Wind Effects on Long Span Cable Stayed Bridges: Assessment and Validation

by

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ABSTRACT

The well-known collapse of Tacoma Narrows Bridge in 1940 clearly identified the importance of aeroelastic effects on long-span bridge performance. Extensive research has been carried out since then to better understand the effects of wind on long-span bridges, producing various analytical response prediction techniques. An example of the application of such techniques will be presented. However, due to challenges related with full-scale measurements, these prediction techniques have commonly been validated using only wind-tunnel experiments. Recent research has revolved around the conduct of long-term full-scale measurements on a cable-stayed bridge to compare actual bridge performance with those of analytical predictions. In order to ensure the reliability of predicted response, the input parameters, such as wind conditions at the site and modal properties of the bridge are also calibrated using corresponding measured quantities. This paper will also summarize some of the preliminary results and outline their implications.

KEYWORDS: bridge engineering, wind engineering, flutter, buffeting, long-span bridges

1.0 INTRODUCTION

The maximum span of long-span bridges has been extended in recent decades to where today, the Akashi-Kaikyo Bridge (central span 1991 m) has been completed, and longer bridges are planned (e.g., Messina Straits (3300 m), Gibraltar Straits (5000m)). These successes are due in particular to progress in wind-resistant design; a primary component in the design of long-span bridges. Recently, multi-mode flutter and buffeting analysis procedures have been developed. These procedures, which were based on frequency-domain methods, take into account the fully coupled aeroelastic and aerodynamic response of long-span bridges to wind excitation.

The current methodology for the estimation of the response of long-span bridges to wind loads incorporates the following components:

- Measurement of a comprehensive set of aerodynamic and aeroelastic parameters for a given cross section using a suitably (i.e., aerodynamically) scaled section model. These parameters include: the static coefficients (lift, moment, and drag at a number of different angles of attack) and the flutter derivatives, generally also at several positive and negative angles of attack. It is emphasized that these quantities are intended to be sectional quantities that will be used in the analytical model. Examples of procedures can be found in Sarkar et al. (1994) and Singh et al (1996).
- A detailed numerical (generally finite element) dynamic model for the bridge under consideration. This model will be expected to provide a set of eigenvalues and eigenvectors for the structure and a corresponding set of generalized inertias. Generally, this will include at least 20 modes, but in some cases more may be required (e.g., up to 50 for very long structures).
- An analytical framework and computational aids for synthesizing the above data. Scanlan and Jones (1990) provide a comprehensive overview of the single-degree of freedom theory, while Jain et al. (1996a, 1996b) and Katsuchi et al. (1998a, 1998b,1999) outline the extension of this theory to consider the interaction of multiple modes.

In addition to the above components, knowledge or assumptions about modal damping values and

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the wind environment are also required.

One of the most commonly used prediction techniques is the frequency-domain analysis described by Scanlan and Jones (1990), Jain et al. (1996a) and Katsuchi et al. (1999), and is based on modal analysis in the frequency domain. A suite of computer programs has been created to enable fast and efficient implementation of multi-mode frequency-domain prediction methods. For brevity, details are not included here; interested readers are referred to the above-referenced publications for this material.

2.0 EXAMPLE APPLICATION

This section summarizes the results of the flutter and buffeting analysis carried out for a cable-stayed bridge: a 1169 ft. main span structure and shows the capabilities of frequency-domain-based analysis tools. The input parameters in Table 1 were used in the analysis to model the structural and climatological properties of the bridge. Table 2 lists the first ten modal frequencies of the bridge, and their associated descriptions. The A_2^* flutter derivative for different wind directions and angles of attack are shown in Figure 1. The potential flutter susceptibility is indicated by the crossing of the A_2^* from negative to positive at a reduced velocity (*U/nB*) of about 4.

2.1 Flutter analysis

For some long-span bridges, the lowest torsional mode may couple with the first vertical mode of the bridge to cause flutter at a lower wind velocity than predicted from the single-mode analysis alone. To evaluate the possible coupling of modes, a two-mode flutter analysis was carried out for the bridge using Modes 2 and 7 (first vertical and first torsional). The two-mode flutter analysis was repeated using all of the flutter derivative sets; results are summarized in Table 3.

According to these results, the most critical condition corresponds to a south with an angle of attack of -3 degrees. Coupling was observed to be minimal in this case: this is primarily a single-mode flutter, as would generally be expected for a structure of this size.

2.2 Buffeting Analysis

Buffeting analysis of Pomeroy Bridge was carried out using two sets of flutter derivative data, one with force coefficients corresponding to a north wind at zero degrees and one with force coefficients corresponding to a south wind at zero degrees. In the results reported below, the mean wind speed *U* is taken as 33 m/s (109 ft/s).

