Investigation of Critical Wind Speed of Suspension Bridges with Multiple Main Cables

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Abstract: This paper investigated the critical wind velocity of long-span suspension bridges with multiple main cables. It should be noted here that due to the inherent flexibility of long-span bridges, self-excited forces play a role in the overall stiffness and damping of the structure, making them wind speed dependent. This characteristic is modelled through the flutter derivatives, which show a range of values for each mode. A comparative study has been conducted three virtual suspension bridges, first one with two central spans of 1500 m and a navigation clearance of 152 m; the second one with a central span of 1500 m and a navigation clearance of 152 m; the third one with a central span of 2100m and a navigation clearance of 90 m.

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1. Introduction

With the increasing central span length of modern cable-supported bridges, the trend of the bridge is to use more shallow and slender stiffening girders to meet the requirements of aerodynamics. In this case, bridge safety (strength, stiffness, and stability) under service loadings and environmental dynamic loadings (such as impacts, winds, and earthquakes) present's increasingly important concerns in both design and construction.

Studying the history of bridge failure concluded clearly that aerodynamic instabilities are the main reason of bridge failure, where their effects were catastrophic, as occurred with Brighton Chain Pier suspension Bridge, England 1836 and Tacoma Narrows Suspension Bridge, Washington State 1940.

To avoid undesirable movements, aeroelastic verification has been adopted as a usual procedure in modern flexible bridge design, self excited forces play a role in the overall stiffness and damping of the structure, making them wind-speed dependent. This catachrestic is modelled through the flutter derivative.

Flutter instability is one of the most important types of aerodynamic instabilities. Increasing lateral stability using additional stabilizing technique could increase the flutter critical wind speed of long-span cable-supported bridges.

Flutter Critical Wind Speed

The Selberg formula is generally applied as the method that the flutter critical wind velocity is estimated at easy. This formula is expressed as Equation:

$$U_{cr} = 3.71 \cdot f_{\phi^\circ} \cdot B \cdot (\frac{m \cdot r}{\rho \cdot B^3} \cdot (1 - (\frac{f_{\eta^\circ}}{f_{\phi^\circ}})^2)^{1/2} \qquad (1)$$

Where,

$$r = \sqrt{\frac{I}{m}} \qquad (2)$$

Where,

Ucr	is the flutter critical wind velocity,
fΦ° = fT	is the torsional natural characteristic frequency,
fη° = fB	is the heaving (Vertical or Flexural) natural characteristic frequency,
fΦ°/fη°	is the torsional / heaving characteristic number of frequency ratio,
B	is the full chord length,
m	is the mass per unit length,
r	is the radius of gyration, and
I	is the mass inertia per unit length.

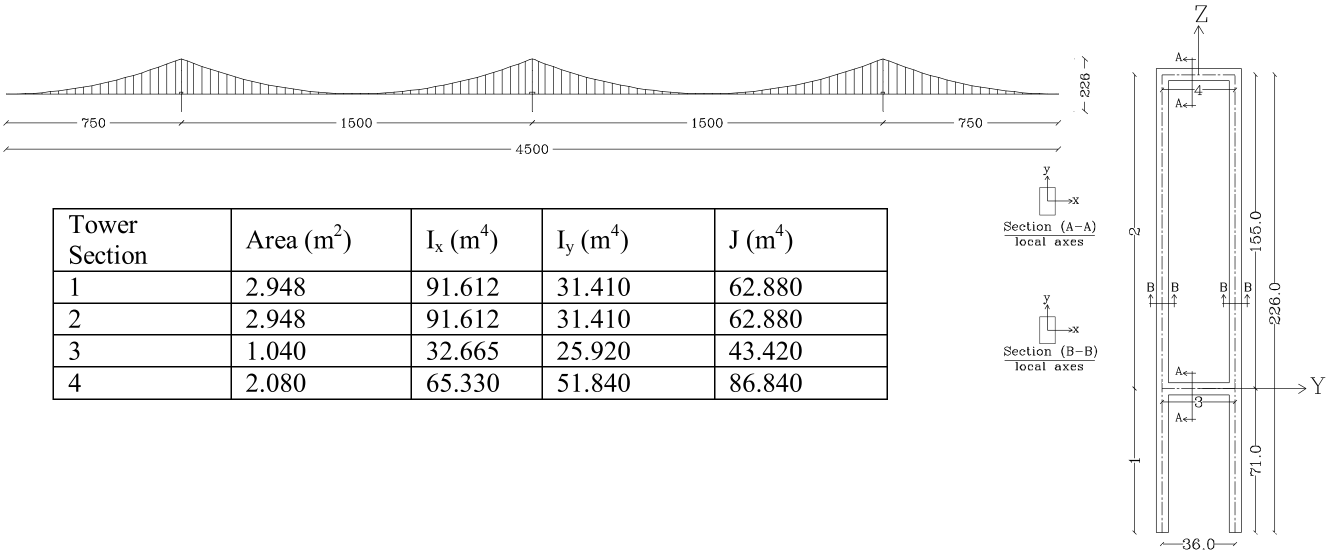
This formula is adjusted about the influence of sections forms and characteristics of vibrations based on the findings of many wind tunnel experiences. A compensation coefficient is adopted toward the bluff sections seen by actual structures. Since various section forms are developed for their sake in the stability toward the wind in recent years, it is doubt that this formula is applied for them. The flutter critical velocity of two-dimensional plate given by this formula was compared with the one obtained from the eigen value analysis.

