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Dynamic Wind Forces on Long Span Bridges

Effets dynamiques du vent sur les ponts de grande portée

Dynamische Windlasten auf weitgespannte Brücken

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SUMMARY
This paper describes a method for defining static wind loads acting on a long span bridge equivalent to the important dynamic motions due to gust buffeting and wake excitation, as well as the influence of the aeroelastic stability characteristics of the deck. The new approach makes use of the results of wind tunnel experiments in a turbulent airstream on dynamically mounted section models and uses theory to adjust these results to the conditions of full scale.

RESUME
Une méthode est proposée pour déterminer les charges statiques du vent sur un pont de grande portée, équivalentes aux effets dynamiques et aux mouvements dus à des coups de vent, et tenant compte des caractéristiques aéroélastiques du tablier. Cette nouvelle méthode tient compte des résultats d'essais en soufflerie, avec des turbulences, sur des modèles soumis à des charges dynamiques et fait appel à la théorie pour ajuster les résultats aux conditions réelles.

ZUSAMMENFASSUNG
Dieser Beitrag beschreibt eine Methode zur Bestimmung von statischen Ersatzlasten auf weitgespannte Brücken, aequivalent den dynamischen Beanspruchungen durch Windstösse und durch Anregung durch Luftturbulenzen. Ferner beschreibt er den Einfluss der Charakteristik der aero-elastischen Stabilität des Brückendecks. Die neue Näherung resultiert aus Experimenten im Windtunnel mit turbulenten Luftströmen an dynamisch gelagerten Querschnittsmodellen, unter Anwendung einer Theorie zur Angleichung dieser Resultate an die Verhältnisse der Gesamtstruktur.

1. INTRODUCTION

The conventional treatment of wind loading on long span bridges has tended to consider the static design wind loading used in normal strength design, and the aerodynamic stability as two separate and distinct aspects. The procedure described in this paper takes a more unified approach. It depends on the measurement of the dynamic response of section models to grid turbulence rather than smooth flow. The response is corrected for discrepancies in the intensity and spectrum of turbulence, the damping, and the joint acceptance function for the mode shape. A small correction is also added for the deficiency in low frequency excitation from grid turbulence. The design loads are found from the estimates of dynamic motion in the lowest symmetric and asymmetric modes a well as the mean load. This approach is an outgrowth of earlier studies in turbulent flow on the Murray MacKay Bridge (1), the Bronx-Whitestone Bridge (2), and Sunshine Skyway Bridge (3).

2. THE DESCRIPTION OF DESIGN LOADS

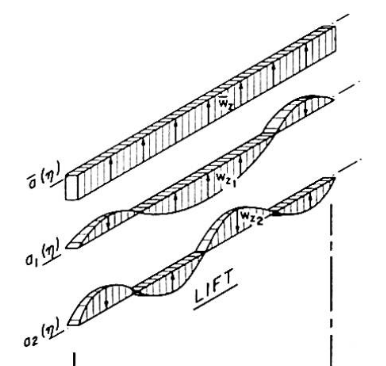
The persistent movements of any long span bridge (4,5) in strong wind are organized through its various mode shapes - horizontal, vertical and torsional. They cover a range of frequencies but take place mostly at or near the natural frequencies of the individual modes and have a random character due to the continual shifts in phase and amplitude.

To summarize the variety of load actions which the dynamic movements will produce in a severe wind storm, a wind load description for design has been proposed as in Fig. 1.

$$W_x(\eta) = \overline{W}_x \bar{a}(\eta) \pm \gamma \widetilde{W}_{1_x} a_1(\eta) \pm \gamma \widetilde{W}_{2_x} a_2(\eta) \qquad (1a)$$

$$W_z(\eta) = \overline{W}_z \bar{a}(\eta) \pm \gamma \widetilde{W}_{1_z} a_1(\eta) \pm \gamma \widetilde{W}_{2_z} a_2(\eta) \qquad (1b)$$

$$W_\theta(\theta) = \overline{W}_\theta \bar{a}(\eta) \pm \gamma \widetilde{W}_{1_\theta} a_1(\eta) \pm \gamma \widetilde{W}_{2_\theta} a_2(\eta) \qquad (1c)$$