Table 3 summarizes the results of this investigation, and Figures 2 and 3 show the RMS vertical and torsional displacement estimated as a function of span location for varying number of modes included in the analysis. Note that the responses converge rapidly after the significant modes that contribute are included in the analysis. Figures 4 and 5 show spectra of response at midspan and quarter-span points, and demonstrate the different modal contributions expected at these locations. Again, analysis confirmed that the modal coupling in this structure is insignificant, and analysis using a mode-by-mode approach is generally adequate.

3.0 FULL-SCALE MEASUREMENTS

As noted above, few opportunities have existed to quantitatively verify the above results at full scale. A long-term measurement program is currently underway at the Fred Hartman Bridge in Texas to continuously monitor its response to ambient loading conditions. The Fred Hartman Bridge (Fig. 6) is a twin-deck cable-stayed bridge with a main span of 380 m. and two side spans of 147 m. The decks are carried by a total of 192 cables, arranged in four inclined planes and connected to the deck at 15 m intervals.

Measurements are carried out using a PC-based self-triggering system that collects data on the basis of exceedance of threshold motion and wind levels. Each recorded data file contains 5-minute trigger runs collected at 40 Hz, which are stored on high-capacity disks. The recorded files are later processed to extract deck and cable accelerations, cable displacements and loads, wind speeds and other relevant meteorological factors, all of which are summarized in a comprehensive database for subsequent analysis. Further details of data collection and processing can be found in Ozkan et al. (2001a).

As noted earlier, there are three main components used in a bridge wind analysis: knowledge of the meteorological conditions at the bridge site, information on the modal properties of the structure and the experimentally determined flutter derivatives and associated aerodynamic parameters associated with the cross section. The first component, through the wind spectra, can be evaluated directly using measured wind speeds and compared to theoretical meteorological models. Preliminary comparison of wind spectra show reasonable agreement (see Figure 7); detailed results will not be reported herein.

The modal properties predicted for the bridge can also be evaluated directly from the measured deck frequencies through comparison to the results obtained from a 3-D finite element model of the bridge; good agreement has generally been obtained. 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 modeled through the flutter derivatives, the effects of which can be seen in histograms of modal frequencies, which show a range of values for each mode. Studies are also being performed to better evaluate the wind-speed dependence of frequency and damping of the structure and relate them to the flutter derivatives.

Comparison of overall bridge response is made using root-mean-square (RMS) acceleration and displacement response of the bridge. Since multiple modes contribute to the response, RMS displacement is estimated for each mode individually. This is done for each record, and the results consequently compared to analytical predictions obtained from the programs mentioned above. However, the nature of the structure and the measurement program gives rise to observations that should be considered carefully to ensure the reliability of results. An example of these is the localized effect of cable vibrations. These are instances of large-amplitude cable vibrations that are recorded by deck transducers (Ozkan et al. 2001a). Measurements taken after the installation of dampers on the cables show a much-reduced level of such vibrations and more evident global vibrations of the deck. Another interesting observation is the instances of cable-deck interaction, initiated by moderate vibrations of the deck that induces oscillation of cables (Ozkan et al. 2001b).

3.1 Deck Vibration Measurements and Data Analysis

A significant challenge related with long-term monitoring projects is the process of analyzing large quantities of data without loss of interesting information that might not have been expected. More than 20000 trigger files have been recorded during the four years of the test program and more are continuously being collected. Analyzing such a large number of data files demands extensive use of automated procedures. However, the use of such procedures must be carefully controlled to ensure that flawed or questionable data are not included in the study. The data analysis techniques used in this project have been automated to the greatest extent considered prudent, with careful consideration to maintaining the integrity and accuracy of the data and not missing important features of individual records.

The recorded files are initially processed to determine the general features of the raw data. These features include the mean, standard deviation and other higher moments of the data as well as one-minute average wind speeds and directions, accelerations and displacements, all of which are automatically added to a database. The database provides for easy analysis and correlation of these statistical quantities. It is also possible to readily interrogate the data using queries created and stored in the database.

Modal frequencies and mode shapes have been found and these values have been compared with values obtained from finite element (FE) analysis. Preliminary results of this comparison have been presented previously (Ozkan et al. 2001a). Table 5 shows the comparison of measured modal frequencies with those obtained from a FE analysis for the first 20 modes. In general, good agreement between the two data sets is observed. Similarly, the mode shapes have been found for the first 20 modes, showing reasonable agreement with those calculated from the FE analysis (Ozkan et al. 2001a).

To investigate the wind-vibration characteristics of the bridge deck, plots of root mean square (RMS) displacement of the deck versus wind speed have been made (Figure 8). A general trend of increasing RMS acceleration with wind speed can be observed from this figure. Comparison with predicted responses using the procedure outlined above and parameters suitable for the recording environment show reasonable agreement in large measure; "outliers" are currently being studied in more detail.

