DYNAMIC MONITORING OF THE CONFEDERATION BRIDGE

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SUMMARY

The Confederation Bridge is one of the world's longest continuous prestressed concrete box girder bridge built over sea water. Because of its location and long span length, the bridge is subjected to significant dynamic loads due to wind, sea current, ice floe impact, earthquakes and heavy vehicles. This paper describes a long-term monitoring program on the dynamic behaviour and performance of the Confederation Bridge. The objectives and scope of the monitoring program, and the design and layout of the instrumentation, are presented. The network of monitoring instruments includes over 100 channels of accelerometers, dynamic tiltmeters, displacement transducers, strain gauges and wind anemometers, to obtain information about the vibrational behaviour of the various components of the bridge. Some ambient vibration data collected as part of the calibration and testing of the monitoring instruments are presented. The field measured data agree well with the results computed using three-dimensional finite element models of the bridge, thus confirming the proper installation and operation of the monitoring equipment. In the study of the dynamic properties of the bridge, the effects of the non-structural components, such as the barrier walls and pavement materials, and the interaction effect of the surrounding water are considered. The monitoring project will not only establish a large comprehensive database on the dynamic behaviour and performance of such a unique concrete structure, but will also provide information for effective maintenance of the facility

INTRODUCTION

The Confederation Bridge is a unique long-span structure. Because of its large size and long span length, its design is not covered by any existing design codes or standards. Typically, long-span bridges are very flexible structures. For the design of this type of structure, the dynamic and vibrational load effects are especially important factors, which must be carefully considered in the design. The ability to accurately predict the dynamic response of the structure to various critical transient load effects, such as wind and earthquake and traffic induced vibrations, is essential for a safe and high performance design. At present, engineers lack information and data on the dynamic behaviour and performance of long-span bridges. Full-scale monitoring of complex long-span bridge structures is rare. The Confederation Bridge offers an excellent opportunity to obtain vital information and to verify the design assumptions adopted in the design of this structure [Tadros, 1997]. As part of a comprehensive monitoring and research project on the behaviour and performance of the Confederation Bridge, this paper describes the design and layout of the instrumentation for dynamic monitoring of the Confederation Bridge. Other monitoring areas in the overall program are ice forces, thermal stresses and short and long-term deformations [Cheung et al, 1997].

The dynamic behaviour and performance of bridges depend on a number of structural parameters and environmental factors. These include the geometric and material properties of the structure, the sub-soil conditions and the degree of fixity and flexibility of the bridge foundation, and the environment and geological conditions of the region. Presently, little information is available on the effects of earthquake on the

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performance of long-span structures. Historical seismological records show that major earthquakes had occurred near the bridge site in nearby New Brunswick [Hasegawa, 1986]. As presently, there is very little information and data on the characteristics of eastern North America earthquakes, seismic monitoring of the Confederation Bridge will provide useful information on east coast seismic activities in the region as well as the effects of seismic ground motions on long-span large scale structures.

DYNAMICS MONITORING

The main part of the bridge consists of 45 spans in 22 repetitive units. Each unit is a one-bay rigid frame of 250 m wide with two 96 m overhangs at a height of 40 m above the mean sea level. There are two types of drop-in span girders used in the bridge, continuous and simply supported. The continuous drop-in span girder forms the centre part of the rigid frame unit. Adjacent rigid frame units are connected by a simply supported drop-in span of 58 m long making the total span length of the hinged span 250 m, same as the rigid frame span.

To minimize the cost of monitoring and to obtain data that are correlated with other monitoring areas in the Confederation Bridge monitoring program, the dynamic monitoring instruments primarily consisting of accelerometers are installed in the same two consecutive spans as the other areas, one rigid frame span and one hinged drop-in span, located in the deep-sea part of the strait. In addition, the dynamic response of four consecutive piers are also monitored, two within the instrumented spans and two adjacent to them, to investigate the spatial effects in the response of large structures. Overall, the dynamic response due to wind, ice floe impact, earthquake and traffic induced vibration are measured by a network of 76 accelerometers, 6 dynamic tiltmeters, and 8 displacement transducers across the expansion joints of the instrumented spans. Locations and installation details of the accelerometers are shown in Figures 1 and 2, respectively.

