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Evaluation of FRP and hybrid FRP cables for super long-span cable-stayed bridges

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ABSTRACT

This paper evaluates the safety factors, the applicable lengths, and relative cost of FRP (fiber reinforced polymer) and hybrid FRP cables that are potentially suitable for cable-stayed bridges with a super long-span of between 1000 m and 10,000 m. Following previous studies on 1000-m scale cable-stayed bridges with FRP cables, two kinds of hybrid FRP cables – the previously discussed hybrid basalt and carbon FRP (B/CFRP) cable and the newly-developed basalt and steel-wire FRP (B/SFRP) cable – as well as conventional steel cable, CFRP cable, and BFRP cable are further investigated focusing on their promise in meeting potential requirements for super long-span bridges. Some major results are as follows: (1) a three-stage model for determining safety factors of cables with different kinds and lengths is proposed; (2) a threshold of λ^2 is suggested to achieve both high material and stiffness utilization efficiency, based on which the applicable lengths for different kinds of cables were evaluated; and (3) hybrid B/SFRP cables and BFRP cables are comparable in cost to steel cables within a 3000 m span, while hybrid B/CFRP cables and CFRP cables demonstrate a superior performance/cost ratio over a longer span.

1. Introduction

Cable-stayed bridges have become a widely accepted type of long-span bridge in the past 30 years, due to their superior self-balancing structural system, higher overall stiffness and better aerodynamic behavior in comparison to suspension bridges [1]. The completion of the Sutong Bridge (1088 m, China) and the Stonecutters Bridge (1018 m, Hong Kong) indicate that the main span of the cable-stayed bridge has reached the 1000-m scale in practice, a length that previously could only be realized by suspension bridges. Even longer spans of cable-stayed bridges have also been investigated, tentatively designed, or even under construction, such as a 1400 m span cable-stayed bridge with steel cables [2], an 8400 m span cable-stayed bridge across the Strait of Gibraltar with CFRP cables [3], and 1104 m span Russky Island bridge in Russia scheduled to be completed in 2012 [4]. Additionally, in the past 10 years, long-span bridges have been required worldwide, including across the Tsugaru Strait in Japan, the Strait of Messina in Italy and the Qiongzhou strait in China [5], requiring not only improvement of current design and construction technology but also innovation of advanced new materials for bridge components. The cable-stayed bridge is characterized by its stay cables, which are prime candidates for replacement by new materials due to its simplicity in terms of required mechanical properties. The major disadvantages of conventional steel cables in a super long-span cable-stayed bridge lie in its pronounced sag effect, which will lower the material utilization and overall stiffness of the bridge, and the durability deficiency induced by corrosion, which will greatly limit the initial advantages of a cable-stayed bridge with super long-span.

To meet the requirements of super long-span bridges, many efforts have been made by researchers all over the world. One direction involved the invention of new bridge structures or hybrid bridge structures based on conventional materials, such as the spatial four-cable style bridge (Gimsing [1]) and the suspension-stay cable system (Billington [6]). In addition, researchers have proposed super long-span bridges based on the mature style of the cable-stayed bridge through adoption of advanced fiber reinforced polymer (FRP) materials as structural components, to essentially overcome the limitations caused by conventional materials [7–13]. The FRP, as a structural material, has been developed over the last 20 years for use both in structural retrofitting and strengthening and in new structures like FRP bridge decks, girders, and FRP bars [14–17]. Moreover, in some novel structures FRP components such as FRP strings and pipes can realize superior performance compared with conventional materials [18]. The wide applications of FRP composites are attributed to their superior mechanical and chemical properties, such as a high strength-to-weight ratio, anti-corrosion properties, fatigue resistance, and ease of tailoring [15]. FRP composites as stay cables are regarded as the most effective way of using FRP because of the tension-only

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component in the cable. Due to the essential advantages of FRP composites as stay cables, the carbon FRP (CFRP), which has the best mechanical and chemical behavior among different kinds of common FRP materials, was initially proposed for use in the long-span cable-stayed bridge. Several studies have already demonstrated its high static and dynamic performance at the 1000-m scale [3,7–9]. However, the high and continually-increasing cost of carbon fibers limits their applications in new structures, especially in large-scale construction, such as bridges. Additionally, the sensitivity of CFRP cables to wind load is difficult to control due to their extremely light weight and high strength [12]. Considering the limitations of CFRP, the feasibility of other FRP materials as stay cables was investigated [10], including that of aramid FRP (AFRP), glass FRP (GFRP), and the newly-developed basalt FRP (BFRP). It should be mentioned that basalt continuous fibers are an environmentally friendly and nonhazardous material that is produced from basalt rock by using a single-component raw material and then drawing and winding fibers from the melt. BFRP composites display not only a higher strength and modulus, but also a similar cost and greater chemical stability compared to E-glass FRP composites [19]. A detailed discussion on the differences between CFRP, AFRP, GFRP, and BFRP as stay cables was presented in [10], with the conclusion that GFRP and AFRP were not suitable for stay cables due to chemical instability and high cost, respectively, while BFRP can satisfy stay cable requirements by enhancing their stiffness. Based on this conclusion, the concept of hybrid FRP cables, consisting of basalt FRP and a small proportion of CFRP, was proposed for 1000-m scale cable-stayed bridges [11]. In this way, not only high static and dynamic performances can be achieved, but also a superior aerodynamic stability and relatively low cost compared to CFRP cables.