3.2 Deck-Stay Interaction

An example of an interesting record is given in Fig. 9. This record forms the initial five-minutes of a series of triggers during the passage of a meteorological event. For this specific record, Fig. 9(a) and (b) show the time-histories and power spectral densities (PSD's) of vertical deck acceleration at midspan and of the adjacent stay cable AS24 (length 198 m; natural frequency approximately 0.59Hz), respectively. Fig. 9(c) shows the wind speed at deck level. These figures, and others similar that have been made for different deck instruments, show a dominant frequency of vibration at approximately 0.58 Hz. It is important to note that this frequency corresponds to the third symmetric vertical mode of the deck (given as approximately 0.56 Hz in Table-1), and is also close to the first mode of the stay cable AS24. This is an interesting and important observation since the first-mode vibrations of a cable at this level of acceleration are generally associated with large displacements. In fact, by integrating the acceleration time-history, a displacement amplitude of approximately one meter (peak to peak) was estimated.

Furthermore, by observing the time-histories it can be seen that the significant vibrations are initially observed at the deck instead of the cable. This observation, as well as the similarity of modal frequencies suggests that the deck is driving the cable to vibrate with large amplitude in its fundamental mode. Vortex-induced vibration of the deck is thought to be the driving mechanism for this motion. Further studies are continuing to better understand the underlying mechanisms involved in this behavior and its consequences, and will be reported in future publications.

4.0 CONCLUDING REMARKS

The preceding paper presents an overview of long-term efforts to monitor a cable-stayed bridge for a variety of purposes, including understanding the modal characteristics and wind-induced responses under ambient wind conditions. Using data files collected during various meteorological conditions, natural frequencies and mode shapes of the deck were found using an automated data analysis procedure. The measured modal frequencies, mode shapes, and RMS responses are observed to agree with the predicted values found from a finite element and aerodynamic analysis.

The analysis and comparison described above demonstrates acceptable performance of the analytical model in its ability to predict the response of long-span bridges to wind loading. The analytical model (with suitable choice of parameters) may therefore be considered suitable for the prediction of the prototype response. Overall, the methodology employed in the present paper represents the general versatility of the analytical and experimental techniques for the aeroelastic design of long-span bridges.

It is noted that while automated data analysis procedures are clearly necessary for such large volumes of data, care must be taken not to miss or obscure important phenomena or characteristics through this approach. The interaction observed between the deck and a stay is a good example of a situation where careful interpretation of the data is required to fully understand the relevant underlying mechanics.

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Table 1: Parameters for Example Structure

ζ (structural damping)	0.003
B (width) – ft	76.75
L (total length) – ft	1169.0
Air Density, ρ, – lbs^2/ft^4	0.002378
Lift coeffcient C_L	-0.0344
Drag coeffcient C_D	0.134
Moment coeffcient C_M	-0.0293
Derivative of lift coefficient $C_L^{'}$	5.107
Derivative of moment coefficient $C_M^{'}$	0.332
Z (deck height) - ft	78
Z_0 (roughness length) - ft	0.25
Correlation Constant	5

Table 2: Modal frequencies

Mode No.	Frequency (Hz.)	Period (Second)	Description
1	0.172	5.825	1st Longitudinal Deck Mode
2	0.294	3.398	1st Vertical Deck Mode
3	0.446	2.241	1st Lateral Deck Mode
4	0.473	2.113	
5	0.718	1.392	
6	0.723	1.383	1st Torsional Deck Mode
7	0.784	1.276	
8	0.867	1.153	
9	0.919	1.088	
10	0.933	1.072	

Table 3: Critical flutter velocities

Angle of Attack	Critical Flutter Velocity
North 0 deg	163 mph
North +3 deg	>191 mph
North -3 deg	158 mph
South -3 deg	**145 mph**
South 0 deg	161 mph
South +3 deg	>178 mph

Table 4: Buffeting analysis results (0.5% damping)

Configuration	Modes Analyzed	Vertical RMS Disp. at Midspan (inch (cm))
North Wind	1&2	4.44 (11.3)
	1, 2 & 3	4.45 (11.3)
	10 Modes	4.48 (11.4)
	18 Modes	4.49 (11.4)
South Wind	1 & 2	4.52 (11.5)
	1, 2 & 3	4.53 (11.5)

Table 5: Comparison of measured deck modes with FE analysis

Mode	Long-Term Measured Frequency (Hz)	FEM Frequency (Hz)	Percentage Difference	Phasing (I :in-phase O: Out-of-phase)	Description of the Mode (FE)
1	0.290	0.286	1.4	I	Vertical
2	0.299	0.291	2.8	O	Vertical
3	0.375	0.366	2.5	I	Vertical
4	-	0.377	-	O	Vertical
5	0.432	0.410	5.4	O	Lateral
6	-	0.426	-	I	Lateral
7	0.564	0.556	1.4	I	Vertical
8	-	0.562	-	O	Vertical
9	-	0.612	-	O	Torsional
10	0.586	0.625	6.2	I	Vertical
11	-	0.634	-	O	Vertical
12	0.665	0.658	1.1	I	Vertical
13	-	0.659	-	-	Torsional-Lateral
14	0.683	0.662	3.2	-	Torsional-Bending
15	0.714	0.735	2.9	I	Vertical
16	-	0.736	-	O	Vertical
17	-	0.756	-	I	Torsional
18	0.784	0.757	3.6	O	Vertical
19	-	0.817	-	I	Torsional
20	0.924	0.856	7.9	I	Vertical