Main girders

Because long-span bridges are very flexible structures, torsional components as well as transverse components are important in the vibrational response of these structures. In the dynamic monitoring program, the acceleration response at 13 sections of the main girders are measured. To study the difference in the vibrational behaviour of the two types of spans and the influence of the expansion joints on the propagation of vibrational motion along the bridge, the dynamic behaviour of an adjacent simply supported drop-in span are also monitored. Three accelerometers are installed on each monitored girder section. The locations of these accelerometers on the cross-section and the orientations of their measurement directions are shown in Figure 1(b). The vibration instruments are installed on the interior surfaces near the top of the webs. The torsional, lateral transverse and vertical transverse vibrational responses of the cross-section are measured. The relative sliding movement at the expansion joints between piers 30 and 31 and between piers 32 and 33 are measured by displacement transducers. Four displacement transducers are installed at each joint to detect the relative translational movement and rotation at the joint. Details of the displacement measurement can be found in the reference by Dilger and Loptson (1997).

Pier shafts

The dynamic response of the pier shaft are measured at two locations, one at the top of the ice shield approximately 3 m above the mean sea level and another at the top of the pier shaft about 0.5 m below the matchcast at the junction between the pier shaft and the main girder, as shown in Figure 2. Accelerations in both the longitudinal and transverse directions are measured by two accelerometers mounted perpendicular to each other at each location. It is noted here that while the present dynamic instrumentation scheme can capture the flexural response of the pier shaft, the torsional components in the pier shaft response are not directly measured but can be determined from analysis of the pier shaft and the main girder monitoring data.

In addition to monitoring the acceleration response at the two indicated locations of the pier shafts, dynamic tiltmeters that can measure rotation or tilt of the pier shaft in both the longitudinal and transverse vertical planes are installed at the same locations of the accelerometers in the centre two pier shafts to give additional information on the deformation of the pier structures. The tiltmeters are part of the instrumentation for ice force monitoring [Brown, 1997].

Pier bases

For measuring the dynamic response at the pier base, accelerometers specially designed for underwater application to withstand immersion pressure up to 5 MPa are installed on the vertical interior surface of the pier base at a location approximately 2 m above the base of the ring footing, as shown in Figure 2. All three translational components of the motion, in the transverse, longitudinal and vertical directions, are measured. The ring footing of the pier base is placed directly on the ocean bedrock. The bottom of the pier base is not anchored to the supporting subgrade. Thus under large lateral loads such as that due to strong wind, severe earthquakes or major ice events, the ring footing may rock or uplift from its supporting foundation. The rocking or rotational dynamic response at the bottom of the two centre pier bases can be determined from measurements of additional accelerometers shown in Figures 2(a) and 2(c).

Spatial effect

For large structures with dimensions that are significant in comparison with the propagation velocity of the seismic waves, such as long-span bridges and dams, the input motions at different support points of the structures can vary significantly from each other. The effects of these spatial and temporal variations in the excitation motions on the response of large structures have not been fully investigated. Presently, there is very little information and no detailed systematic field observation data on this spatial effect. The Confederation Bridge offers an excellent opportunity to obtain information. By examining the time delay effect and the differences in the measured data from the four monitored pier bases, the spatial variation effects of earthquake ground motions and their correlation with the dynamic response of the bridge can be studied through evaluation of the power spectral density function, cross correlation function, envelope function and duration of the measured data [Hao and Lau 1992].

