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Buffeting Response of Cable-stayed Bridge under Skew Wind

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ABSTRACT

In order to refine the studies of static wind load on the deck of cable-stayed bridge under skew wind, a full bridge 'aero-stiff' model technique was used to identify the aerostatic loads on each deck segment, in smooth oncoming flow, with various yaw angles. the experimental results indicated that the shelter effect of the pylon may not be ignored, which can amplify the aerostatic loading on the bridge deck under skew winds (10º-30º) with certain wind attack angles, and consequently results in the "cosine rule" becoming invalid for the buffeting estimation of cable-stayed bridge for these wind directions. Based on this study, the buffeting response of cable-stayed bridge under skew wind is investigated by taking the pylon's shelter effect into consideration. The results shown that pylon's shelter effect may not be accounted for the larger buffeting response of cable-stayed bridge under skew wind usually measured in wind tunnel test, and the effect of pylon on the spatial distribution of gusting loading on the girder needs to be further studied.

1) INTRODUCTION

Traditionally, the effects of wind yaw angle are usually ignored with an assumption that wind normal to the bridge axis should be the worst case in estimating buffeting response and designing these auxiliary structures. However, the natural wind field is stochastic both in its magnitude and in its direction, which means that the strong wind does not always have the highest probability of occurrence from the directions normal to the bridge axis. Therefore, it may be possible to exceed the ultimate stress level when a bridge is in a skew wind. Furthermore, a large number of investigations, including theoretical studies, wind tunnel tests and field measurements, indicated that the buffeting response of cable-stayed bridge with a skew wind may exceed those under a normal wind, thus indicating the limitation of the assumption mentioned above.

In the early 1950's, Scruton (1951) studied the response of a full suspension bridge model under skew wind in smooth flow. The critical wind speeds for vertical and

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torsional induced oscillations were observed to be higher when the wind was inclined to normal direction. Davenport et al. (1969) conducted a full aeroelastic model test to investigate the response of a suspension bridge under skew wind. For the completed bridge, it was observed that the vertical buffeting response was considerably smaller under skew wind. However, for some erection stages, the response did not decrease as much with increase of wind yaw angle.

Tanaka and Davenport (1982) proposed the so-called "cosine rule", skew wind decomposition method, to predict the buffeting response of a structure under skew wind in the frequency domain. The effect of yaw angle was fairly well represented by taking the cosine component as representative wind speed when the flow is relatively smooth. However, Zan's (1987), and Gamble and Irwin's (1985) experimental studies indicated that this approach may underestimate the actual response of a cable-stayed bridge in an erection stage under skew wind for highly turbulent wind.

Zhu et al. (2007) conducted a full model test of cable-stayed bridge under skew wind and found that most unfavorable buffeting responses often occurred within the yaw angle range of 5º-30º. Li et al. (2013) proposed an accurate cross-spectral density of wind fluctuations and developed a coherence model of buffeting force under skew winds; the traditional buffeting analysis approach could then be conveniently employed, decomposing the skew wind into a body coordinate system.

All the analytical methods mentioned above assumed that the aerostatic coefficients along a bridge deck were constant and that the strip assumption can be applied to calculate the total buffeting forces along span. However, for a cable-stayed bridge under skew wind, the flow field, especially on the leeward side, may be modified by the bridge pylon more significantly as the wind is inclined to the normal direction. Thus, the wind load acting on the bridge deck may not be constant, but may depend on the location away from pylon. The aerostatic coefficients obtained from sectional model tests thus cannot confidently be used directly to estimate the response of a bridge under skew winds. Therefore, it is necessary to study the shelter effect of the pylon on the distribution of wind loading on a bridge deck under skew winds.

In this paper, we focus on determination of the static wind loading at arbitrary locations along the deck of a cable-stayed bridge under skew winds, especially studying the shelter effect of the pylon. A rigid model of a cable-stayed bridge during the double cantilever erection stage was designed to identify the aerostatic loading on the deck segments. To investigate the effect of wind direction and pylon on aerostatic loads, the yaw angle was varied from -90° to 90°. In addition, the effect of the attack angle of wind was also studied. Finally, the buffeting response of cable-stayed bridge under skew wind will be analyzed by taking the pylon's shelter effect into consideration.

