges of hybrid stay cable system with cost $5\,\psi_{steel}$ or $5\,\psi_{CFRP}$. The superior ranges of hybrid stay cable system (the rangs of area ratio) with regard to different costs, price ratios, and cable span lengths can be also obtained



(a) Price ratio = 27:1

(b) Price ratio = 20:1

(c) Price ratio = 15:1

(d) Price ratio = 10:1

(e) Price ratio = 5:1

(f) Price ratio = 2:1

Fig. 14 Equivalent stiffness of stay cables with 1000 m span length and different price ratios

based on the design criterion 3, which are shown in Figs. 15 (price ratio = 15:1) and 16 (price ratio = 10:1) as a design guide, and results for other price ratios are not shown here due to the page limit.

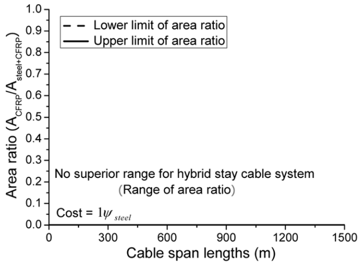
Based on the design guide shown in Figs. 15, 16, and other figures with more different price ratios, the hybrid stay cable system can be easily designed using design criterion 3 as:

Step 1: Determining the cable span lengths of stay cables;

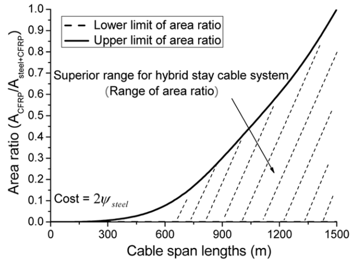
Step 2: Pre-determining the costs (budget) for the cable design including the materials and construction;

Step 3: Checking the recent price ratio of CFRP stay cables to steel stay cables;

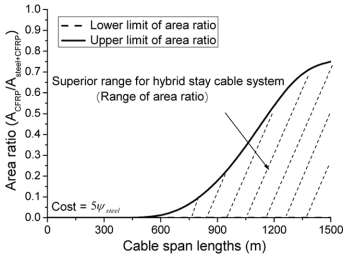
Step 4: From the design guide shown in Figs. 15, 16, and other figures with more different price



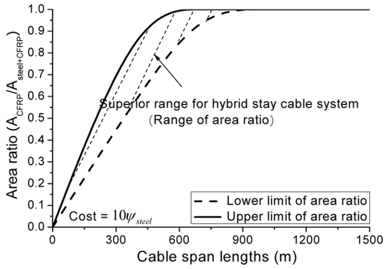
(a) Design guide with cost $1\psi_{steel}$



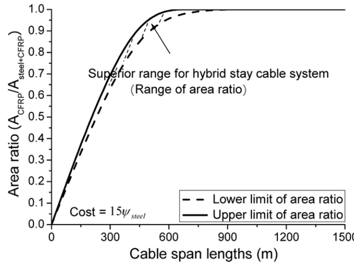
(b) Design guide with cost $2\psi_{steel}$



(c) Design guide with cost $5\psi_{steel}$

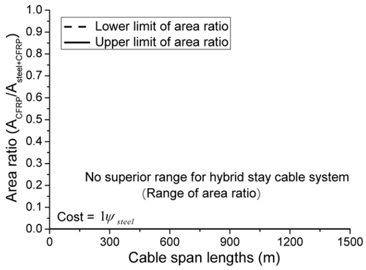


(d) Design guide with cost $10\psi_{steel}$

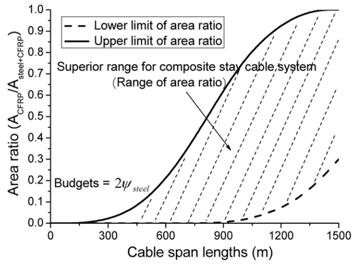


(e) Design guide with cost $15\psi_{steel}$

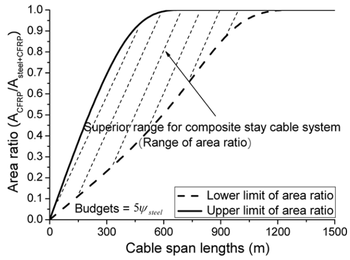
Fig. 15 Design guide for hybrid stay cable system based on design criterion 3 (price ratio = 15:1)



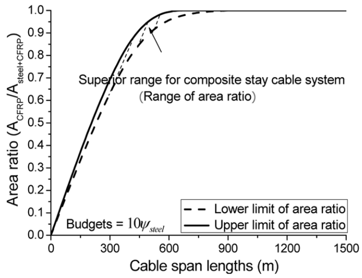
(a) Design guide with cost $1\psi_{steel}$



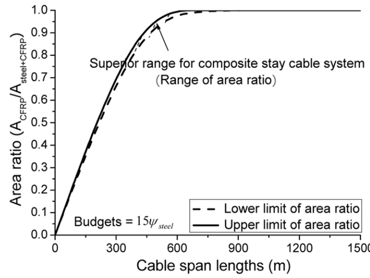
(b) Design guide with cost $2\psi_{steel}$