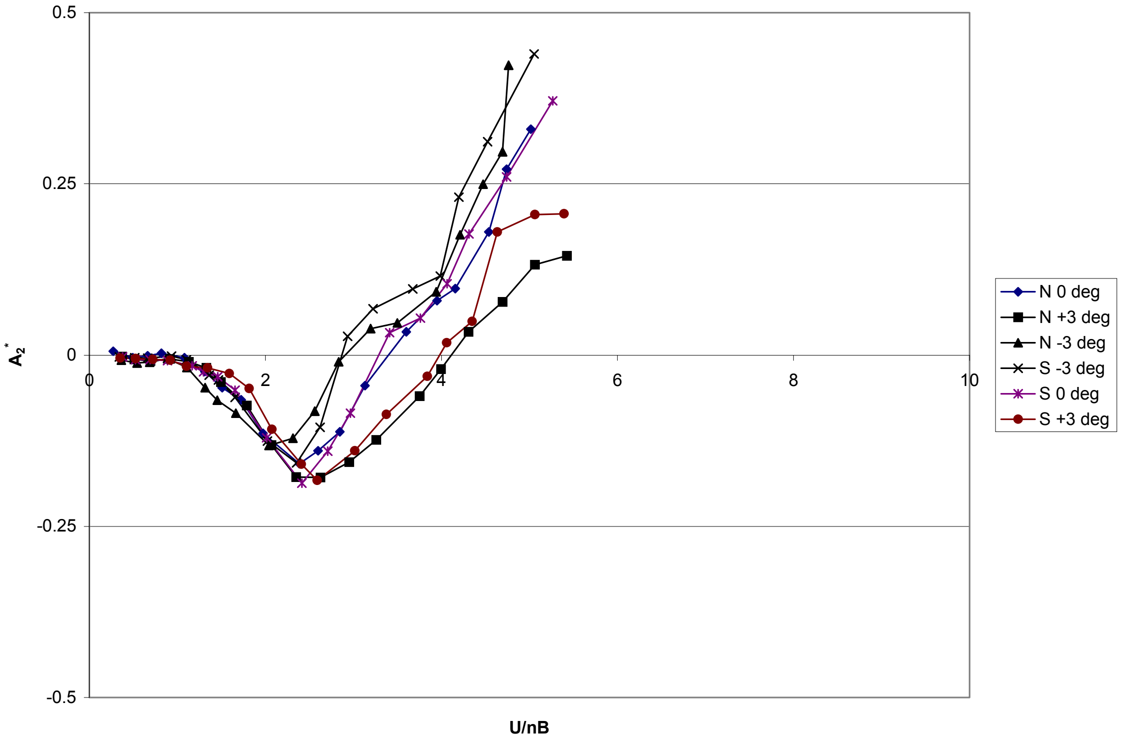

Figure 1: Flutter derivative A_2^* for various wind directions and angles of attack.