Wind measurement

Wind tunnel tests of models of the bridge were conducted at the Boundary Layer Wind Tunnel Laboratory in the University of Western Ontario to determine the wind design loads [King and Davenport, 1994]. Information on wind speed and distribution around the bridge girder were obtained from these tests and used in the design of the bridge structure. One objective of the dynamic monitoring program is to verify these design parameters and improve the wind tunnel testing techniques and the design procedures of using wind tunnel test data. For wind monitoring, the critical wind data including wind speed and direction at the instrumented span and at the navigation span, which is the highest point of the bridge and thus subjected to the highest wind speed at the bridge site, are measured by two anemometers at each location. At the instrumented span, all three components of the wind speed in the transverse, longitudinal and vertical directions to the bridge span are measured. The wind monitoring instruments are mounted 2 m above the top of the light posts at a height of about 12.2 m above the road surface on both sides of the bridge deck.

The wind anemometer data are sampled at the rate of 1 Hz. The measured wind data are statistically evaluated and stored by the data loggers. In the monitoring program, the data loggers are programmed to operate in one of two operating modes as follows

- Normal operating mode: Under normal operating condition, only the statistical values of the mean, standard deviation, maximum and minimum calculated over a 10 minute time interval are stored by the data acquisition system.
- Event triggering mode: Under high wind condition when the measured wind speed exceeds a pre-defined threshold value of 25 m/s, time history wind data are collected by the data loggers at the sampling frequency of 1 Hz.

The measured wind data show that significant changes in the wind condition and wind speed can occur at the bridge site within short period of time. It can also be observed that windy condition may sustain over a period of more than 24 hours, whereas moderate gusty wind condition can last for several days.

Dynamic Response Data collection

The dynamic structural responses of the bridge due to wind, traffic, ice floe and ridge impact and earthquake are measured by a network of accelerometers, tiltmeters and displacement transducers connected to a high speed data acquisition system made up of six high speed data logger units distributed over the instrumented sections of the bridge. Typically in the layout of the data acquisition system, the analogue signal outputs from the sensors are passed through a signal conditioning stage for amplification and anti-aliasing filtering. In the design of the monitoring system, particular attentions are paid to the requirements of the data acquisition system on high accuracy, long-term reliability and flexibility for future modification and improvement. Based on these performance criteria, the data loggers selected for the project have reserved speed and capacity to scan the dynamic monitoring channels at the sampling rate of 300 Hz with the corner frequency of the 8-pole low-pass Bessel filter used for anti-aliasing filter set at 50 Hz. The Bessel anti-aliasing filter is selected for its linear behaviour in the phase response of the concerned frequency bandwidth. Although the data loggers have the capacity to sample the dynamic response at 300 Hz, typical vibrational responses such as those at the pier shafts due to ice flow impact are sampled at the rate of 50 Hz with the corner frequency of the low-pass filter set at 5 Hz. For all dynamic monitoring data, the error due to aliasing is less than 1 part in 1000. After the filtering stage, all analogue signals are converted to digital form (A/D conversion) with 16-bit resolution for data storage. Finally, the data loggers are connected to a central control computer housed in a data control room inside the box girder on top of pier 31 by the integrated fibre-optic links of the data logger system. The central computer controls and coordinates the triggering and data collection functions of all the data logger units for both the high speed and slow speed data acquisition systems. It is mentioned here that the overall monitoring project has separate high speed and slow speed data acquisition systems to meet the different needs and requirements of the monitoring tasks from the individual monitoring areas. The main function of the slow speed data logger system, which consists of nine logger units, is to collect data for temperature effect and deformation monitoring. Although the two systems are essentially separated, they are controlled by the same central computer and the collected data from both systems are stored in shared hard disks, which are later automatically downloaded to a on-shore computer located in the bridge operating building on the PEI side of the bridge through two high speed fibre-optic lines. From the on-shore computer which serves as the on-site data management and communication node of the monitoring system, the monitoring data are transmitted to Ottawa via high speed data links for detailed analyses and research.

