Structural behavior of suspension bridge with a stabilizing cable

Anatoliy Konovalov¹, Marina Pustovalova^{2*}

¹Structural Mechanics and Strength of Materials Department, Head of Department

²Structural Mechanics and Strength of Materials Department, Northern (Arctic) Federal University named after M.V. Lomonosov, Arhangelsk, Russia

Abstract. Suspended structures are commonly used in construction of motorway and pedestrian bridges. These structures allow wide spans without the need for intermediate supports. Suspension bridges are noted for lower structural stiffness as compared to beam bridges and arc bridges. The stiffness control depending on the environment and external effects (moving loads, wind, seismic forces, etc.) is a real-life challenge [1, 2]. The authors of this paper have evaluated the use of stabilizing cable installed in the central span under the stiffening girder as the means of stiffness control. A plane 3D model of a suspension bridge was developed using the ANSYS software. The study compared the stress deformed state and dynamic properties of the models with and without a stabilizing cable. The displacement in the model equipped with a stabilizing cable, as compared to the one without, was noted to be lower in all relevant sections: 2.6 times in the middle of the central span of the stiffening girder; 15 times in the middle of the end span; and displacement of the tower top was 3.5 times lower.

1 Structural design

This paper presents the structural design of a suspension bridge as referenced to the actual location of proposed bridge across the Northern Dvina River in Arkhangelsk [3]. The 3D plane finite element model was built using ANSYS software. It is a full-scale model with the end spans of 200 m and the central span of 450 m. The tower height was 90 meters including 30 meters of the bridge height. The height of the tower from the stiffening girder to the tower top was 60 m.

Each tower comprised a box section with the stiffness expressed as $EA_t = 1.907E+5$ MN, $EI_{max_t} = 1.7E+6 \text{ MN}\cdot\text{m}^2$, $EI_{min_t} = 5.8E+5 \text{ MN}\cdot\text{m}^2$. The tower was rigidly bonded to the ground and was a continuous structure.

The steel stiffness girder was a closed box-type structure [1] with the stiffness expressed as $EA_g = 5.4E+5$ MN, $EI_{max_g} = 5E+7 \text{ MN}\cdot\text{m}^2$, $EI_{min_g} = 2E+6 \text{ MN}\cdot\text{m}^2$. The stiffness girder rested on the ground though a hinged immovable support on one side, and through a hinged movable support on the other side.

The main cable was assumed with a stiffness of $EA_c = 2.1E+5$ MN, and was fixed to independent anchors independently from the girder. The main cable was a continuous structure having no rigid ties with the towers. Stay cables were assumed to have the

* Corresponding author: m.pustovalova@narfu.ru

stiffness expressed as $EA_s= 5.3E+4$ MN, and were pin-jointed to the main cable and to the girder. In the middle third of the central span, stay cables had crosswise configuration with 10 m spacing; and vertical configuration with the same spacing in the rest of the model. The stabilizing cable with the stiffness equal to that of the main cable was fixed by means of parallel vertical suspension cables (hangers) in the central span under the stiffening girder (fig. 1).

Fig. 1. The schematic structural design of 3D plane FE model of suspension bridge with a stabilizing cable.

2 Comparative analysis of stress deformed state

The comparative analysis of the stress deformed state between the model of the bridge equipped with a stabilizing cable and the model of the bridge without a stabilizing cable (initial model) caused by the dead-load is presented below in Table 1.

As shown in Table 1, tensile axial forces in the main cable of the model equipped with a stabilizing cable are 36% lower, than in the model which lacks a stabilizing cable, all other conditions being equal. In the stiffening girder, the axial forces are compressive throughout the entire length of the girder. In the middle of the central span, these forces are of the same order of magnitude as in the model discussed above, but their direction has changed. In the model with a stabilizing cable, the axial forces have appeared to be 5.4 times less than in the model without the stabilizer.

Table 1. The axial forces and displacements in compared models.