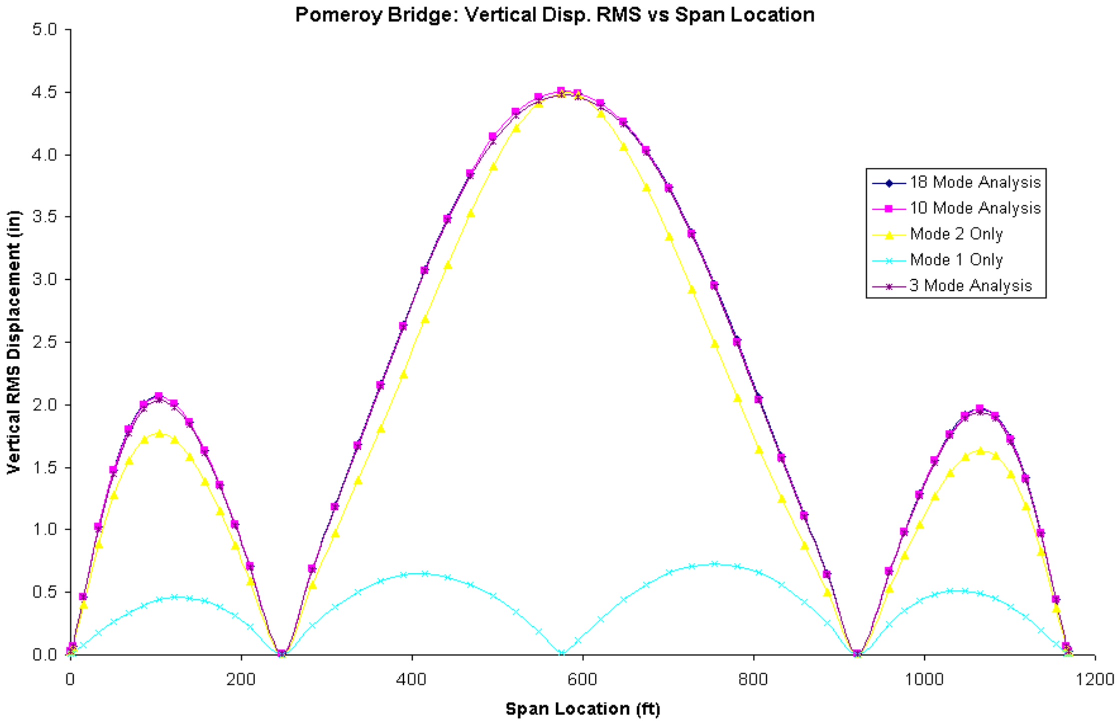

Figure 2: RMS Vertical displacement vs span location: North wind; 0.5% damping

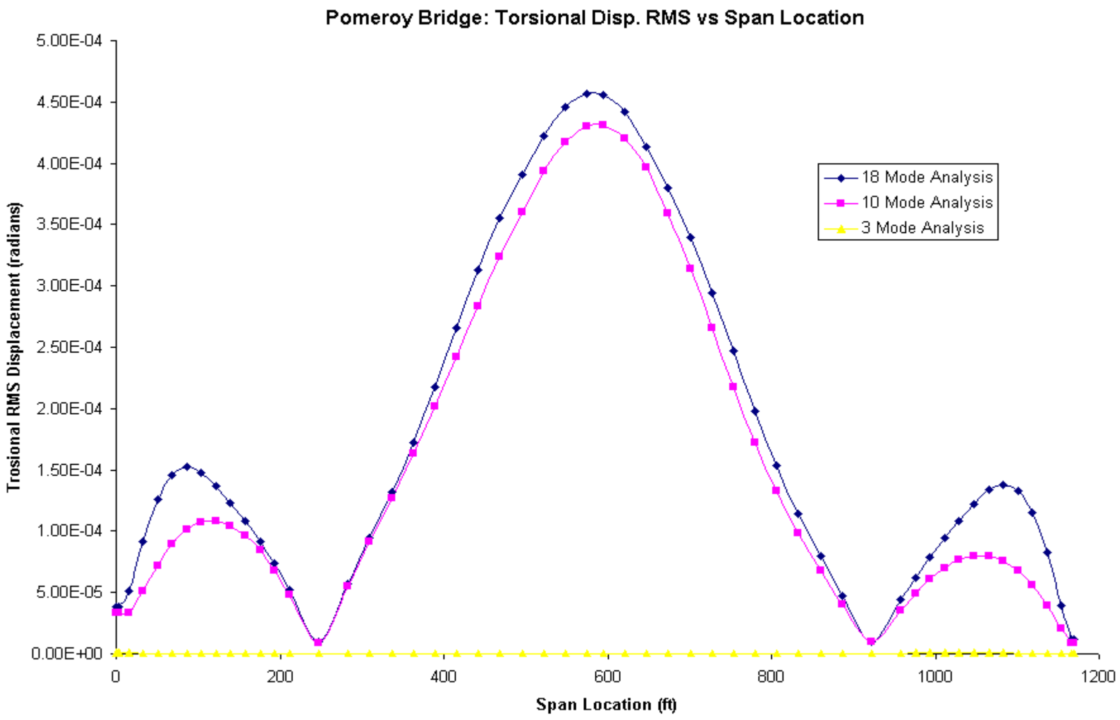

Figure 3: RMS Torsional displacement vs span location: North wind; 0.5% damping