Similar to the procedure in measuring wind data that in addition to manual triggering, the data loggers collects dynamic response data in two operating modes:

- Normal operating mode: Under normal operating condition, the dynamic response data are collected continuously in a 60 second time interval overwriting loop. With the continuous time loop data collection process, the data loggers will always keep track of 60 seconds of time history response data from all the monitoring sensors. If there is no major dynamic event at the end of the time loop interval, the data loggers will store the time-averaged statistical values of the mean, variance, and maxima and minima of the dynamic data collected during the time period.
- Event triggering mode: In the event of significant dynamic activities due to wind, traffic, ice floe impact and earthquakes detected by any one of a pre-selected set of triggering sensors exceeding the pre-defined threshold value, the entire set of the time-series data from all the dynamic monitoring channels will be collected and stored by the network of high speed data loggers. Upon termination of the triggering event, the system will continue to collect dynamic time history data for an appropriate short period to capture the free vibration response of the structure.

All the dynamic monitoring data are synchronized in time by the data logger system, so that the dynamic responses of the bridge due to different transient load effects can be differentiated and separated out from one another, if necessary.

FREE VIBRATION MODAL ANALYSIS

The free vibrational behaviour of a rigid frame unit in 30 m depth of water have been analyzed to provide insight on the dynamic behaviour of the completed structure, and to establish requirements on the range of response measurement needed for the design of the dynamic monitoring instrumentation scheme. The modal properties of the rigid frame unit are determined by a finite element model of the bridge using 3D solid and shell elements. The model has a total of 1281 nodes and 508 elements with 7686 degrees-of-freedom. The first 4 vibrational mode shapes and the natural frequencies are presented in Figures 3-6.

The results of the three-dimensional model have been used to calibrate an equivalent beam model of the bridge, which employs three-dimensional beam elements to represent the behaviour of the structure. Forty equivalent beam elements are used to model the girder, and seven for each pier. The averaged geometric and mass properties are used in defining the dynamic properties of the element. The ice-shield is modeled as a concentrated mass lumped to the beam model of the pier at the mean sea level. The inertia effect of the neighboring drop-in span on each side of the structure is considered by adding one half of its total mass to the end of the supporting overhang. The results on the modal frequencies and mode shapes are the same as that obtained from the three-dimensional solid and shell finite element model.

To obtain information on the dynamic behaviour of the instrumented spans of the bridge, the rigid frame unit 15 of P29-30 and frame unit 16 of P31-32 together with the connecting hinged drop-in span are analyzed using the equivalent beam model. The effects of the non-structural components of the bridge are investigated by considering also the masses of the barrier walls and pavement materials in the analysis model. The effect of the water-pier interaction is also approximately accounted for by adding the distributed mass of the water displaced by the pier to the beam elements under water [Goyal and Chopra, 1989]. The analysis results are presented in Table 1 and Figures 7 and 8. The results show that the effect of the additional masses from the barrier walls and pavement are significant resulting in the reduction of the vibration frequencies by about 8 %, whereas the effect of the surrounding water is negligible for the size and weight of the pier considered. Similar results are obtained for the vibrational behaviour of three rigid frames which confirms that the vibration characteristics of the bridge can be obtained by measuring the dynamic behaviour of selected sections on the repeated components of the bridge as in the present dynamic monitoring program.

CALIBRATION AND FIELD TESTS

The dynamic properties and behaviour of the bridge can be significantly influenced by the environment and other factors at the bridge site. As an example, the effect of the piers vibrating and interacting with the surrounding water can be taken into account in the determination of the dynamic properties of the bridge by an added-mass procedure. But the determination of the effect of the winter ice cover in the strait on the dynamic behaviour and properties of the bridge is not as simple. For verification of the operation of the dynamic monitoring instruments as well as calibration of the dynamic models of the bridge, a series of ambient vibration and pull-release tests have been carried out to obtain information on the characteristics of some of the modeling parameters in the dynamic response models under different environmental, seasonal and load conditions. Ambient vibration tests of a partially connected rigid frame unit have also been carried out during the construction stage of the project.

Figures 9 and 10 show the sample time histories and Fourier amplitude spectra of the transverse and longitudinal accelerations, respectively, measured at location 4 on top of pier 32 due to wind loads. The first peak in the spectrum of the longitudinal component occurs at 0.4 Hz. This correlates well with the numerical results of 0.45 Hz for mode 5, the first vibration mode in the longitudinal direction by the two-frame equivalent beam model, as indicated in Figure 7. For the transverse component, the first peak of the amplitude spectrum occurs at 0.65 Hz. Similar results can be obtained in Figure 11 of the amplitude spectrum for the transverse acceleration component measured at location 5 of the main girder. This correlates with the transverse vibration mode shown in Figure 8.

