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Normandie Bridge: Wind Measurements and Validation of Previsional Studies

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Summary

At the design stage of the Normandie Bridge, previsional studies were carried out in order to estimate the wind induced dynamic behaviour of the bridge. These studies concerned the turbulent characteristics of the wind field at the site, the aeroelastic stability of the bridge, and the bridge response to the turbulent wind. During two years (1995-1996), in-situ measurements of the wind and of the dynamic response of the bridge have allowed to check the validity of the wind turbulence characteristics used for the design, and to compare the dynamic participation of height vibration modes to the predicted values corresponding to CSTB wind-tunnel measurements carried out on a taut-tube model and to theoretical computations made by SETRA. The results confirm the wind stability of the bridge and the conservative nature of its design.

1. Introduction

When it opened in January 1995, the Normandie Bridge (France), was, with a span of 856m long, the first cable-stayed bridge entering the domain of very long spans, which was reserved up to now for suspension bridges. The design of such bridges being governed by wind effects, various studies were conducted for its wind design [1,2]. These previsional studies have concerned both the estimation of the turbulent wind characteristics on the site [3,4], leading to a "wind model", and the previsions of the dynamic response obtained by a combined approach: theoretical computations using the « quasi-steady » spectral approach, and wind tunnel experiments on a taut-tube model [1,5].

In order to validate the different stages of the wind design, the completed bridge was equipped in 1995 with four anemometers, six accelerometers shared in two sections of the deck, and one accelerometer at mid-height of the South pylon. The field measurements lasted two years, allowing acquisition of data during strong wind periods.

We present here a first analysis of these data. For turbulence characteristics, the comparison of measurements with design data was made for the variances of the 3D fluctuations, their spectral distribution, the lateral turbulent length scales, and the spectral distribution of the lateral correlations (coherence functions). Concerning the dynamic response, fourteen vibration modes of the bridge were identified. Dynamic participation of eight of them was compared to the wind tunnel results, and the aerodynamic damping was evaluated.

2. Instrumentation - Data processing

Four tilted Gill 3-D propeller anemometers were set up along the deck, at a height of 69m (7 m above the deck), with distances between them covering the range 5.4 m - 38.7 m. The propeller distance constant is 2.1 m, i.e. a response length of 0.14 s. for a wind-speed of 15 m/s, which is adequate due to the large turbulence scales at this height, as it was proven by comparison with sonic anemometers. The propeller arms were tilted in order to avoid an under-estimation of the vertical fluctuations. Corrections for the propeller non-cosine response were made.

Inside two deck sections, respectively at mid-span and 100m south the mid-span, vertical accelerations were measured on both sides at a distance of 7.95 m from the deck longitudinal axis, and horizontal accelerations were measured in the direction perpendicular to the deck. On the south pylone, the horizontal accelerations were measured in the direction of the deck axis.

The instantaneous values of the wind components, and of the accelerations were filtered and recorded at a frequency of 10 Hz. Sequences of 4096 points (6mn50s) were stored when the mean wind speed exceeded 12 m/s with a mean direction between 235 and 285 deg. (the direction perpendicular to the deck is 270 deg.). More than 130 hours of data have been recorded during the two measurement years, including runs with mean wind speeds up to 22 m/s.

To reduce the sampling error in the estimation of the power spectral density (p.s.d.) of the acceleration, it is necessary to average a lot of spectral estimates together. In the same time, the determination of the damping coefficients requires a good frequency resolution, and then a long stationnary series of data. To overcome these contradictions, the method of selective ensemble averaging was used [6], which consists in grouping sequences of 1024 points according the mean wind speed and direction (the range width stands between 1 m/s and 2 m/s for the speed and is about 10 deg. for the direction), and in linking them to process series of 4096 or 9192 points by Fast Fourier Transform.

