DESIGN CONSIDERATIONS OF FRP STAY CABLE FOR EXTRA LONG SPAN CABLE-STAYED BRIDGE

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Introduction

FRP materials are regarded as idealized choices for long-span cable supported bridge due to their extremely high strength to weight ratio and superior chemical behavior in comparison with conventional high-strength steel wires/stands cables[1-2]. CFRP stay cables have been studied in large-span cable-stayed bridge; however, they are limited by the high-cost and potential aerodynamic instability. To overcome these limitations and achieve integrated high performance, hybridizing basalt FRP and carbon FRP (B/CFRP) or high strength steel wires (B/SFRP) are suggested to be possible solutions. The objectives of hybridization lies in three aspects: the first is to achieve sufficient mechanical and chemical performance for stay cables; the second is to lower overall cost through decreasing or excluding the use of carbon fibers; and the last is to increase internal damping by interacting of two materials of the cable. In terms of above ideas, the design considerations of hybrid FRP cables will be summarized from two aspects: static and aerodynamic considerations, which are developed on the basis of the previous studies [3-4].

Static consideration

Material properties

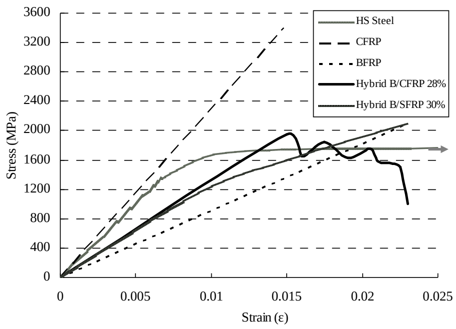


Figure 1 Stress-strain relationship of different materials

Basalt FRP hybridized with CFRP or high-strength steel wires can effectively improve their entire modulus that contributes to higher efficiency of material utilization. Meanwhile, hybrid B/CFRP cables exhibit nonlinearity at the high stress stage that can be regarded as safety storage under some ultimate conditions.

Accuracy of equivalent modulus

Due to the existing of sag effect caused by self-weight, the relationship between cable force and elongation exhibits nonlinearity. For convenience, the equivalent tangent or secant modulus in stead of accurate modulus by centenary equation are often adopted to represent reduced modulus [5]. However, tangent modulus can achieve adequate accuracy (5%) only within 1000 m span (Fig.1). Thus, secant modulus is adopted to evaluate cable behavior in longer span bridge (Eq.1).

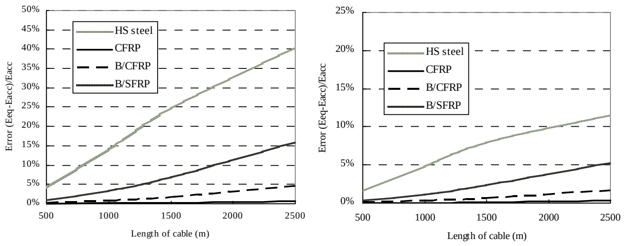


Figure 2 Error in equivalent modulus with respect to length of cable

Efficiency of material utilization

$$\frac{E_{sec}}{E}=\frac{1}{1+\lambda^2/12} \quad \text{and} \quad \frac{K}{K_{max}}=\frac{\sqrt[3]{36\lambda^2}}{4\left(1+\lambda^2/12\right)} \qquad (1)$$

where $\lambda^2=\frac{\gamma_{cb}^2 a^2 E}{2\sigma_2^3}\left(\frac{1+k}{k^2}\right)$

K is the stiffness of cable by multiplying Esec and sectional area A, and the other denotations in Eq. (1) are referred to [6]. The ratio of equivalent modulus to initial modulus that is inversely proportional to λ^2 (introduced by Irvine [7]) represents the cable's efficiency of handling external load. The ratio of cable stiffness K to maximum cable stiffness Kmax is also only dependent on λ^2. Considering the deficiency of modulus for hybrid FRP cable, strength and stiffness ratios are needed to evaluate simultaneously in order to achieve integrated high performance in long-span bridge. Fig. 3 reveals that when λ^2 approximately equals to 1.7, both high ratios of E/E0 and K/Kmax can be obtained. Thus, we define this λ^2 as a critical value for optimizing efficiency of cables.