CONCLUSIONS

A long-term dynamic monitoring program for the Confederation Bridge is described. The design and layout of the monitoring instruments are briefly discussed. The dynamic behaviour and properties of a single rigid frame unit and a section of the bridge comprising two consecutive rigid frames and one hinged drop-in span obtained from field measurements and computer analysis are presented. The results confirm the proper installation and operation of the dynamic monitoring instruments and provide insight on the expected dynamic behaviour of the Confederation Bridge.

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Table1: Natural frequencies (Hz) of two frames

	1	2	3	4	5	6	7	8	9	10
Case 1	0.3262	0.3417	0.3748	0.4471	0.4781	0.4888	0.5079	0.6527	0.7034	0.7546
Case 2	0.3031	0.3176	0.3484	0.4179	0.4462	0.4561	0.4742	0.6046	0.6541	0.7149
Case 3	0.3031	0.3175	0.3484	0.4176	0.4460	0.4560	0.4741	0.6043	0.6538	0.7132

Note: Case 1: Structure only, Case 2: Structure, Barriers & Pavement, Case 3: Structure, Barriers, Pavement & Water Effects

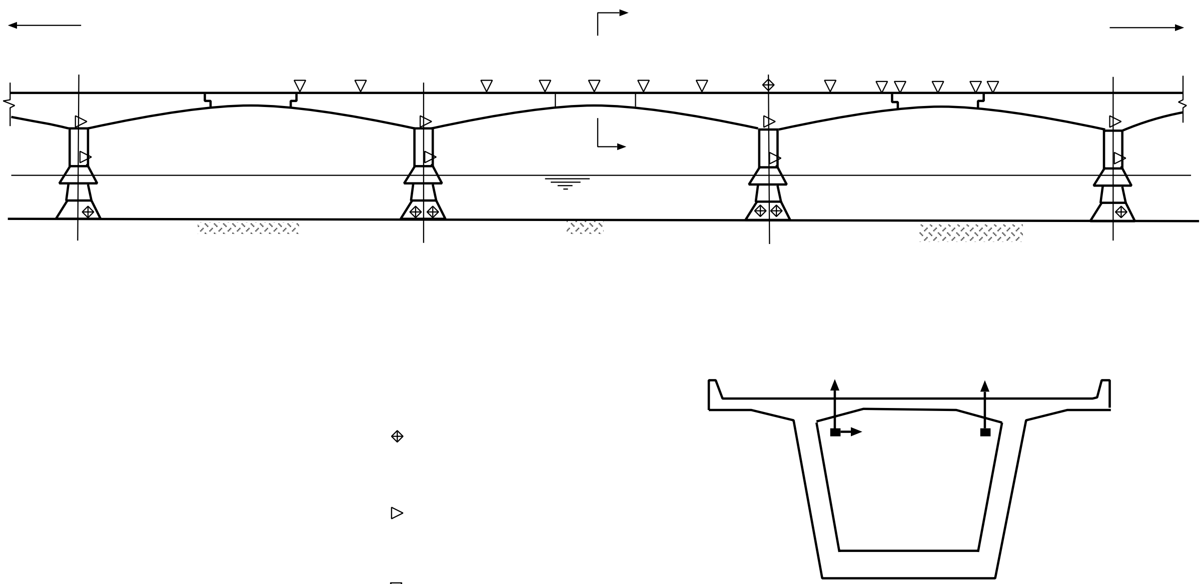

Figure 1: Location of accelerometers

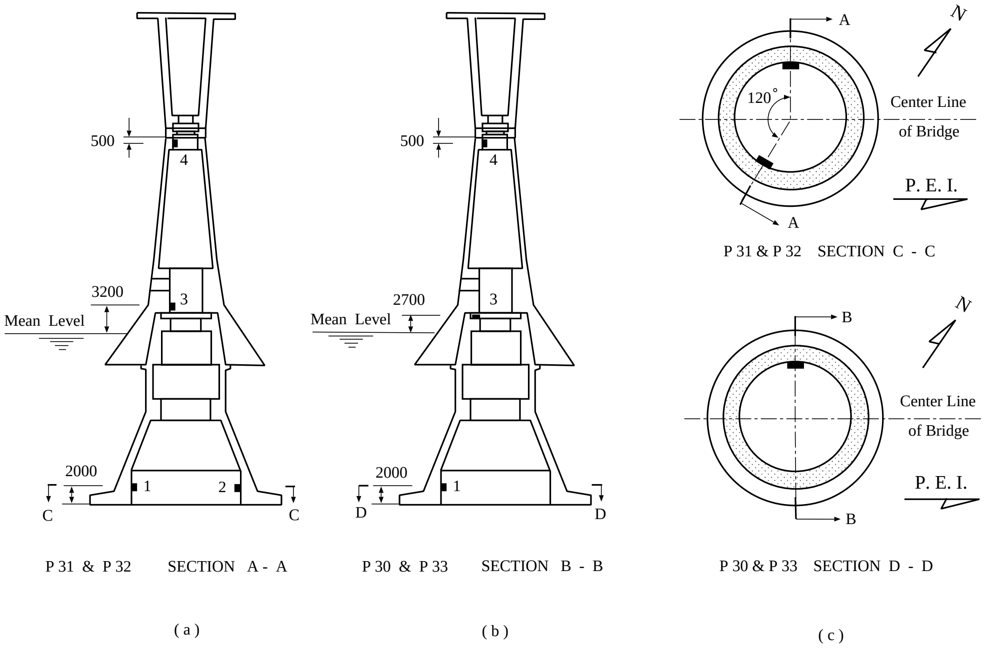

Figure 2: Typical installation details of accelerometers in bridge pier

