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In-plane modal frequencies and mode shapes of two stay cables interconnected by uniformly distributed cross-ties

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ABSTRACT

Stay cables are important load-bearing structural elements of cable-stayed bridges. Suppressing the large vibrations of the stay cables under the external excitations is of worldwide concern for the bridge engineers and researchers. Over the past decade, the use of crosstie has become one of the most practical and effective methods. Extensive research has led to a better understanding of the mechanics of cable networks, and the effects of different parameters, such as length ratio, mass-tension ratio, and segment ratio on the effectiveness of the crosstie have been investigated. In this study, uniformly distributed elastic crossties serve to replace the traditional single, or several cross-ties, aiming to delay "mode localization." A numerical method is developed by replacing the uniformly distributed, discrete elastic cross-tie model with an equivalent, continuously distributed, elastic cross-tie model in order to calculate the modal frequencies and mode shapes of the cable-crosstie system. The effectiveness of the proposed method is verified by comparing the elicited results with those obtained using the previous method. The uniformly distributed elastic cross-ties are shown to significantly delay "mode localization."

1. Introduction

Stay cables on bridges have the inherent characteristics of low damping and great flexibility. They are prone to large vibrations under external excitations, such as the wind [1–4], rain and wind [5–13], and anchorage motion [14,15]. These large vibrations may have severe effects on stay cables. Many researchers and engineers have expended considerable efforts to suppress these undesirable cable vibrations. Several aerodynamic [6,16,17] and mechanical methods [18–20] were proposed and successfully applied on stay cables. One of them is the use of cross-ties [19,21–37], which has become increasingly popular over the past decade. The cross-tie links the main stay cables together to form a complex cable system. This strategy enhances in-plane stiffness, increases modal mass in comparison with the mass of an isolated-cable vibrating system, and redistributes energy [22], and thus improves cable stability. Extensive research studies investigated the mechanics of cross-ties using physical experiments, finite element method simulations, and analytical methods.

Yamaguchi and Nagahawatta [21] experimentally investigated the modal frequency, shape, and damping of a cable network, consisting of two stay cables and two cross-ties, and proposed an energy-based method for evaluating the damping

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ratio of this system. They concluded that cross-ties could increase the damping ratio of the network, and their use was more effective when more flexible and more energy-dissipative cross-ties were used. Yamaguchi and Alauddin [22] further studied the nonlinearity effect of the cross-tie on the free vibration of the main cables. They reported that the nonlinearity of the cross-tie induced multiharmonic and multimodal vibrations. Sun et al. [23] experimentally investigated the effect of cross-tie stiffness on the in-plane stiffness and damping of the network. They noted that a stiffer cross-tie contributed more in enhancing the in-plane stiffness, whereas a softer one was more effective in increasing the damping ratio.

The experimental results were supported and supplemented by analytical and FEM studies. Caracoglia and Jones [19,24] developed an analytical procedure on the basis of the taut cable theory to resolve the in-plane, free vibration of the cable network. They derived the closed-form solutions for the in-plane free vibration of two cables that were interconnected by a single cross-tie, and the numerical solutions for the in-plane free vibration of multiple cables that were interconnected by multiple cross-ties. Caracoglia and Jones [25] analyzed the effectiveness of the hybrid method combining cross-ties and dampers through numerical simulations. They pointed out that adding in-plane dampers could enhance the damping of the global in-plane modes of the network, whereas the localized mode vibration was still difficult to suppress. These results were verified in full-scale measurements by Caracoglia and Zuo [26]. Zhou et al. [27,28] analytically investigated the combination effects of cross-ties and dampers on the cable network. They concluded that the damping of the system was related to the cross-tie location and the mode shapes, and that local mode vibrations could occur when only a single cross-tie is used.