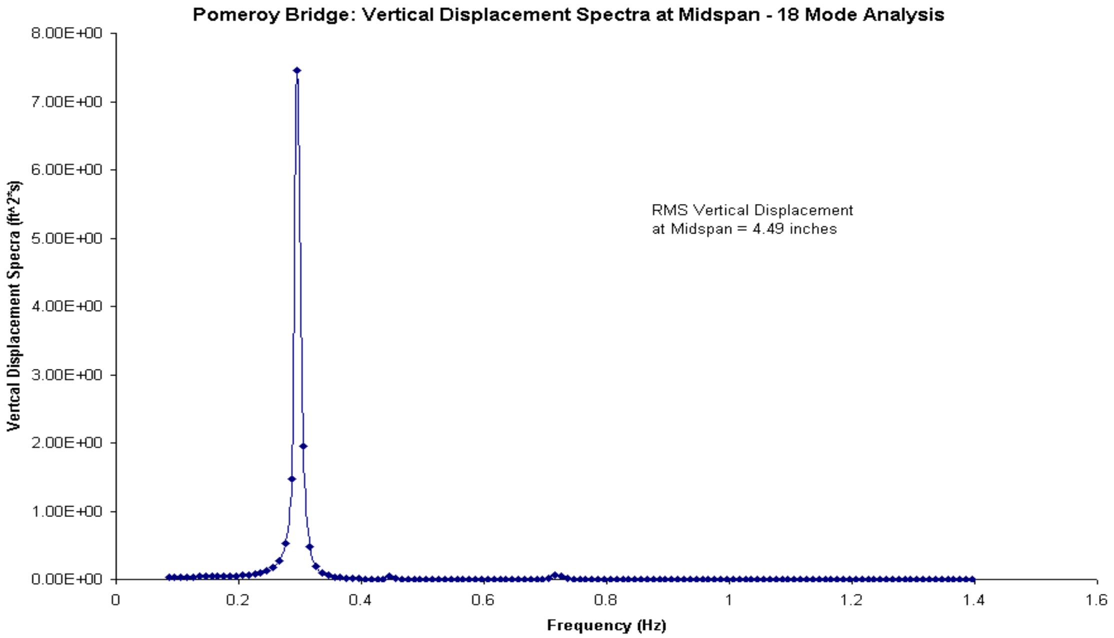

Figure 4: Vertical displacement spectrum at midspan: 18 mode analysis; North wind; 0.5% damping

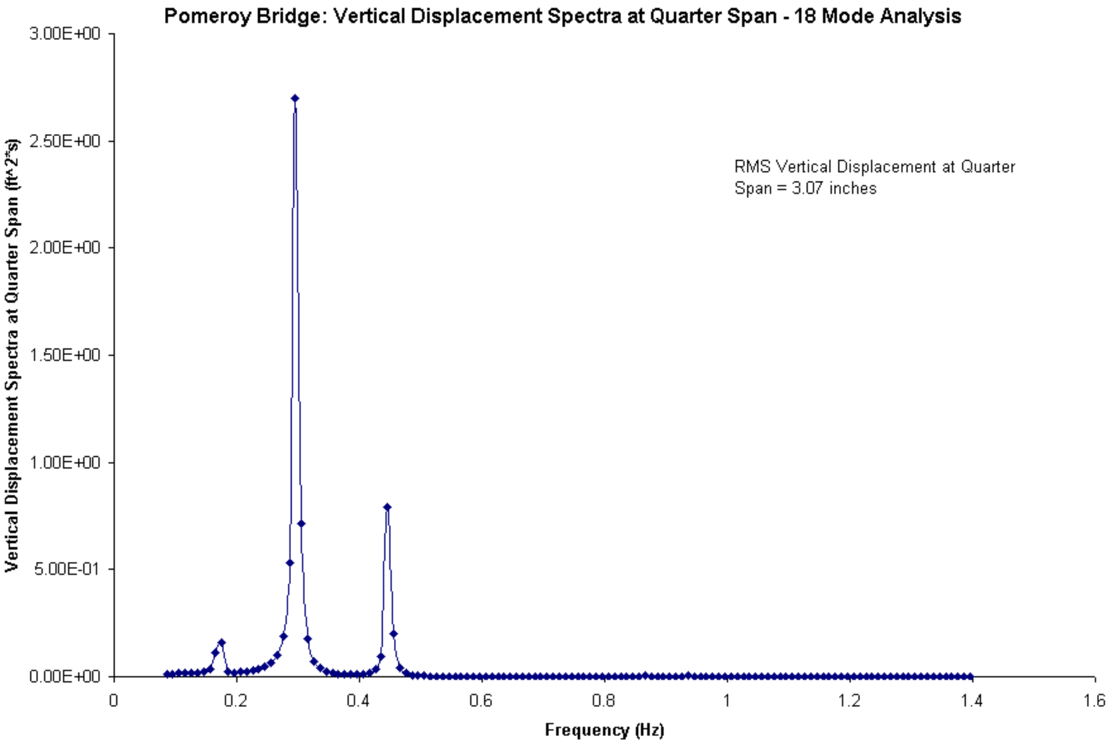

Figure 5: Vertical displacement spectrum at quarter-span: 18 mode analysis; North wind; 0.5% damping