Configuration Of The Basic Bridges Studied Case

In the earth anchored suspension bridge the main cable is in most cases supported at four points: at each anchor block and on the two pylons. The supporting points at the anchor blocks can generally be assumed to be completely fixed, whereas the supporting points at the pylon tops are often represented best by longitudinally movable bearings (due to the horizontal flexibility of the slender pylon legs).

The geometry of the cable system in the dead load condition is determined by assuming that the stiffening girder and the pylons are moment free, so that the cable curve coincides with the funicular curve of the total dead load.

The considered suspension bridges selected for this study are virtual bridges, first one is four spans with central span 1500m, the second one is three spans with central span 1500m, and the third one is three spans with central span 2100m.



Tower Section	Area (m^2)	I$_x$ (m^4)	I$_y$ (m^4)	J (m^4)
1	2.948	91.612	31.410	62.880
2	2.948	91.612	31.410	62.880
3	1.040	32.665	25.920	43.420
4	2.080	65.330	51.840	86.840

Fig. 1: Four Spans Suspension Bridge Layout – Two Central Spans 1500m Each

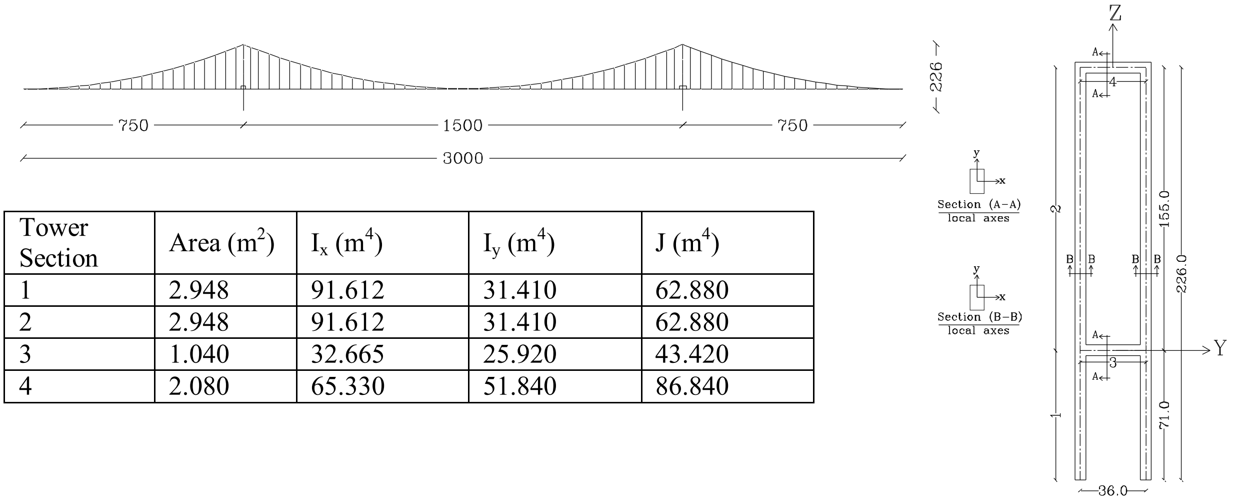


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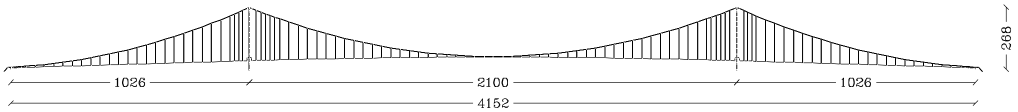
Fig. 2: Three Spans Suspension Bridge Layout - Central Span 1500m