3. Turbulence characteristics

We consider here the horizontal component u in the mean wind direction and the vertical component w. Table 1 gives the turbulence intensities I_u and I_w , the longitudinal turbulence scales L^x_u, L^x_w, obtained by fitting a Von Karman spectrum to the p.s.d. of the fluctuations, and the coefficients of the lateral coherence, defined as the square of the normalized co-spectrum between fluctuations in two points. The wind model values are also given, as well as the wind-tunnel values during testings on the taut-tube model.

		Turbulence Intensity (%)		**Longitudinal turbulent scales (m)**		**Lateral coherence coefficients**	
Wind Sector		I_u	I_w	L^x_u	L^x_w	C^y_u	C^y_w
	(1)	7.1	4.6	260	22	15.8	13.5
Sea winds	(2)	9.0	5.0	200	35	11.0	12.0
	(3)	9.5	6.8	100	20	10.0	10.0
	(1)	12.5	8.8	170	24	41.4	23.2
Land winds	(2)	14.6	8.2	100	30	10.0	10.0
	(3)	15.0	11.6	80	20	12.0	10.0

(1) Field measurements (2) wind model (3) wind tunnel values

Table 1 : Turbulence characteristics on the site

In the wind model, the turbulence intensities and turbulent scales are used to estimate $S_i(n)$, the p.s.d. of the wind fluctuations. The standard deviation of the modal acceleration of the structure being proportional to $\sqrt{nS_i(n)}$ where n is the mode frequency, the comparison between measurements and wind model, is made on the values of this term, corrected by the wind oblicity ($\cos\theta$), and in the frequency domain of the 14 first modes (0.15-0.95 Hz) (fig.1). In case of sea winds (270 deg.) the model fits well measurements, but in case of land/sea winds (250 deg.) the model over-estimates of about 20%, the excitation due to the longitudinal component, and under-estimates of about 15% the excitation due to the vertical component.

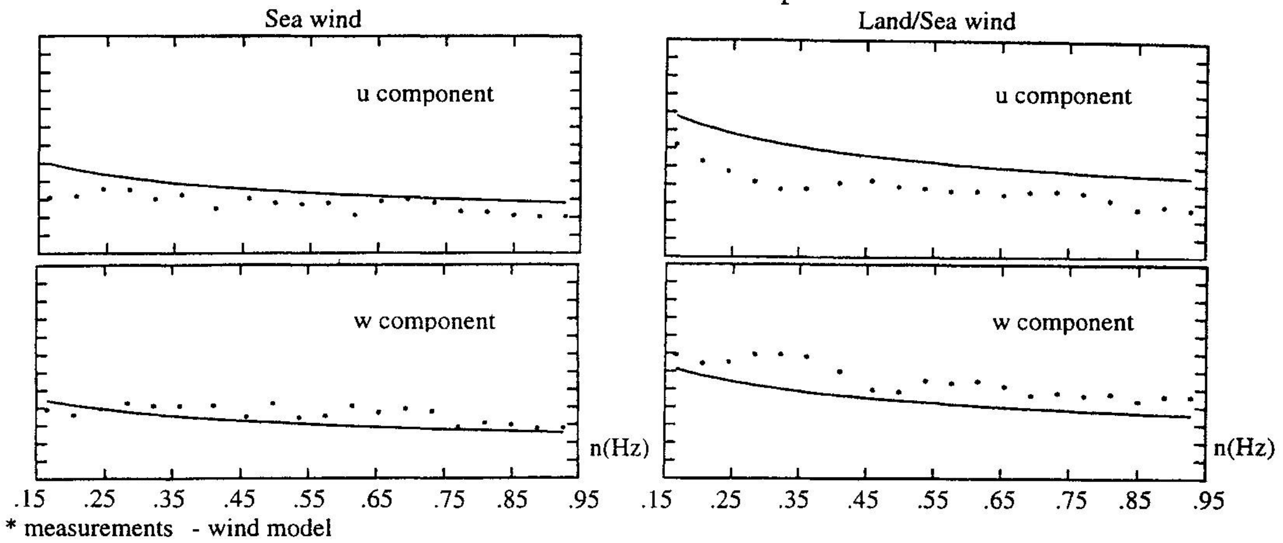

Figure 1 : Dsp of wind fluctuations $\sqrt{nS_i(n)}\cos\theta$

The coherence coefficients deduced from the measurements are higher than in the wind model, but as their values are greatly influenced by low frequency fluctuations, of minor importance for the bridge response, a direct comparison of the coherence functions in the frequency domain 0.15 Hz - 0.95 Hz (fig.2) is more adequate. The model fits well the measurements for the vertical fluctuations, but it overestimates the correlation between longitudinal fluctuations, when the separation between points is greater than 10 m, which is conservative for the structure.