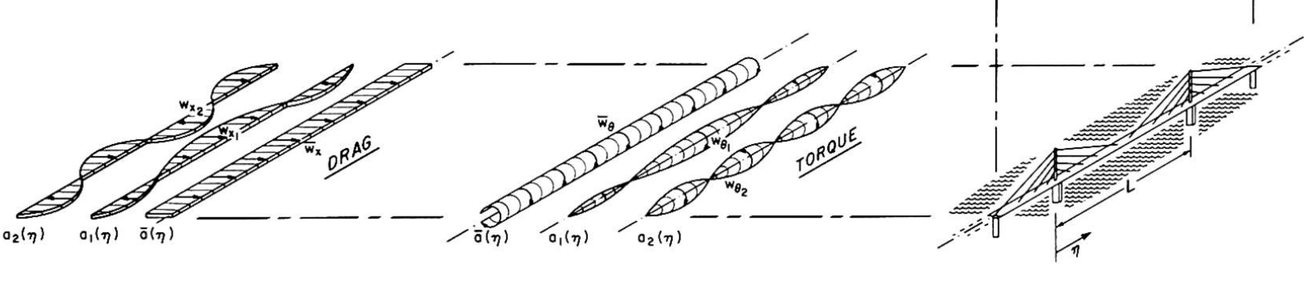


Fig. 1 Distributed Wind Load Components

In this x, z and θ denote the horizontal (downwind), vertical (upward) and torsional (nose-up) components; (see Fig. 2); $\overline{W}$, $\widetilde{W}_1$ and $\widetilde{W}_2$ are the mean, symmetric and antisymmetric load components per unit length of deck; $\bar{a}(\eta)$, $a_1(\eta)$ and $a_2(\eta)$ are the mean and modal load distribution functions; γ_1 and γ_2 are statistical load combination factors and take on values $\pm$ 1.0 if only one modal term is included; $\pm$ 0.8 for two terms; $\pm$ 0.7 for three terms and $\pm$ 0.6 for four or more terms.

The description of the mean time average wind load components produced by the mean wind is straightforward. They are defined through the force coefficients $C_x(a)$, $C_z(a)$ and $C_\theta(a)$ which may be measured for a range of angles of attack a, the deck width B, and the mean reference velocity pressure at deck height H, $q_H = \frac{1}{2}\rho U_H^2$. The three mean forces per unit length are then:

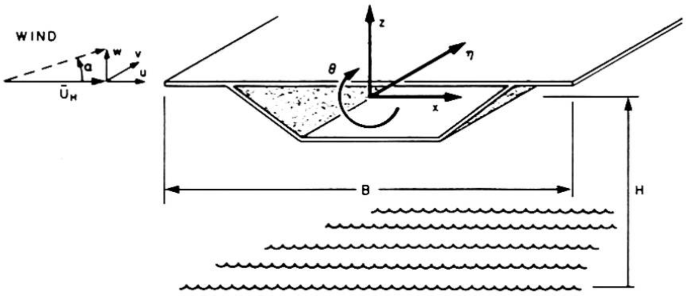


Fig. 2 Notation

$$\bar{W}_x = q_H B\, C_x(0); \quad \bar{W}_z = q_H B\, C_z(0); \quad \bar{W}_\theta = q_H B^2\, C_\theta(0) \qquad (2)$$

Two points should be made. First the coefficients in turbulent flow may differ from those in smooth flow. Second, normally only horizontal mean winds need to be considered. Only in steep mountainous valleys is there likely to be any appreciable inclination to the mean flow.

3. EVALUATION OF THE MODAL LOAD COMPONENTS W_1 AND W_2

Although the response of a suspension bridge deck has been represented by coupled vertical and torsional equations of motion (6,7), in fact the aerodynamic coupling terms are usually negligible, and the aerodynamic stiffness terms are usually small in comparison to the stiffness of the bridge itself. This leaves the aerodynamic damping as the most significant aerodynamic force induced by motion. If this is negative and numerically greater than the structural damping, large motion will result. The response of each uncoupled mode of vibration to the turbulent wind can be studied separately and superimposed at the end; usually, only the lowest modes are significant.

We can represent the peak modal load amplitude by the following: -

$$W = g\sqrt{\sigma^2 w_b + \sigma^2 w_r} \qquad (3)$$

where g is a statistical peak factor, $\sigma^2 w_b$ is the mean square background excitation acting quasi-statically, and $\sigma^2 w_r$ is the mean square excitation at or near the resonant frequency.