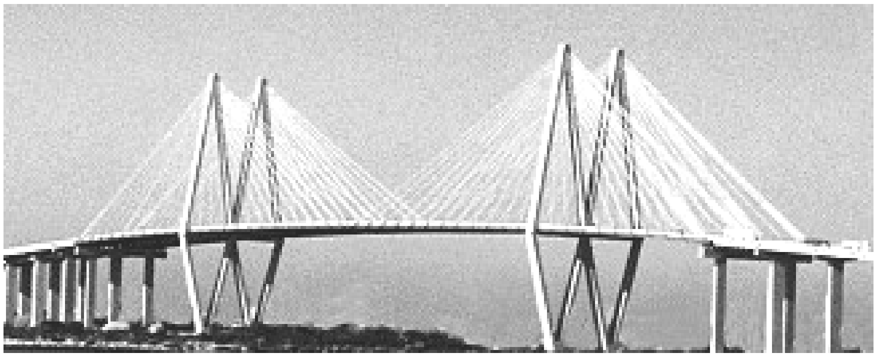

Figure 6. The Fred Hartman Bridge

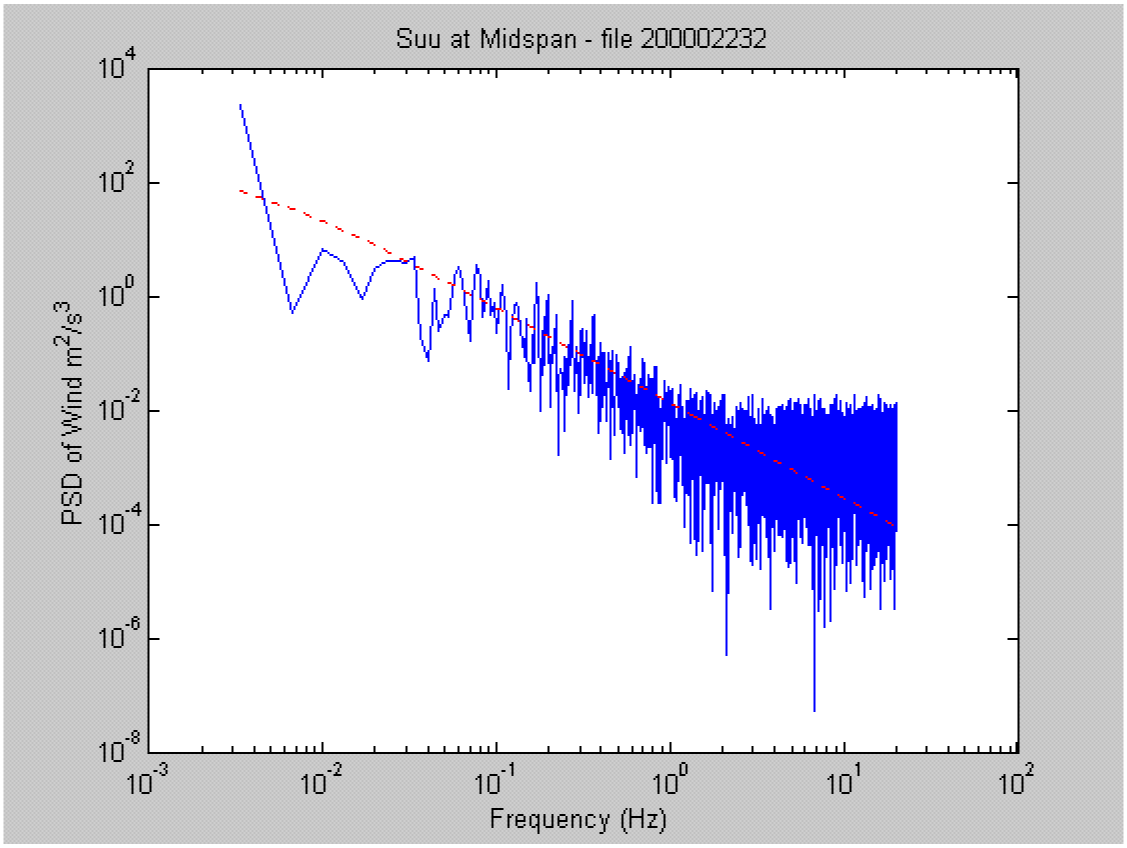

Figure 7. Example wind speed spectrum: Measured and predicted.