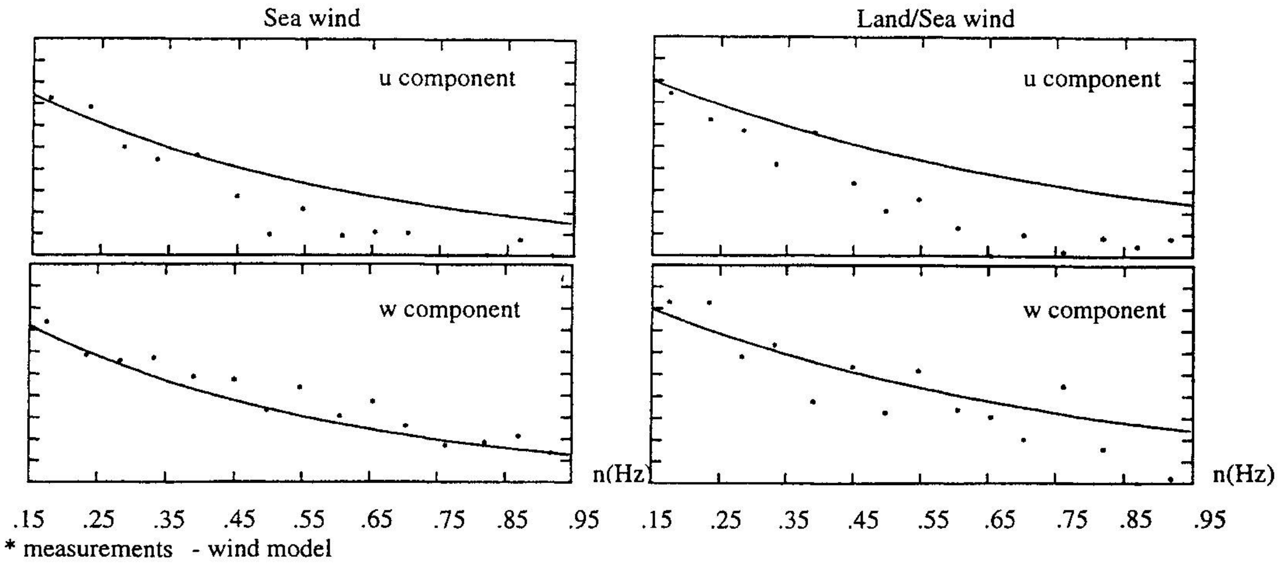

Figure 2 : Lateral root-coherence (Separation 5 m)

4. Dynamic behaviour of the bridge

By comparing the p.s.d. of acceleration at the various measurements points, seven vertical flexion modes, three horizontal oscillation modes and three torsional modes have been identified (table 2). One mode at 0.606 Hz has been observed on the pylon only. These observed modes are compared with the results of computations [1] and with the previous modal identification on the bridge, made by forced vibration testings [7]. The modal frequencies are very close to the previous estimations, except the frequency of the first torsional mode (0.727 Hz) which is higher than the value predicted by computations (0.486 Hz). As the modelisation of the torsional stiffness was not perfect in the computational model, a higher torsional frequency was expected. However, a so large frequency shift is rather surprising ans it adds security to the bridge.