Tower Section	Area (m^2)	I_x (m^4)	I_y (m^4)	J (m^4)
1	5.069	202.960	46.290	69.250
2	5.349	187.300	45.040	66.380
3	5.223	171.050	43.759	63.410
4	5.114	160.410	42.779	61.190
5	4.867	136.919	40.569	56.150
6	4.522	109.470	37.529	49.590
7	4.053	86.040	33.479	42.350
8	3.052	64.839	28.780	34.810
9	0.694	3.170	16.450	7.730
10	0.396	1.730	2.269	2.950
11	0.360	1.059	1.940	2.070

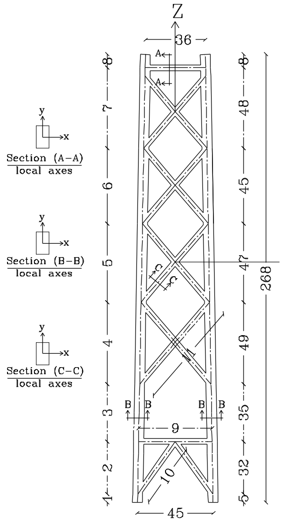


Fig. 3: Three Spans Suspension Bridge Layout - Central Span 2100m

Comparative Models

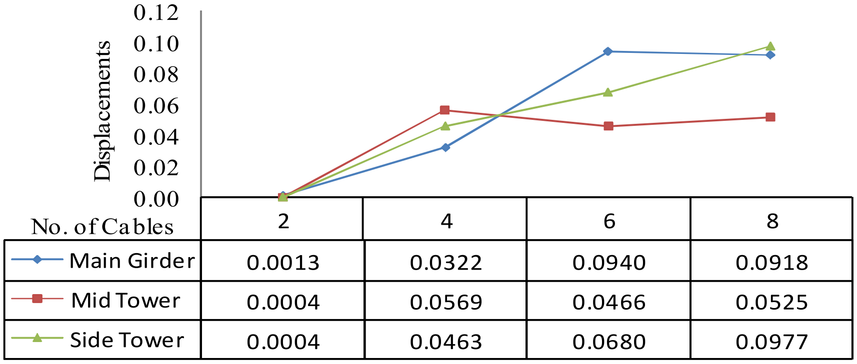
In order to evaluate the effect of the multiple main cables on the critical wind velocity of long-span suspension bridges a comparative study has been conducted for four situations. The first was the original basic bridge, which did not have any additional main cables. The second was the basic bridge with one additional main cable per side. The third was the basic bridge with two additional main cables per side. The fourth was the basic bridge with three additional main cables per side. Then, Selberg formula was applied to determine the flutter critical wind velocity for each model in case of each studied bridge, which consists twelve models.

The studied twelve models were chosen to illustrate possible arrangements for the multiple main cables. The natural frequencies corresponding to different vibration models were estimated for each model and result were compared to recommend the optimum layout for increasing the critical wind speed such kind of bridges. The displacements corresponding to arrangement for the multiple main cables were estimated and results were compared to recommend the optimum solution for decreasing the displacement of such kind of bridges.

Effect of Using Multiple Main Cables

It should be noted here that due to the inherent flexibility of long-span bridges, self-excited forces play a role in the overall stiffness and damping of the structure making them wind-speed dependent. This characteristic is modelled through the flutter derivatives, the effect of which can be seen in histograms of modal frequencies, which show a range of values for each mode.

A comparative study has been conducted for the three basic bridges, for evaluation of the effect of the of the multiple main cables on the improvement of flutter critical wind velocity and the displacements of the bridge girder with respect to the increase of the bridge span.