To pursue the advantages of the hybrid FRP in long-span cable-stayed bridges, several additional types of hybrid FRP and different hybrid proportions are proposed in this paper for use in bridges with spans from 1000 m to 10,000 m in length. Aside from the previously proposed hybrid B/CFRP with a 25% volume proportion of carbon fibers (B/CFRP 25%), a hybrid B/CFRP 50% is also investigated. Furthermore, a newly-developed hybrid basalt and steel-wire FRP (B/SFRP) is also proposed for stay cables based on the success of experimental studies on hybrid B/SFRP sheets, which revealed that reliable bonding between basalt fibers and steel wires was achieved and obtained pronounced hybrid mechanical behavior [19,20]. By adopting hybrid B/SFRP for stay cables, relatively high stiffness of the cable can be maintained while also further lowering the cost from the hybrid B/CFRP cable. Meanwhile, a small proportion of steel wires (20–30%) will not increase the sag effect apparently, due to the overall light weight and the elimination of steel corrosion can be achieved by covering with basalt fibers and a matrix. Therefore, the potentially suitable cables for super long-span bridges, including these two types of hybrid FRP cable along with CFRP and BFRP, are all investigated in this study of their suitability in different lengths of spans, while conventional steel cables served as the reference point.

It was revealed in previous studies that the essential difference in static performance of cable-stayed bridges with different kinds of cables lay in their different equivalent modulus of cable, caused by the sag effect [10–12], and that different safety factors will greatly affect the equivalent modulus and the corresponding equivalent stiffness. Therefore, in this paper, the characteristic of equivalent modulus and stiffness of different cables will be thoroughly studied for main spans from 1000 m to 10,000 m, from which a safety factor model will be proposed for different cables. Given the proposed safety factors and the derived equation of stiffness utilization efficiency, the applicable lengths for different kinds of cables will be evaluated. Finally, a comparison of relative cost among different kinds of cables within 3000 m span will be conducted for guiding practical application of FRP cables.

2. Material properties

The mechanical properties of conventional high strength (HS) steel, CFRP, BFRP, and corresponding hybrid B/CFRP and B/SFRP sheets, which are used in this paper, are listed in Table 1, in which the data for HS steel, CFRP, and BFRP sheets is provided by the manufacturers [21,22], while the data for hybrid B/SFRP and B/CFRP sheets is calculated by the composite hybridization principle [20], which were also validated by tests [19,23] according to JSCE-E 541 [24]. Because the tensile strength of FRP composites is only determined by the strength of fibers instead of matrix [20], the strength of FRP sheets excluding the fraction of matrix can represent essential material strength of a certain FRP composite. Thus, for different kinds of FRP cables, the mechanical properties of corresponding FRP sheets are adopted in this study. For hybrid B/CFRP, the fracture strain of carbon fibers controls the entire tensile strength of hybrid FRP, while for hybrid B/SFRP the fracture strain of basalt fibers controls the entire tensile strength of hybrid FRP.

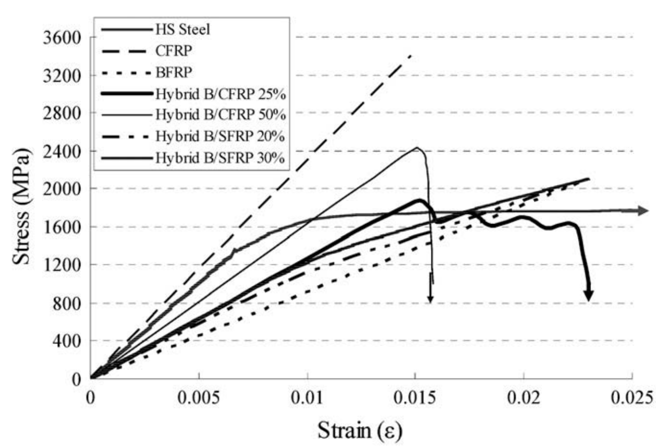

Fig. 1. Stress–strain relationship of different cable materials.

Table 1
Mechanical properties of different cable materials.

Type	Density (kg/m^3)	Tensile strength (MPa)	Elastic modulus (GPa)	Failure elongation (%)	Data source remarks
HS steel	7800	1770	200*	>3.50	Provided by [21]
CFRP	1800	3400	230	1.48	Provided by [21]
BFRP	2650	2100	91	2.30	Provided by [22]
B/CFRP 25%	2438	1860	126	2.30	Calculated according to [23]
B/CFRP 50%	2225	2383	161	1.48	
B/SFRP 20%	3680	2100	113*	2.30	Calculated according to [19]
B/SFRP 30%	4195	2100	124*	2.30	

* The modulus before first yielding of steel wires.