Observed modes during strong winds			Measured natural frequencies (Hz)	Computed natural frequencies (Hz)
Natural frequency (Hz)	Type	Code	Identification 1995 from [7]	SETRA from [7]
0.168	Horizontal sway 1 (symmetric)	BH1	0.171	0.154
0.233	Vertical flexion 1 (symmetric)	FV1	0.232	0.226
0.295	Vertical flexion 2 (anti-symmetric)	FV2	0.293	0.27
0.388	Vertical flexion 3 (symmetric)	FV3	0.388	0.383
0.397	Horizontal sway 2 (anti-symmetric)	BH2	0.399	0.362
0.42	Horizontal sway 2bis (anti-symmetric)	BH2b	0.423	not computed
not observed	Vertical flexion 4 (anti-symmetric)	FV4*	not observed	0.385
0.466	Vertical flexion 4 (anti-symmetric)	FV4	0.464	0.475
0.544	Vertical flexion 5 (symmetric)	FV5	0.543	0.525
0.606	only observed on the pylon	8bis	not observed	not computed
0.618	Torsion (symmetric) + horizontal sway	9	0.622	0.52
0.678	Torsion (symmetric, very weak level)	10	0.677	not computed
0.696	Vertical flexion 6 (anti-symmetric)	FV6	0.694	0.616
0.727	Torsion 1 (symmetric)	T1	0.727	0.486
0.93	Vertical flexion 7 (symmetric)	FV7	0.925	0.714

Table 2 : Observed modes on the site

The modal amplitudes are computed by integration of the p.s.d. of the displacements, in the vicinity of the mode frequency. To take into account a frequency shift between the real bridge and the project, and consequently on the taut-tube model, the modal amplitudes are plotted versus the reduced wind speed Vr=V/nB, (n is the mode frequency and B the deck width) corrected by $\cos\theta$. The modal amplitudes are normalized by $I_u B$ (for horizontal modes) or $I_w B$ (for vertical modes), in order to make the results independant of the upstream turbulence intensity.

Figure 3 shows the results for the first horizontal oscillation mode (BH1) and the first vertical flexion mode (FV1). For the mode BH1, the wind-tunnel measurements gave lower values (of about 30-50%) than the field measurements. This can be easily explained by the effects of drag forces on the stays, not considered on the taut-tube model, but introduced in the design process of the bridge. Considering the five first vertical flexion modes, the measured amplitudes are very close to the values obtained with the taut-tube model. For the first torsional mode, the measurements appear to be slighly lower than the taut-tube model values.