Giaccu and Caracoglia [29–32] further developed an analytical method by considering the nonlinearities of a cross-tie, that is, the imperfect transfer of a restoring force (slackening, snapping, or pre-tension loss), and the stochastic nature of the network caused by the stochastic initial condition. They concluded that the free vibration dynamics of the cable network was significantly affected by the nonlinear cross-tie behavior, and its combination with stochastic initial vibration amplitude. The performance of the cross-tie degraded by more than 50% at several network modes, even though the equivalent frequency was reduced by only 10–15% in the nonlinear model [31]. When the stochastic characteristics were considered, the mean value of the cross-tie performance varied, even under the same level of nonlinearity, according to the tension in the cables and the pretension in the cross-tie [32].

Ahmad et al. [33] extended the linear analytical procedure by considering the inherent damping of the stay cables, and conducted a series of comprehensive parametric studies. The key parameters of the cable network were identified as the length ratio, mass ratio, mass–tension ratio, and frequency ratio, and the number of cross-ties and stay cables, and their effects on the free vibration of the cable network, were investigated in detail [34–37]. In addition, they proposed a new parameter, degree of mode localization (DML), to evaluate the global nature of the single mode of the cable network, and suggested the use of softer but more cross-ties to avoid or delay the local mode.

Through these studies, the mechanics of the cable network with single or several individual cross-ties were revealed, and the effects of different parameters, such as the length ratio, mass–tension ratio, and segment ratio, on the effectiveness of the cross-tie have been investigated in detail. However, the cable network with a single or a few cross-ties (equal to, or less than four cross-ties) may yield potential deficiencies in local modal vibrations [26,36], while the bridge aesthetics may also be considerably affected by the increased number of the cross-ties [38].

This study proposes the replacement of single, or several individual, large-sized cross-ties with numerous smaller-sized elastic cross-ties that are uniformly distributed along the longitudinal direction, aiming to delay “mode localization.” A numerical procedure has been developed by replacing the uniformly distributed, discrete elastic cross-tie model with an equivalent continuously distributed elastic cross-tie model on the basis of the previous method proposed by Caracoglia and Jones [19]. The proposed numerical method was verified to be effective for solving the free vibration of the cable network system. The uniformly distributed elastic cross-tie scheme significantly delayed “mode localization.” Although the practical implementation of this strategy is more difficult compared to the conventional strategy employing single or several cross-ties, we believe that it would become much easier and applicable in view of the anticipated rapid development of robotic technology in the future.

2. General problem formulations

Two stay cables linked by numerous, uniformly distributed, small elastic cross-ties (UDSEC), can be simplified as two horizontally laid taut cables segmentally connected by distributed springs, as shown in Fig. 1. The upper cable is assumed to be the target cable (cable 1), which is prone to vibration under the external loads, whereas the lower one is regarded as its neighboring cable (cable 2). The two cables have different lengths, L_1 and L_2, mass-per-unit lengths, m_1 and m_2, and pretensions in the horizontal directions, T_1 and T_2. Therefore, ΔL is the horizontal offset between the target cable and its neighboring cable. Both cables are fixed at both ends, and four nodes ($\mathrm{P_I}, \quad \mathrm{I}=1,2,3,4$) separate the two stay cables into six segments. The segments are referred to as elements *j*-*p*, where *j* is the *j*th cable, and *p* is the *p*th segment of each cable. The length of the element *j*-*p* is denoted by $L_{j,p}$. The displacement of element *j*-*p* is defined as $v_{j,p}$ according to the subcoordinate $x_{j,p}$ (Fig. 1). The two central segments, $\mathrm{P_1}$ to $\mathrm{P_3}$ and $\mathrm{P_2}$ to $\mathrm{P_4}$ are orthogonally connected by elastic cross-ties. Successive cross-ties are separated by a distance interval l. The stiffness of each elastic cross-tie is defined as k_e. For the elements on the right side ($L_{1,3}$ and $L_{2,3}$), the *x*-coordinates originate from the right ends through which the unknown parameters in the mode shape function could be reduced.

The stay cables are idealized as two taut cables because upon practical use on real cable-stayed bridges they are highly prestressed compared with their mass and elastic stiffness [39]. They are extensible in the longitudinal direction, but the