2) EXPERIMENTAL TECHNIQUE

In order to study the effect of pylon on the distribution of aerostatic loads on the girder, a full 'aero-stiff ' model was introduced. (see Fig. 1).

The full 'aero-stiff' model of cable-stayed bridge in the erection stage (see Fig. 1(a)), with a geometric scale of 1:70, was constructed. Compared with an aero-elastic model, the full aero-stiff model has sufficiently high stiffness and remains stationary under high-speed wind. This approach makes it possible to measure the aerostatic forces on each segment by a force balance attached to the spine structure.

The metal spine assembly of main girder was designed as a rectangular steel beam with high stiffness. External elements of the girder were made of fibre-glass and ABS (Acrylonitrile Butadiene Styrene) material. To avoid interference between two adjacent sections, a 3mm gap between sections was included.

(a) Full 'aero-stiff' model (b) Force balance system

Fig. 1 Schematic diagram of full 'aero-stiff' model and force balance system

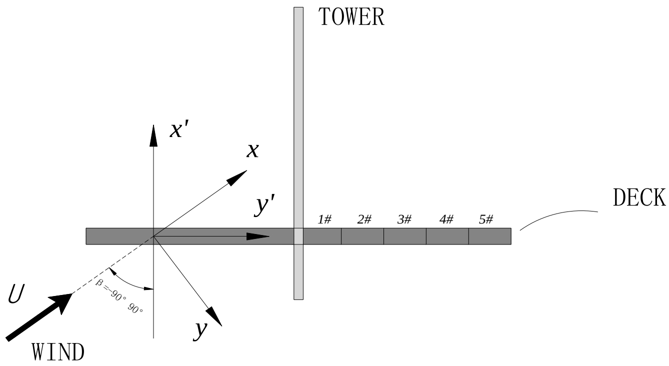

Fig. 2 Deck segments and definition of coordinate systems

Five sets of balance systems were used to measure the forces on all the sections simultaneously. Balances with a load range of 10N were used in these tests. They were fixed to the metal spine, and the segments of girder were connected with the balances directly (see Fig. 1(b)). Prior to the experiments, the balances were calibrated by applying a series of loads for lift and drag forces directly. The results show that these balances were of high accuracy with the relative error of less than 0.5%. Then the drag force, axis force and lift force on each element induced by wind could be measured in body coordinates. As shown in Fig. 2, the static wind loads on five sections were measured, with wind yaw angle varying from -90° to 90°. The 0° yaw angle is defined as the wind normal to the bridge deck axis, and the yaw angle of 90° is defined with the measured segments located upstream; at the yaw angle of -90° these are located downstream.

3) EXPERIMENTAL RESULTS

The sectional static coefficients of lift and drag force, varying with the location along bridge deck, and with the wind direction, are shown in Fig. 3. The lift load reached a maximum under skew winds due to the pylon shelter effect. In addition, it is also seen that the occurrence of maximum wind loads under skew wind is related to the attack angle; this may enhance the shelter effect of the pylon.

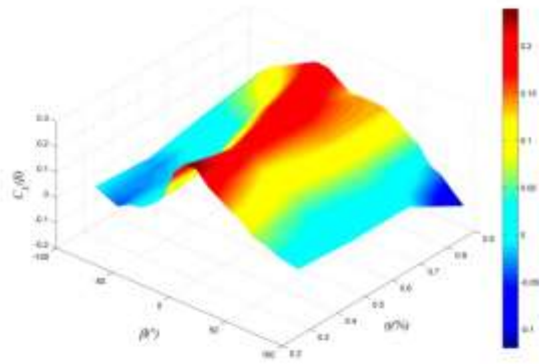

Fig. 3 Static lift coefficient varying with location and wind direction (α=+1.5º)

In order to estimate the validation of “cosine rule”, the ratio proposed by Liu et al. (2008) is defined as,

$$\cos^2(\beta) = \frac{C_i(\alpha,\beta)}{C_i(\alpha,0)} \tag{1}$$

where β is yaw angle; α is attack angle; $C_i(\alpha,\beta)$ is the aerostatic coefficient; *i* represents drag coefficient (*D*) and lift coefficient (*L*).