(c) Design guide with cost $5\psi_{steel}$



(d) Design guide with cost $10\psi_{steel}$



(e) Design guide with cost $15\psi_{steel}$

Fig. 16 Design guide for hybrid stay cable system based on design criterion 3 (price ratio = 10:1)

ratios, the appropriate area ratio for hybrid stay cable system (dashed area) can be selected based on the pre-determined costs, recent price ratio, and cable span length used in design; furthermore, by using

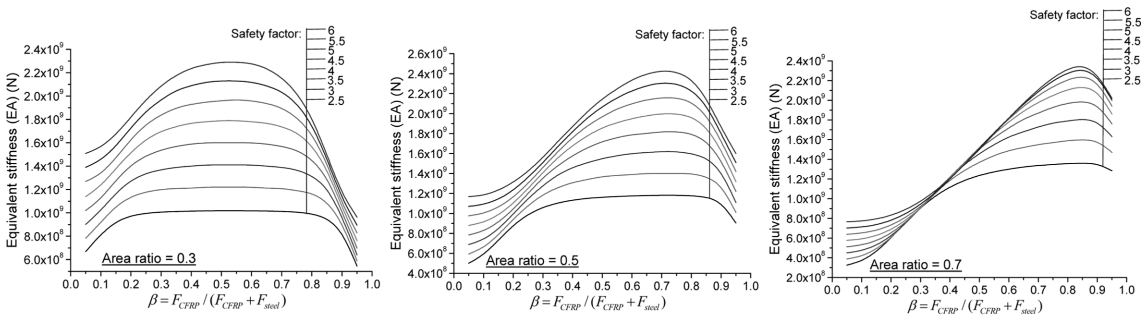
Figs. 13 and 14, the optimal area ratio corresponding to the highest equivalent stiffness can be obtained for a given cost;

Step 5: Similar to criteria 1 and 2, if no appropriate area ratio can be found based on the design criterion 3, the pure steel stay cables can be selected for short cables near the pylon and the pure CFRP stay cables for long cables apart from the pylon.

3.4 Cable force distribution of hybrid stay cable system

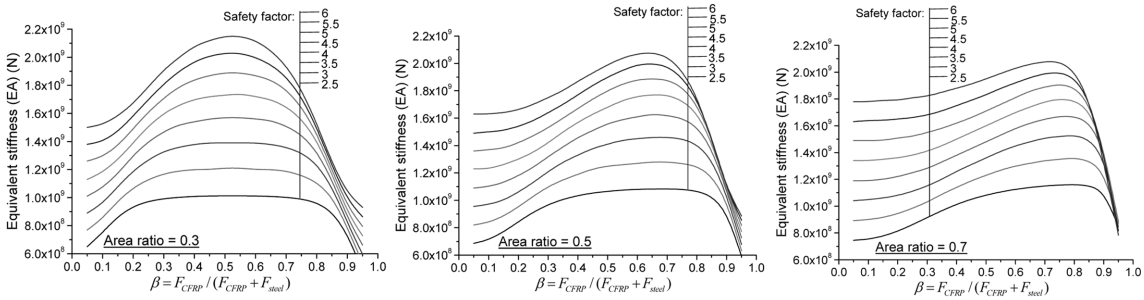
Once the value of area ratio is determined for the hybrid stay cable system, the cable force distribution between the steel and CFRP stay cables should become the next issue. An appropriate cable force distribution affects the stiffness design of stay cables (Ernst 1965, Ahmadi-Kashani 1988, Freire 2006). Therefore, this study further investigated the effects of cable force distribution (defining $\beta = F_{CFRP}/(F_{CFRP} + F_{steel})$, herein) on the equivalent stiffness of stay cables through a parametric study.

From Figs. 17 and 18 and other figures with more cable span lengths (not shown here due to the page limit), the appropriate values of β for each study case usually ranges from 0.4~0.7, where the best equivalent stiffness of stay cables can be reached. The variation of the safety factor values only has little effects on the β design. It can be also observed that the β value with regard to the equivalent stiffness of stay cables increases with the increase of area ratio. This can be explained that CFRP constituent (stay cables) with more section area (higher area ratio) need more cable forces applied on to



(a) Results with area ratio 0.3 (b) Results with area ratio 0.5 (c) Results with area ratio 0.7

Fig. 17 Results for hybrid stay cable system with cable span length of 700 m



(a) Results with area ratio 0.3 (b) Results with area ratio 0.5 (c) Results with area ratio 0.7

Fig. 18 Results for hybrid stay cable system with cable span length of 1000 m keep their high equivalent stiffness. It should be noted that the final decision for the cable force distribution can only be made until the cable stresses also satisfy the strength requirements. In practice, a good selection of the β value can well complement the three design criteria to assure a high equivalent stiffness for the hybrid stay cable system.