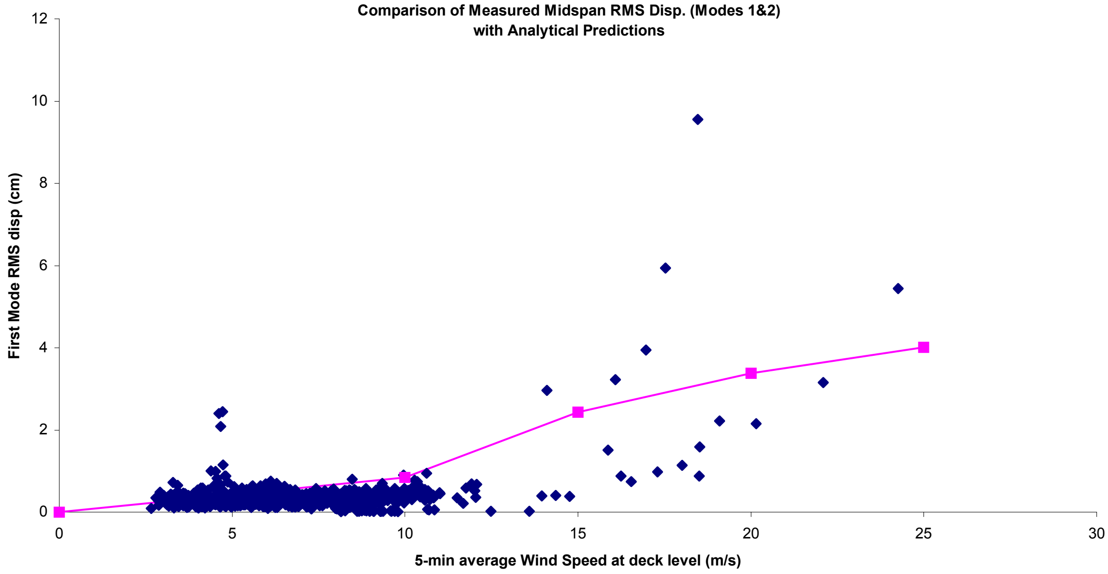

Figure 8. RMS Midspan Displacement in first two modes: Measured and predicted

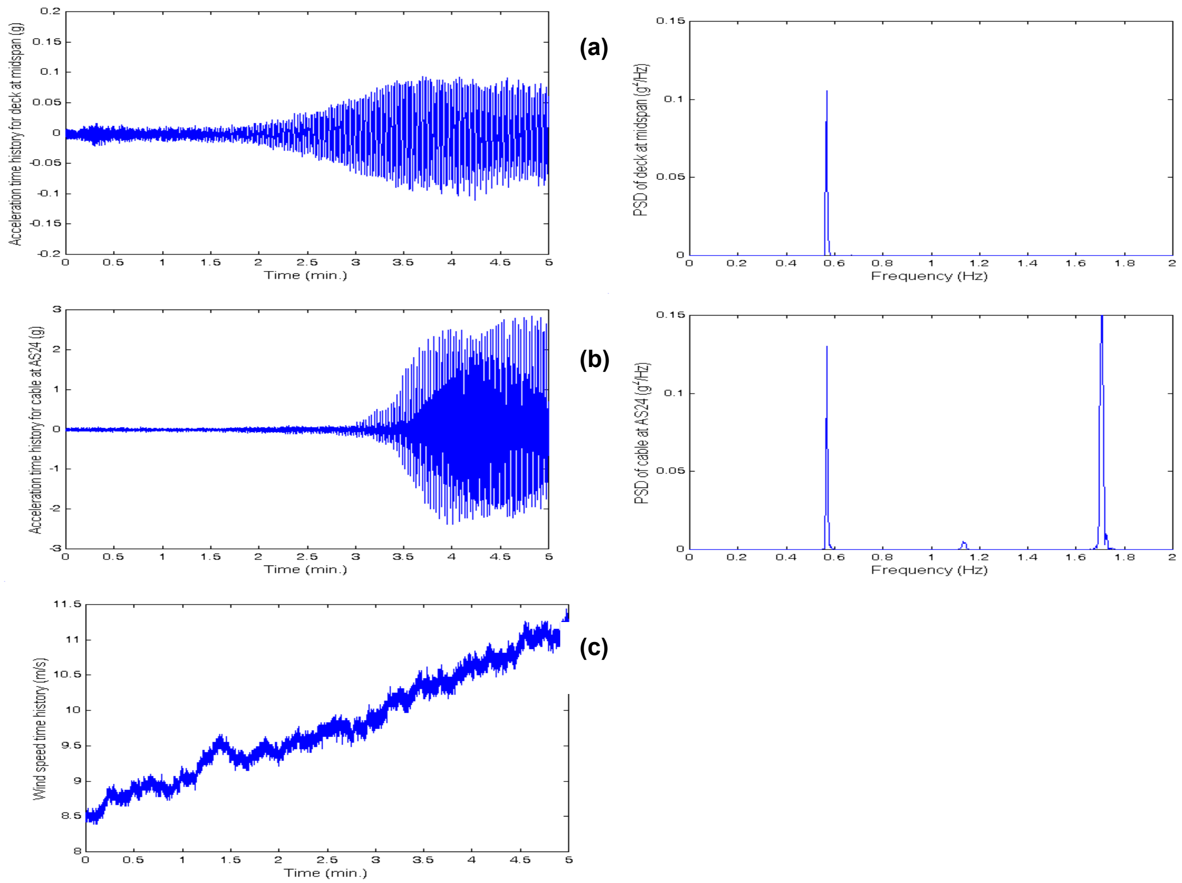

Figure 9. Time history and power spectral density (PSD) of acceleration for a) deck at midspan (vertical dir.), b) cable at AS24 (in-plane dir.) and c) deck level wind speed.