The two components of the excitation can be identified in the typical power spectrum shown in Fig. 3. The background excitation covers a broad frequency band below the natural frequency; the resonant excitation is concentrated in a peak at the natural frequency, the height of which is controlled by the damping. The two components can be estimated from the following expressions:

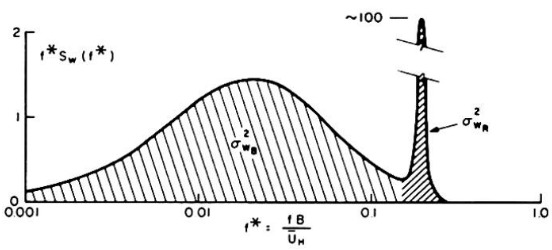


Fig. 3 Spectrum of Modal Load Amplitude

$$\sigma^2 w_{b_{x,z,\theta}} = \int_o^\infty f^*\, S_{F_{x,z,\theta}}(f^*) \cdot |\, J_{x,z,\theta}(f^*)\,|^2 \cdot d(\ln f^*) \qquad (4a)$$

$$\sigma^2 w_{r_{x,z,\theta}} = \frac{(\pi/4)}{(\zeta_s + \zeta_a(f^*_o))} \cdot f^*_o\, S_{F_{x,z,\theta}}(f^*_o) \cdot |\, J_{x,z,\theta}(f^*_o)\,|^2 \qquad (4b)$$

In the above the subscripts x, z, θ imply the equations are written for each variable in turn; f^* and f_o^* are the reduced frequencies fB/U_H and $f_o B/U_H$; ζ_s and $\zeta_a(f^*)$ are the structural damping and aerodynamic damping at frequency f^*; $f^* S_{F_{x,z,\theta}}(f^*)$ is the power spectral density of the externally induced x, z, θ components on a cross-section of the bridge deck at the reduced frequency f^*; $|J_{x,z,\theta}(f^*)|^2$ is the "joint acceptance function", relating the generalized modal force component with the mode shape and the force components at frequency f^* at cross-sections of the bridge and involves the spanwise correlation of the forces.

The external forces on a bridge cross-section arise from either the direct action of turbulence in the wind or through the action of flow fluctuations in the wake. The latter are commonly described as vortex shedding. We can write:

$$f^* S_F(f^*) = (f^* S_F(f^*))_{turb} + (f^* S_F(f^*))_{wake} \quad (5)$$

The turbulent term can be written

$$(f^* S_F(f^*))_{turb} = (q_H B)^2 \cdot (C^2_{x,z,\theta}\ |A(f^*)|^2) \cdot (f^* S_{u,v,w,}(f^*)) \quad (6)$$

where $f^* S_{u,v,w}(f^*)$ = the power spectra of the turbulent velocity fluctuations u, v and w;

$A(f^*)$ = "aerodynamic admittance" which translates the turbulent fluctuations into forces on a cross-section; and

$C_{x,z,\theta}$ = a reference aerodynamic coefficient.

The contributions of the turbulence to the expressions for $\sigma^2 w_b$ and $\sigma^2 w_r$ can be written as follows. To simplify the notation we will consider the lift (z) force and only include the vertical (w) component of turbulence, which normally will dominate.

$$(\sigma^2 w_{b_z}) = (q_H B C'_z)^2 \left(\frac{\sigma_w}{U_H}\right)^2 \int_0^\infty \frac{f^* S_w(f^*)}{\sigma^2_w} |A_z(f^*)|^2 |J_z(f^*)|^2 d\ln f^* \quad (7)$$

$$(\sigma^2 w_{r_z}) = (q_H B C'_z)^2 \left(\frac{\sigma_w}{U_H}\right)^2 \frac{f^*_o S_w(f^*_o)}{\sigma^2_w} |A_z(f^*)|^2 |J_z(f^*_o)|^2 \cdot \frac{(\pi/4)}{(\zeta_s + \zeta_a(f^*_o))} \quad (8)$$

The coefficient C'_z denotes $(\partial C_z/\partial_\alpha)$. Similar expressions for the torsion can be written with θ replacing z and introducing an additional factor B^2. For the drag direction $2 C_x$ replaces C'_z and u replaces w.

If the left hand terms are normalized by the $(q_H B C'_z)^2$ term the response is a function primarily of the reduced frequency f^* and the intensity of turbulence (σ_w/U_H), two homologous quantities which link the full-scale bridge behaviour with any dynamically scaled model. Otherwise the turbulence controlled response is bound up in the functional form of the turbulence spectrum, S_w, the aerodynamic admittance, A_z, the joint acceptance function, J_z, and the aerodynamic damping ζ_a.