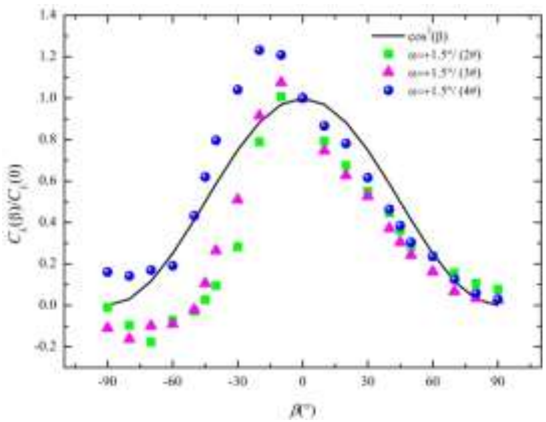

Fig. 4 Error margin of the “cosine rule” (lift coefficient, α=+1.5º)

For positive incident angles, only the windward segments approximately matched the “cosine rule” as shown in Fig. 4. However, for the leeward segments farther away from pylon, the lift reached its maximum when the yaw angle was about 20º. With regard to the leeward segments near the pylon, the maximum lift appeared at yaw angle approaching 10º, and decreased more rapidly with increasing of yaw angle compared with traditional “cosine rule”.

4) EFFECT OF THE PYLON BUFFERING RESPONSE

In order to study the effect of pylon on the buffeting response of cable-stayed bridge, a numerical example will be introduced. A cable-stayed bridge in completed stage was used. The overall length of the bridge is 1510m and the main span is 760m. The double-plane cable system uses a fan-type cable arrangement. The steel streamlined box girder is 36.0m in width and 3.5m in depth. The concrete pylon, with a diamond shape, is 248m high. The mass and mass moment of inertia of the girder per unit length are 36186kg/m and 7.2╳106kg•m2/m. The air density is 1.225kg /m3, and the damping ratio is assumed to be 0.005. In order to investigate the effect of pylon on the gust loading, the static coefficients obtained from the previous aero-stiff model test will be applied directly.

With respect to wind spectra, the longitudinal and vertical Kaimal & Panofsky spectra will be adopted, and the surface roughness length z0 is 0.03, the mean wind speed is 50m/s.

The complete quadratic combination (CQC) approach is adopted to obtain the buffeting response. In the multi-mode coupled buffeting analysis, the first 20 natural modes are considered. The span-wise correlation of buffeting forces is using Davenport’s exponent form coherence model with decay coefficient c=7. The RMS of vertical buffeting response varying with the yaw angle is shown in Fig. 5. The results indicated that the normal wind is the most adverse wind direction for the cable bridge in completed stage even through the pylon’s shelter effect. But the effect of pylon on the spatial distribution of the gust loading is still worth studying.

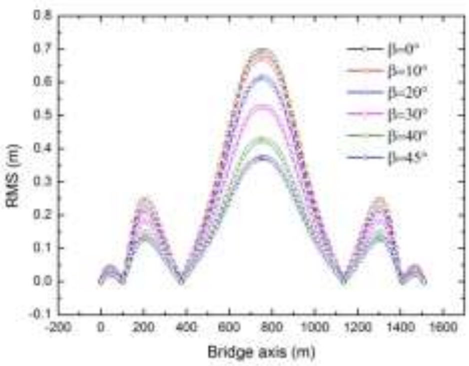

Fig. 5 Buffeting response varying with yaw angle

5) CONCLUDING REMARKS

A full bridge 'aero-stiff' model has been used to investigate the spatial distribution of static wind load on the deck of cable-stayed bridge under skew winds. Compared with the section model test, the measured results obtained from full aero-stiff model tests indicate that the static wind loading acting on bridge deck is not constant in either normal wind or skew winds. Due to this effect, the most disadvantageous static wind loading may occur as the wind yaw angle varies between 10º to 30º. However, with respect to the buffeting response of cable-stayed bridge in completed stage, it is seems that the normal wind is still the most dangerous wind direction and the effect of pylon the spatial distribution of the gust loading is necessary to be further investigated.

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