No. of Cables	2	4	6	8
Main Girder	0.0013	0.0322	0.0940	0.0918
Mid Tower	0.0004	0.0569	0.0466	0.0525
Side Tower	0.0004	0.0463	0.0680	0.0977

Fig. 4: Displacement of The First Basic Bridge

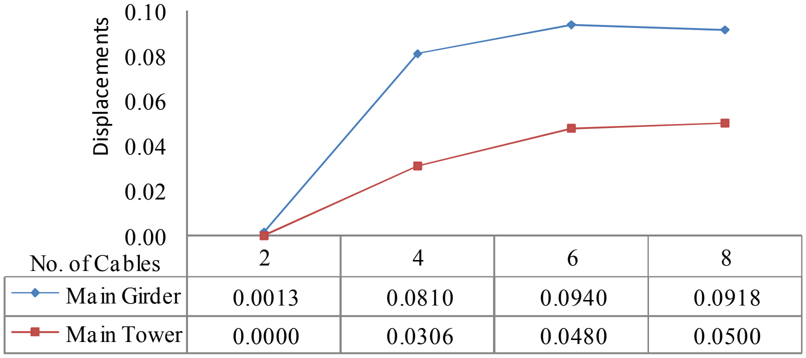


Fig. 5: Displacement of The Second Basic Bridge

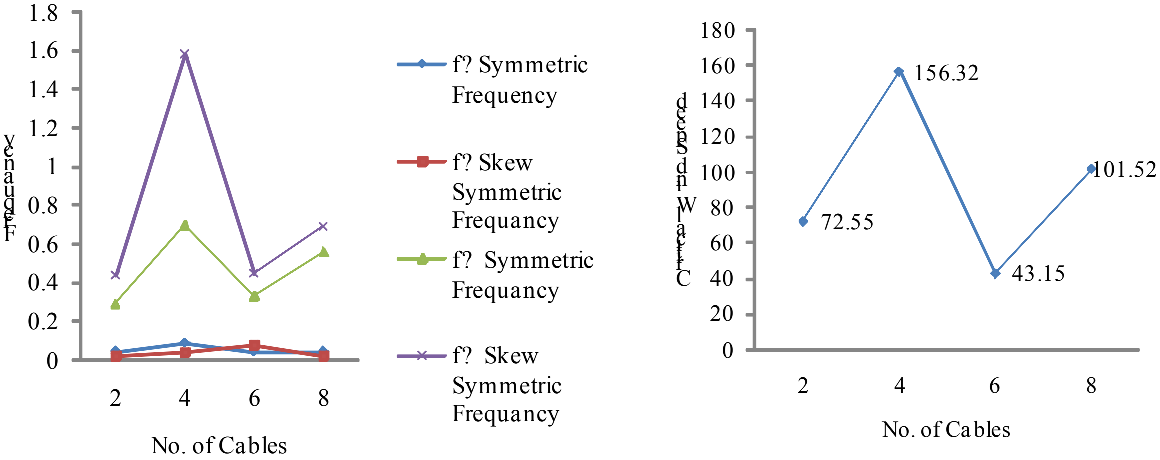


Fig. 7: Relation between No. Of Cables, Frequency, and Critical Wind Velocity – First Basic Bridge