The aerodynamic admittance reflects the efficiency of the bridge deck as a lift generator, as well as the correlation of the flow in the vicinity of the deck. The theoretical and observed form of this function is shown in Fig. 8. The joint acceptance function can be written

$$|J(f^*)|^2 = \int_0^L \int_0^L R_{F_1 F_2}(\eta_1, \eta_2; f^*)\ \mu(\eta_1)\mu(\eta_2)\,d\eta_1\,d\eta_2 \tag{9}$$

where $\mu(\eta)$ = mode shape with unit mean square amplitude; and

$$R_{F_1 F_2}(\eta_1, \eta_2; f^*) = exp\left(-c f^* \frac{L}{B} \frac{|\eta_1 - \eta_2|}{L}\right) \tag{10}$$

in which c is a constant which defines the effective width of the correlation. A similar expression can be written for the spanwise cross-correlation of the velocity component in which case $c \simeq 8$ is representative. It is reasonable to assume the same value holds for the forces F_1 and F_2 on the basis of the "strip assumption".

Equations (7) and (8) apply to both the full scale bridge and a model in a turbulent wind tunnel flow. Ideally the latter should be an exact scaling of the former. This ideal, however, is difficult to satisfy in the wind tunnel and some compromises may have to be made. There are significant advantages to using an elongated section model in a turbulent flow generated behind a coarse grid. Although the turbulence scale and intensity cannot be made to exactly correspond to full scale, the values can be made sufficiently close.

To adapt the results of the dynamic section model testing to full scale, corrections need to be applied as follows: (a) Corrections of the low frequency quasi-static, "background", response, $\sigma^2_{W_b}$, largely omitted from the section model due to the deficit in the vertical velocity spectrum generated by the grid. This can be estimated with reasonable accuracy from equation (7) using either theoretical or experimental data as outlined below. (b) Correction of the terms in the resonant response $\sigma^2_{W_r}$ for the discrepancies in the turbulent intensity, vertical velocity spectrum, joint acceptance function and damping. No correction is needed in the aerodynamic admittance. The following formula encompasses these corrections:

$$(\sigma^2_{W_r})_{full\ scale} = (\sigma^2_{W_r})_{model}\ \phi_{\sigma_w}\ \phi_{S_w}\ \phi_J\ \phi_\zeta \tag{11}$$

where the terms ϕ_{σ_w}, ϕ_{S_w}, ϕ_J and ϕ_ζ reflect corrections to the terms in the response due to the discrepancies between the section model and the full scale. These correction factors are found from the ratios of the quantities involved for model and full-scale. Through the appropriate selection of turbulence characteristics in the section model test and model length these corrections are relatively small. This last fact should lead to satisfactory reliability.

4. EXPERIMENTAL DETERMINATION OF DESIGN LOAD COMPONENTS

The wind tunnel testing of the section models of the two Sunshine Skyway Bridge alternates provided an opportunity to apply the proposed method. The proposed structure, over Tampa Bay in Tampa Florida is a cable-stayed design with a 366m main span. The concrete alternate used a precast, segmental box girder 29.03m wide and 4.27m deep. Two single strut pylons carry a system of radiating stays located on the longitudinal axis of the bridge (Fig. 4).

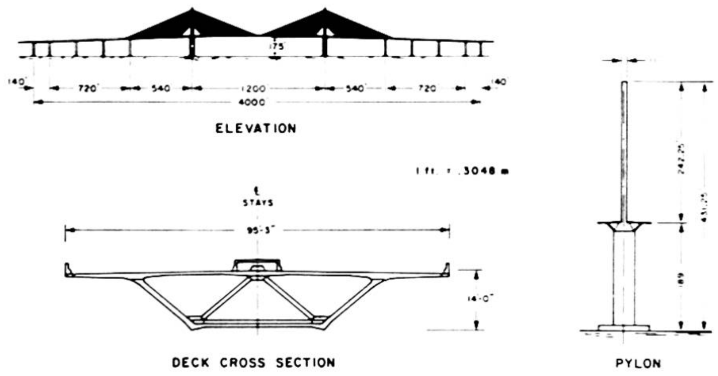


Fig. 4 Sunshine Skyway Bridge

The model of the 1 in 80 scale bridge section shown in Fig. 5 is 7 ft. (∼ 2m) in length corresponding to a 170 m section of the full scale structure. The model was tested with spring mounting giving the correct frequency ratio in lift and torque and 0.5% damping. Measurements of mean and peak dynamic motion are plotted in Fig. 6, and show marked differences between smooth and turbulent flow. With smooth flow there is evidence of some coupling between static lift and torque (i.e. twisting of deck due to torque modifies lift). Although not essential to the method aerodynamic damping and admittance functions were also measured in the experiments.