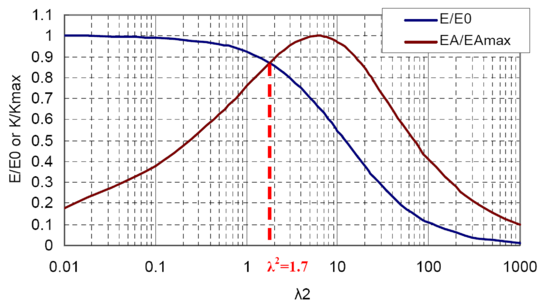


Figure 3 E/E0 and K/Kmax with respect to λ^2

In terms of the critical λ^2, the evaluation of optimized lengths for different cables is shown in Fig.4 that indicates 700m, 1650m, 2550m and 5800m are the critical lengths for steel, B/SFRP, B/CFRP and CFRP cables respectively. These lengths of cables can be referred for determining a type of cables for certain span of bridges, or for arranging different kinds of cable materials in a super-long cable-stayed bridge.

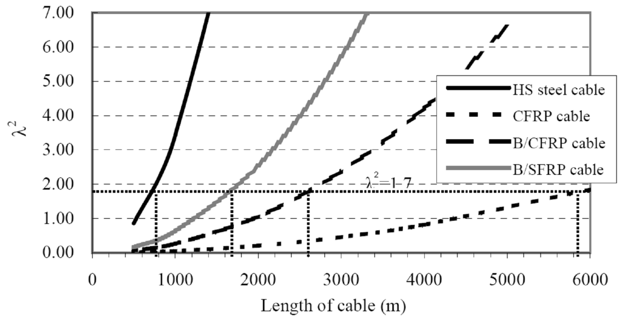


Figure 4 Evaluation of critical length of span

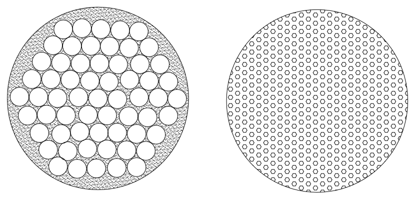
Aerodynamic consideration

Aerodynamic stability

$$S_c = \frac{2\delta m_e}{\rho D^2} \quad (2)$$

The denotations in Eq. (2) are referred to [6]. Scruton number (S_c) is usually adopted to evaluate aerodynamic stability of stay cable subjected to wind-induced vibration. It was reported that the vibration can be avoided when S_c is larger than 20, whereas the risk of vibration will be vey high when S_c is below 10 [7].
For a main span of 1000 m, S_c of the longest CFRP cable lies in the range below 10, while S_c of hybrid B/CFRP is also insufficient (>10 but<20). Therefore, two methods, entire pultrution technology and self-damping arrangement of hybrid FRP cable, are proposed to improve their S_c in terms of FRP's special constitution.

Entire pultrution



(a) Common cable (b) Entire pultruded cable
Figure 4 Constitution of cables

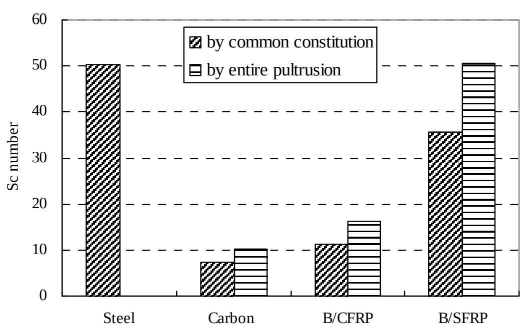


Figure 5 S_c of cables with and without entire pultusion

The steel cable consisted of individual steel wires can only achieve a maximum 74% of packing efficiency. For FRP, pultrusion technology that allows fiber roving form entire cable directly can conveniently produce any profiles with a 100% packing efficiency (Fig. 4). By this technology, S_c can be improved due to the decreased volume of cable, as shown in Fig.5.

Self-damping design

Although entire pultrusion can improve S_c, it is still inadequate for some cable like B/CFRP cable. Focusing on the essential reason of vibration, a special design on improving internal damping is conducted by separately arranging two kinds of materials in the cable, as shown in Fig.6. This design requires two kinds of wires separately arranged inside the cable and inserting a viscoelastic material in the gap, through which the vibrational energy can be absorbed due to the inherently different vibrational characteristics of the two materials.

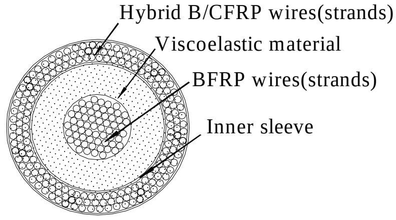


Figure 6 Design of self-damping hybrid FRP cable

Conclusions

Hybrid B/CFRP and B/SFRP cables are proposed to obtain integrated high performance in extra long span cable-stayed bridges. Sufficient accuracy of cable equivalent modulus within 2500 m length can be calculated by secant modulus, in terms of which the critical lengths for different cables are suggested. Moreover, two methods on improving aerodynamic stability are proposed on the basis of special arrangement of two materials in hybrid FRP cable.

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