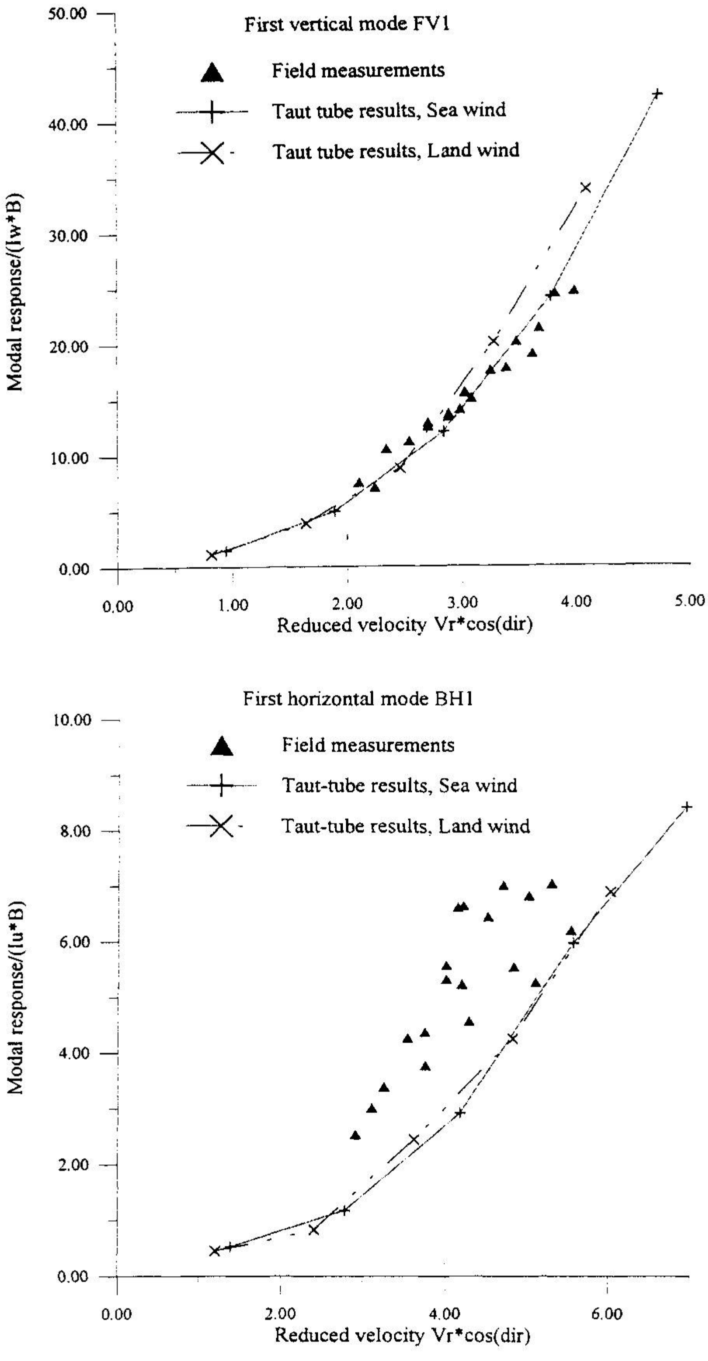

Figure 3 : Normandie Bridge - Comparison field measurements/taut tube model results

The damping ratios are defined relatively to the critical damping, and represent the sum of the structural and the aerodynamic dampings. They are obtained by fitting the theoretical curve of a single degree of freedom linear visco-elastic system, to the resonance peak of each mode. The fitting is made by the maximum likelihood method, which is much more precise than the classical least square method [8].

The damping ratio for the mode BH1 lies between 0.5% and 1.6%, and is generally greater than the structural damping (0.6%) which was measured during the forced-vibration testings. This difference cannot be explained by the aerodynamic damping which is very low for this mode, but probably by the bias due to the little number of spectral lines inside the peak (only seven in the half-power bandwidth when using 8192 points sequences). Concerning the vertical flexion, all the modes give a similar evolution versus the reduced windspeed (fig.4). This evolution was very well predicted by computing an aerodynamic damping using the slope $C'_N = 4.5$ of the curve of the lift coefficient, value which was measured in the wind-tunnel at 1/50 scale [2]. The damping ratio linked to the torsional modes lies between 0.6% and 1%, to be compared to the structural damping of 0.4% obtained from the forced vibration testings. Here, the difference can be explained by the aerodynamic damping, as it was already observed with the taut-tube model tests.

5. Conclusion

The analysis of wind data over a two-year period, including high wind speed sequences, up to 22 m/s for the mean value, have allowed to validate the wind model used for the design of the Normandie Bridge, in terms of the turbulence description. This data base will allow to constitute a new wind model for sea wind, adapted to long-span bridges.

The dynamic behaviour of the bridge has been well defined, by identifying fourteen vibration modes, and by estimating modal amplitudes and damping ratios for eight of them. The results are generally in good agreement with wind-tunnel measurements on the taut-tube model and are from 50% to 100% lower than the values issued of the computational approach which was used in the design of the bridge. This confirms the validity of the previsional studies made in 1991, and the high level of security of the bridge. These results could be completed by new theoretical computations, taking account of the real characteristics of the wind on the site, as well as the new modal characteristics, as they have been measured.