Fig. 5 Section Model in Wind Tunnel

The large mesh size and bar spacing of the turbulence grid was selected to give a close representation of the natural wind. The measured vertical turbulence intensity behind this grid is found to be 0.05 compared to the expected full scale value of 0.06 over open water. The grid turbulence spectrum and the target full scale spectrum are drawn together in Fig. 10 on a double logarithmic scale. Both have similar form, although the full scale has slightly more energy than does the grid turbulence at lower frequency.

5. DETERMINATION OF DESIGN WIND LOADS

Following equation 8 the wind load from the background turbulence excitation is found through the integration with reduced frequency of the product of the vertical wind spectrum (Fig. 7), Aerodynamic Admittance Function (Fig. 8) (assuming the Sears function), and the Joint Acceptance Function for the particular mode (Fig. 9). The form of these functions is such that the bulk of the energy is in the range of reduced frequency f^* between 0.01 and 0.1 and any uncertainty of the functional values at these low frequencies generally introduce little error. Added to this is the resonant component following equation 8. The resonant modal response, measured in terms of deflection has been converted to an equivalent static load through the modal stiffness:

$$\sigma_{W_{r_z}} = m\,(2\,\pi\,f_o)^2\,\sigma_z \quad ; \quad \sigma_{W_{r\theta}} = I_o\,(2\,\pi\,f_o)^2\,\sigma_\theta \qquad (12)$$

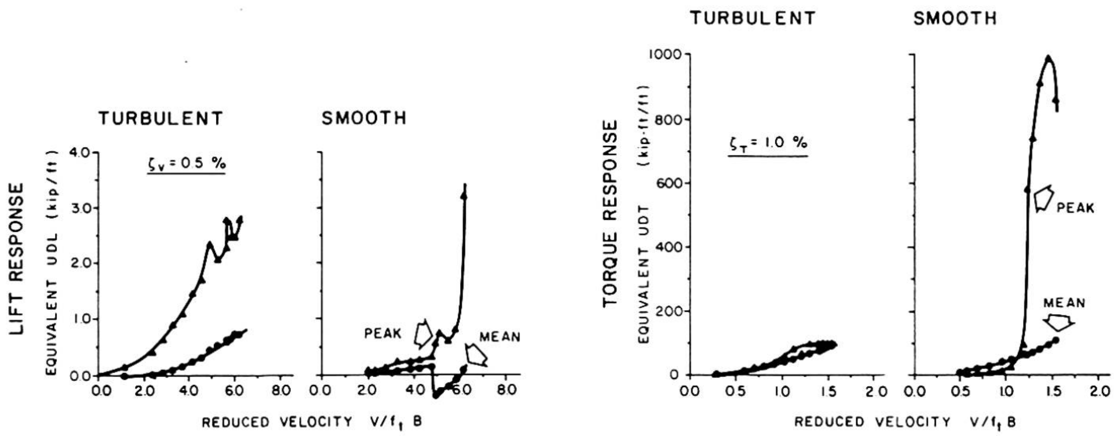


Fig. 6 Section Model Response (Uncorrected)