4. Design procedure of the cable-stayed bridges using the hybrid stay cable system

Based on the discuss of the design methodology for the hybrid stay cable system above, the design procedure of the hybrid cable-stayed bridges with main span lengths of 1400~2800m can be summarized as follows:

Step 1: Determining the main span lengths of cable-stayed bridges and cable span length of each stay cable;

Step 2: Determining the design criterion used for the hybrid stay cable system, namely, the design criterion 1 (best equivalent stiffness with a given safety factor), design criterion 2 (highest ratio of equivalent stiffness to material cost with a given safety factor), or design criterion 3 (best equivalent stiffness under a given cost);

Step 3: Checking the recent price ratio of CFRP stay cables to steel stay cables;

Step 4: Determining/giving the safety factor value or costs (budgets) for the cable design depending on the design criterion selected;

Step 5: From the design guide shown in figures with regard to each design criterion introduced in section 3, the appropriate area ratio for hybrid stay cable system (dashed area) can be selected based on the cable span length, recent price ratio, safety factor or costs used in design. If no appropriate area ratio can be found based on the determined design criterion, the pure steel stay cables can be selected for short cables near the pylon and the pure CFRP stay cables for long cables apart from the pylon;

Step 6: Determining the section area for each hybrid stay cable when the area ratio is set (the area ratios of pure steel and CFRP stay cables can be seen as 0 and 1, respectively);

Step 7: Distributing the cable forces between the steel and CFRP stay cables;

Step 8: Re-designing the stay cables if needed after static and dynamic analysis for the cable-stayed bridges.

Following the design procedure introduced above, the cable-stayed bridges using the hybrid stay cable system can be usually designed as shown in Fig. 19, i.e., the pure steel and pure CFRP stay cables are located near and apart from pylons, respectively, and the hybrid stay cable system is in the middle.

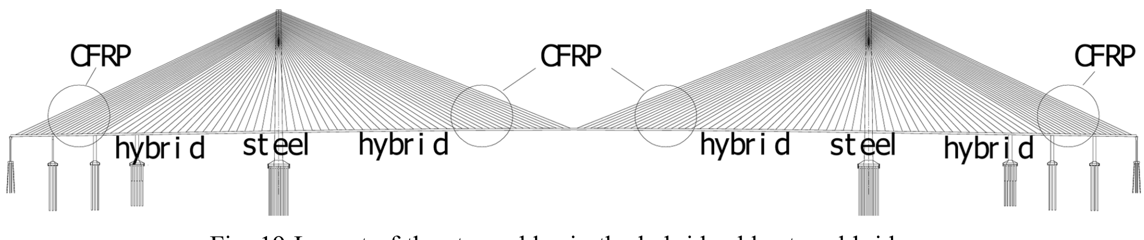


Fig. 19 Layout of the stay cables in the hybrid cable-stayed bridges

5. Concluding remark and future works

In this paper, the hybrid stay cable system using CFRP and steel materials was theoretically proposed and its design strategy and procedure were also introduced in details. The study can be summarized as follows:

Stiffness could be a significant issue in designing the cable-stayed bridges with main span lengths of 1400~2800 m if using the pure steel or pure CFRP stay cables. In such bridge span lengths (or corresponding to cable span lengths of 700~1400 m), the hybrid stay cable system using both CFRP and steel materials was newly proposed as a good alternative.

In the proposed hybrid stay cable system, CFRP stay cables conserve all the advantages of CFRP materials such as their light weight and high strength; while steel stay cables can increase the axial stiffness of stay cables and also reduce the total cost of the materials. The possible structures/ constructions of the hybrid stay cable system were also preliminarily designed.

The equivalent stiffness of hybrid stay cable system can be further improved by increasing the safety factor of stay cables (i.e., increasing section area of stay cables).

Due to the different roles played by CFRP and steel materials, the section area of CFRP stay cables to the whole cable area, $\rho = A_{CFRP}/(A_{steel} + A_{CFRP})$, was determined as the key design parameter for the hybrid stay cable system. A series of parametric studies with this area ratio were carried out.

With the consideration of stiffness and cost, three design strategies/criteria, namely, best equivalent stiffness with a given safety factor, highest ratio of equivalent stiffness to material cost with a given safety factor, and best equivalent stiffness under a given cost were proposed in details. For each design criterion, the design guide was also given step by step using a series of figures, by which the appropriate area ratio for different design conditions can be easily determined.

The cable force distribution (β values) of the hybrid stay cable system was theoretically investigated through a parametric study. The appropriate β values for different design conditions were also suggested.

Based on the proposed cable design strategies, a comprehensive design procedure for the cable-stayed bridges with the hybrid stay cable system was suggested.

Based on the theoretical study, this hybrid stay cable system can be an excellent alternative to the pure CFRP stay cables or traditional steel stay cables from the stiffness viewpoint, especially for the large bridges with main span lengths of 1400~2800 m. In future work, a further experimental study for the proposed stay cables should be performed. A comparative study of the entire bridge system using the proposed hybrid stay cable system and the pure CFRP or traditional pure steel stay cables is also needed, which has been ongoing, through simulation studies using a finite element model of a cable-stayed bridge structure.

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