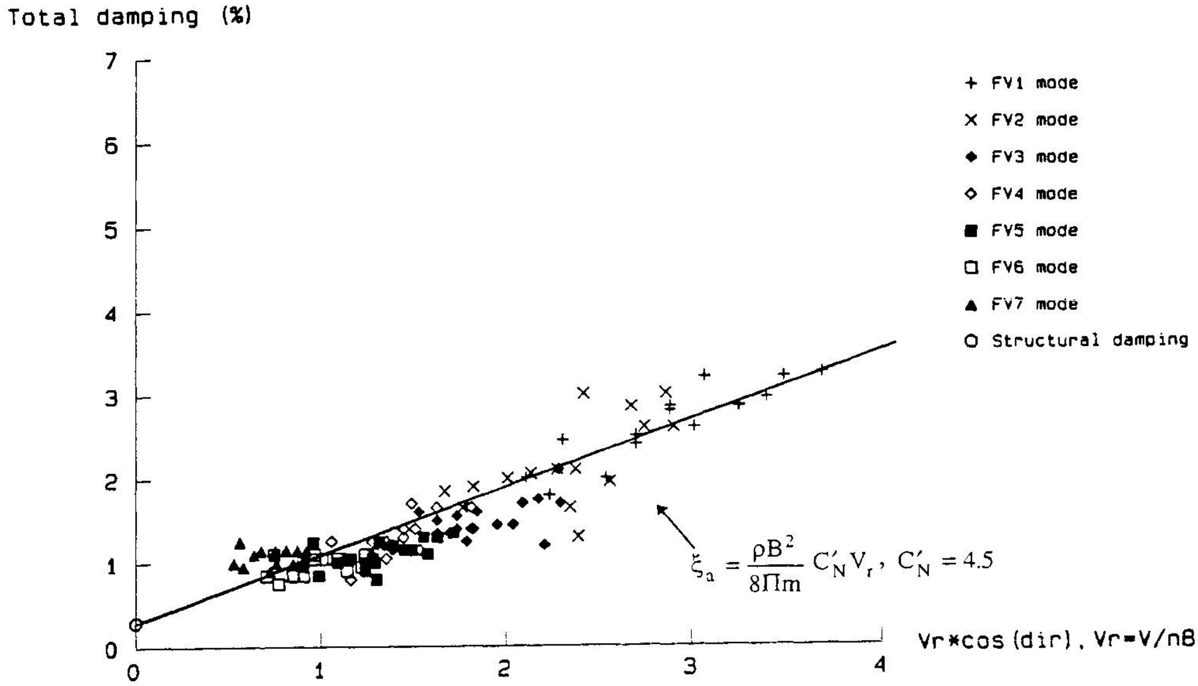

Figure 4 : Normandie Bridge - Field measurements - Damping of the vertical modes

Acknowledgements

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References

[1] Virlogeux M., 1992, "Wind design and Analysis for the Normandie Bridge", Aerodynamics of Large Bridges, A Larsen Ed., 1992 Balkema, Rotterdam, ISBN 905410042 7.

[2] Bietry J., Grillaud G., 1994, "Wind studies for the Normandie Bridge", Ponts Suspendus et à Haubans, Conférence AFPC, 12-15 oct. 1994, Deauville, France.

[3] Delaunay D., 1988, Etude expérimentale, des caractéristiques de la turbulence atmosphérique au-dessus de la mer (site du Pont de St-Nazaire), CSTB, EN-CLI 88C

[4] Delaunay D., 1990, Etude expérimentale de la turbulence atmosphérique sur le Pont de Normandie, CSTB, EN-CLI 90.12C

[5] Grillaud G., Flamand O., Barré C., 1991, Comportement au vent du Pont de Normandie, étude en soufflerie sur maquette aéroélastique à l'échelle du 1/200è., CSTB, EN-AS 91.5 C

[6] Littler J., 1995, An assessment of some of the different methods for estimating damping from full-scale testing, J.Wind Eng. Ind. Aerodyn., 57, 179-189

[7] Bietry J., Jan P., Epreuves dynamiques du Pont de Normandie , CSTB, EN-D 95.5 C

[8] Agrati S., 1995, Estimation of structural parameters from ambient vibration test, Tesi di laurea, Politecnico di Milano (I), Facolta di Ingegneria, Dipartimento di Meccanica.