Parameter	The model without a stabilizing cable (initial)	The model with a stabilizing cable
The axial forces in the main cable, $\times 10^8$ N	1,741	1,11
The axial forces in the stiffening girder in the middle of the span, $\times 10^8$ N	0,430	0,697
The axial forces in the stiffening girder near the tower, $\times 10^8$ N	-0,291	-0,054
Deflection in the middle of the central span, m	2,030	0,772

Deflection in the middle of the end span, m	0,724	0,046
Displacement of the tower top, m	0,457	0,130

2.1 The Main Cable and Stabilizing Cable Pre-Stressing

A change in simultaneous tension of the main cable and the stabilizing cable from zero to the final value of $1.3 \cdot 10^8$ N results in a 42% increase of the axial tensile force in the main cable. There is almost no change of the axial forces in the stiffening girder near the tower. In the middle of the central span of the girder pre-stressed to $1.04 \cdot 10^8$ N, the internal axial forces are compressive, and show only a slight change in response to increasing force. Yet, once pre-stressed force of $1.3 \cdot 10^8$ N is achieved, the tensile force of the same order of magnitude occurs in the middle section (fig. 2).

Fig. 2. The influence of the main cable and stabilizing cable pre-stressing on the axial forces.

Fig. 3. The influence the main cable and stabilizing cable pre-stressing on displacement.

2 Modal Analysis

The use of ANSYS system allows displaying a wide range of natural vibrations and identifying the influence of the structural design on the model’s behavior. Table 2 contains the natural vibration frequencies of the fundamental period output by the initial model and the model with a stabilizing cable.

Table 2. The natural vibration frequencies of the compared models.

Parameter	The model without a stabilizing cable (initial)	The model with a stabilizing cable
Transverse vibrations frequency, Hz	0,251	0,156
Vertical vibrations frequency, Hz	0,254	0,497
Torsional vibrations frequency, Hz	0, 251	0,282

The modal analysis has shown the model with a stabilizing cable to have the frequency of transverse vibrations (see fig. 4, mode 3) 1.6 times lower than a similar model without the stabilizer. At the same time, the frequency of vertical vibrations has increased two fold (see fig. 4, mode 10), while torsional vibrations showed a 6% increase (fig. 4, mode 4). The natural vibration frequencies of the fundamental period have changed in magnitude and direction as compared to the initial model without a stabilizing cable.

Fig. 4. The modal analysis of suspension bridge with a stabilizing cable – modes 3, 4, and 10.

The modal analysis of a suspension bridge with simultaneous stressing of the main and stabilizing cables results in the change of the natural vibration frequency of the fundamental period both in values (fig. 5) and directions of vibrations. As pre-stressing force increases to $0.52 \cdot [10]^8$ N, the first shear mode of vibrations disappears to be replaced by other modes, while the primary mode of vertical vibrations is shifted in the spectrum and corresponds to mode 10. An increase of pre-stressing force eliminates torsional vibrations (fig. 5), but new combined modes of vibrations emerge instead.

As pre-stressing force continues to increase, vertical vibrations move to position 12 with almost no change to the frequency. Figure 6 shows the spectrum of vibration modes of the stabilized suspension bridge model after simultaneous pre-stressing of the main cable and stabilizing cable to force $1.3 \cdot 10^8$ N.

Fig. 5. The influence of the main cable and stabilizing cable pre-stressing on the frequencies of natural vibrations.

Fig. 6. Vibration modes 1-12, pre-stressing of the main cable and stabilizing cable to $1.3 \cdot 10^8$ N

3 Summary

The use of a stabilizing cable in a combined suspension bridge reduced the displacement in all relevant sections: 2.6 times in the middle of the central span of the stiffening girder; 15 times in the middle of the end span, 3.5 times in the tower top; and also changes the behavior of natural vibrations. The main frequencies of natural vibrations having effect on the design analysis of suspension bridges move in the spectrum. While the main modes of vibrations are dampened, new combined vibration modes emerge having no effect on the structural behavior of the bridge. From the engineering standpoint, the use of a stabilizing cable appears to be an advantageous tool for controlling vibrations by pre-tensioning of the main cable and the stabilizing cable.

References

1. N.P. Abovsky, Upravlyaemye konstruktsii/ N.P. Abovskiy – SAU NDS. KISI, Krasnoyarsk., - p.125 (1995)
2. A.S. Dorogan, Raspornye visyachie mosty povyshennoi zhyostkosti // Stroitel'naya mekhanika i raschyot sooruzheniy, 4, p. 4-10 (2011)
3. A. Yu. Kononov, M.A. Pustovalova, Vliyaniye usloviy zakrepleniya nesuschego kabelya i orientatsii vant na napryazhionno deformirovannoye sostoyaniye visyachego mosta // NAUKA, OBRAZOVANIE I INNOVATSII: collection of articles of the International Conference and Workshop (October 15, 2016. Ekaterinburg). 3 volumes, vol. 2/ - Ekaterinburg: AETERNA, p. 31-34 (2016)