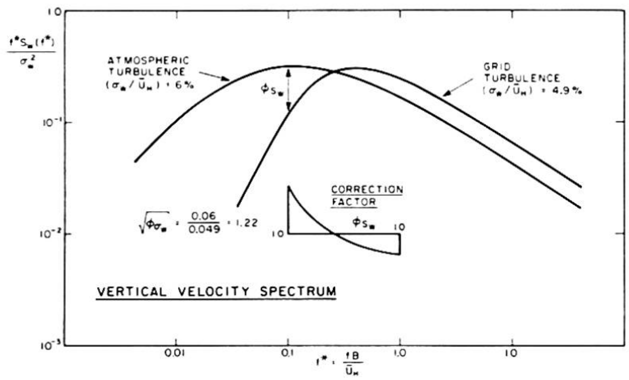


Fig. 7 Vertical Velocity Spectrum

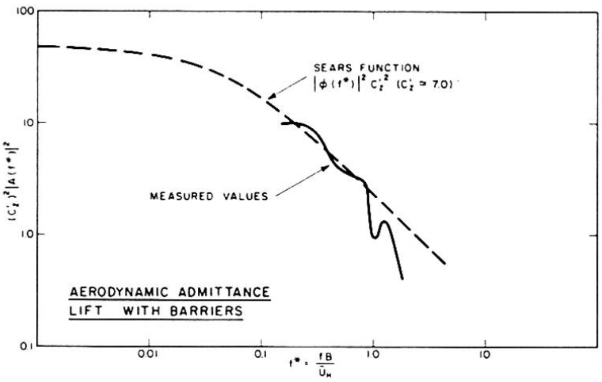


Fig. 8 Aerodynamic Admittance

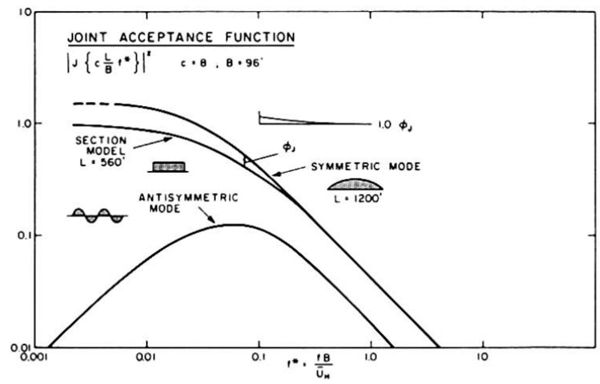


Fig. 9 Joint Acceptance Function

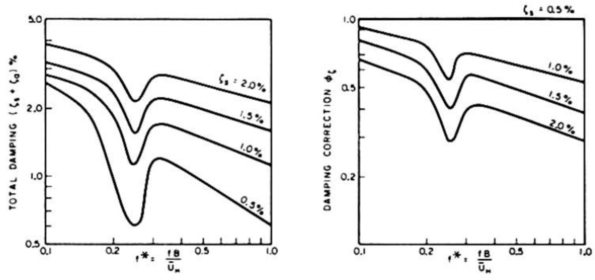


Fig. 10 Damping Functions

The correction terms are determined from the ratios of the quantities involved for full scale and model. That for the turbulence intensity, ϕ_{σ_w} is a constant equal to $(.06/.05)^2 = 1.44$ i.e. the ratio of target full scale to model values. Similarly, the correction factor for the vertical velocity spectrum ϕ_{S_w} is shown in Fig. 7, the joint acceptance function, ϕ_J, in Fig. 9, and the damping, ϕ_ζ, in Fig. 10. The addition of the background and resonant components as in equation (3), result in the loading shown in Figs. 11a and b. The final wind speed scaling will depend upon the final design frequencies of the structure. Thus the example wind loads have been determined for a nominal wind speed at deck height based on the estimates of vertical and torsional frequencies noted in the figures.

Verification of this procedure, using 1:350 scale aeroelastic models of both the steel and concrete bridges tested in a turbulent boundary layer were excellent (3).

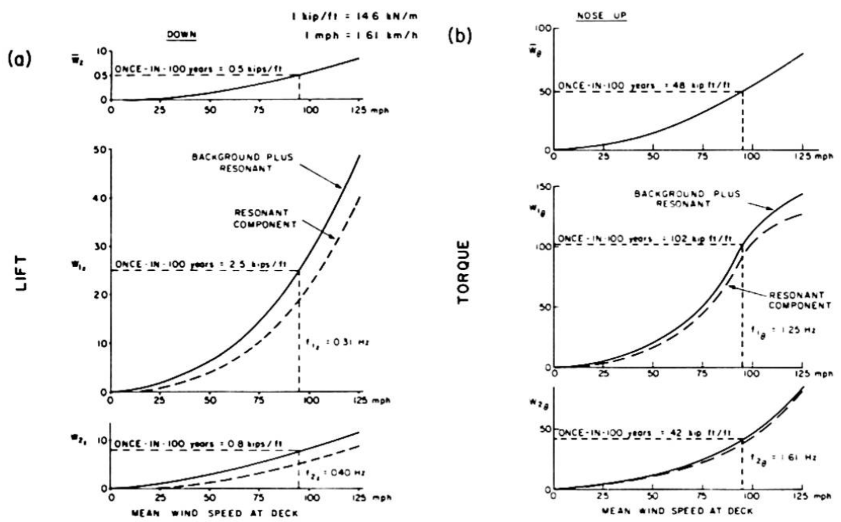


Fig. 11 Wind Load Components on Completed Bridge

6. CONCLUSIONS

A method has been presented whereby wind tunnel section model test results can be incorporated directly into a load format suitable for the definition of the design wind loads of long span structures. The procedure has been verified experimentally with the satisfactory prediction of the response of two full bridge aeroelastic models to boundary layer shear flow.

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