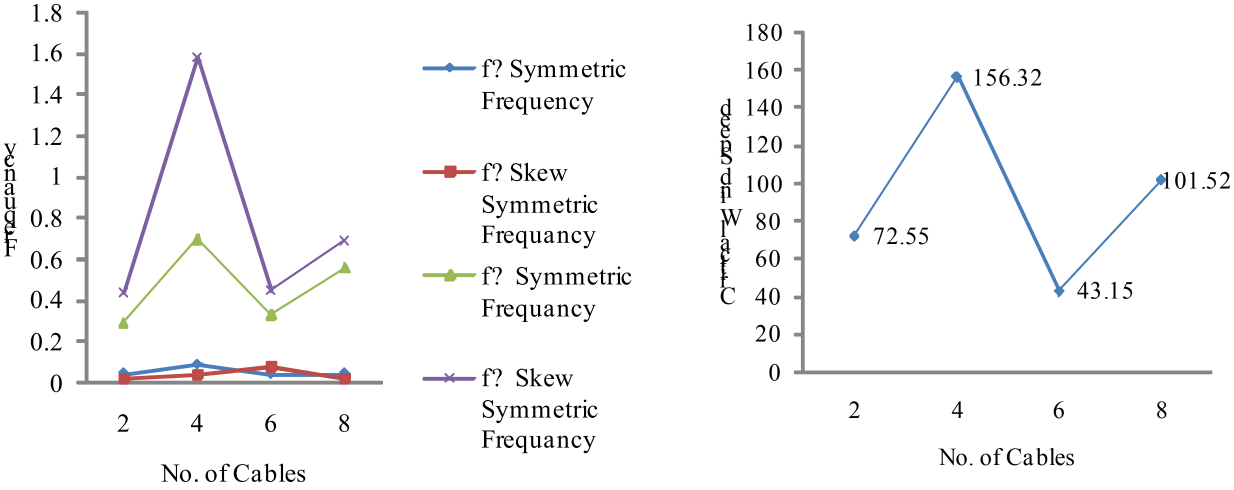


Fig. 8: Relation between No. Of Cables, Frequency, and Critical Wind Velocity – Second Basic Bridge

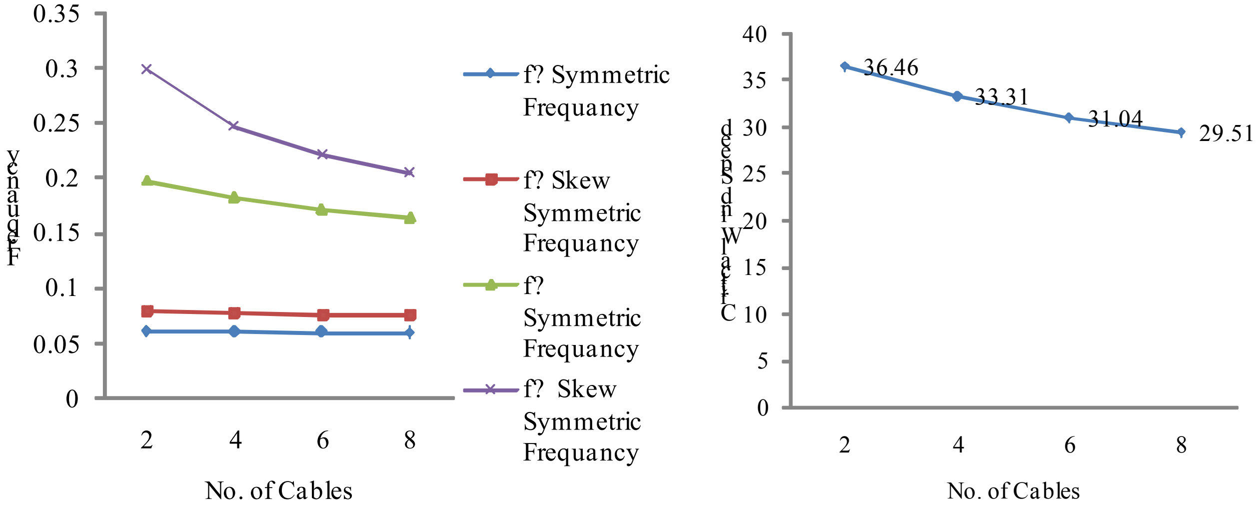


Fig. 9: Relation between No. Of Cables, Frequency, and Critical Wind Velocity – Third Basic Bridge

Conclusions

Based on the comparative results, the following conclusion can be drawn as follows:

1. Using one main cable in each side gives minimum displacement in towers and in bridge deck, for first and second bridge, while for third bridge using four main cables in each side gives minimum displacement in the bridge deck only.
2. By increasing the number of main cables give more displacement in towers and bridge deck, (in some cases displacements are approximately equal for bridges with two, three, and four main cables in each side).
3. Using two main cables per side is significant in improving flutter instability in case of three and four bays suspension bridges with moderate central spans up to 1500 meters.
4. Using multiple main cables in case of three bays suspension bridge with moderate central span 2100 meters, the wind velocities are approximately equal and give its maximum critical value for case of suspension bridge with one cable in each side.
5. For first basic bridge:
   a) Three main cables in each side give good influence on the symmetrical and skew-symmetrical flexural frequencies.
   b) Two main cables in each side give good influence on the symmetrical and skew-symmetrical torsional frequencies.
6. For second basic bridge:
   a) Two main cables in each side give good influence in case of symmetrical flexural, symmetrical torsional, and skew-symmetrical torsional frequencies.
   b) Three main cables in each side give good influence in case of skew-symmetrical flexural frequency.
7. For third basic bridge, using one main cable in each side gives good influence on the symmetrical and skew-symmetrical flexural and torsional frequencies.

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