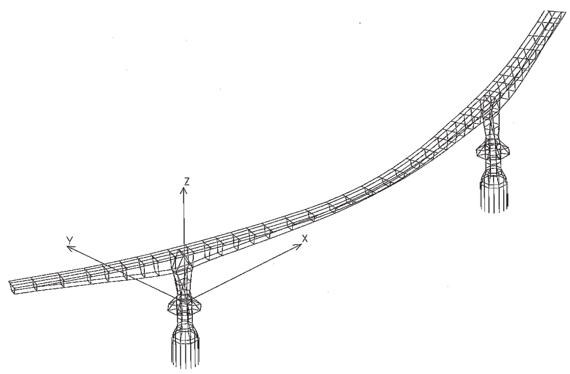

Figure 3: Mode 1, 0.31 Hz

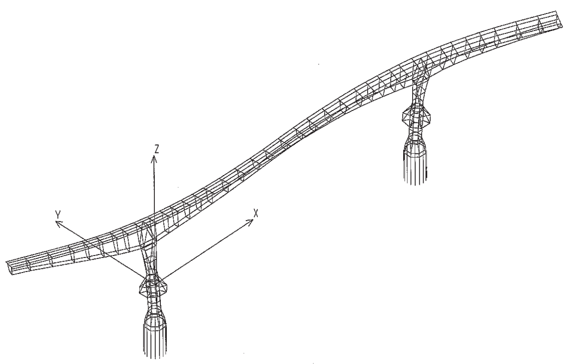

Figure 4: Mode 2, 0.34 Hz

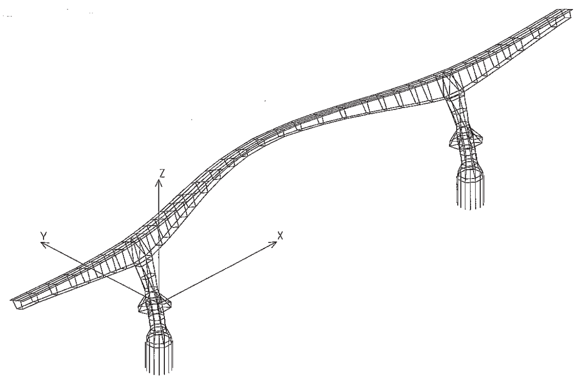

Figure 5: Mode 3, 0.40 Hz

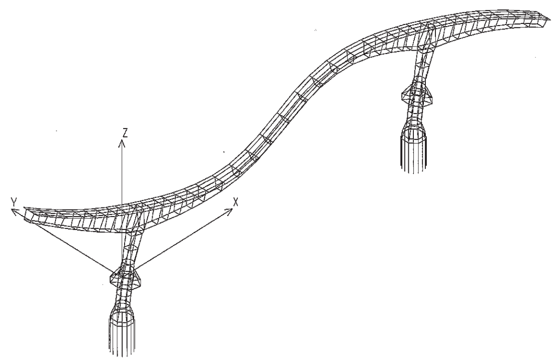

Figure 6: Mode 4, 0.44 Hz

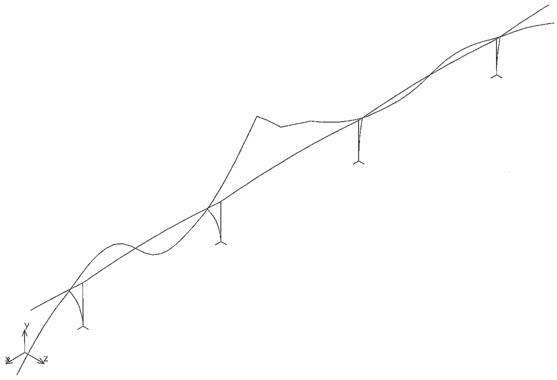

Figure 7: Mode 5 (0.45 Hz) 2-frame beam model

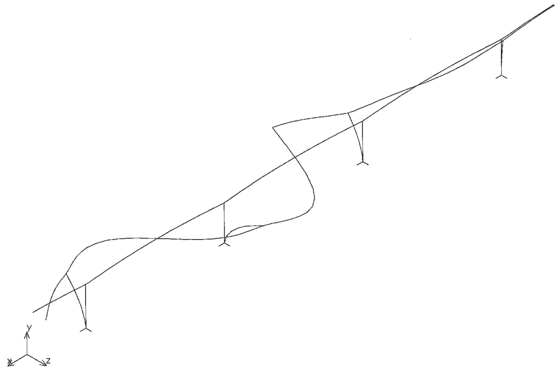

Figure 8: Model 10 (0.71 Hz) 2-frame beam model

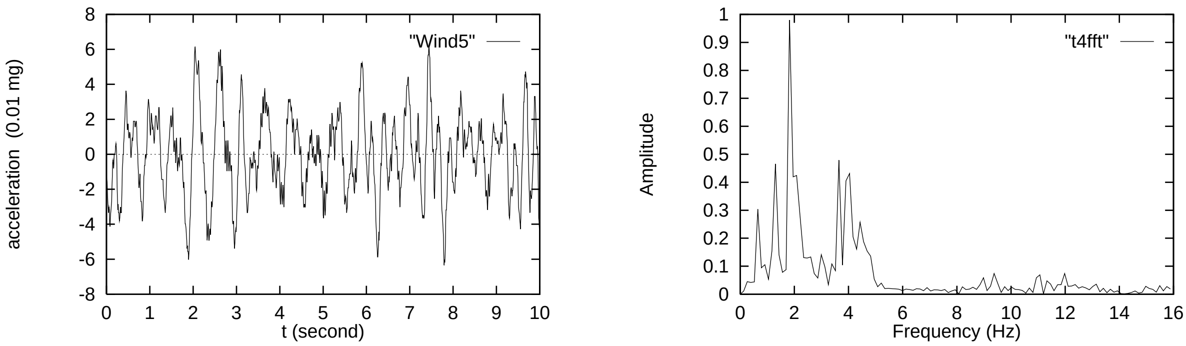

Figure 9: Measured transverse acceleration and amplitude spectrum at location 4

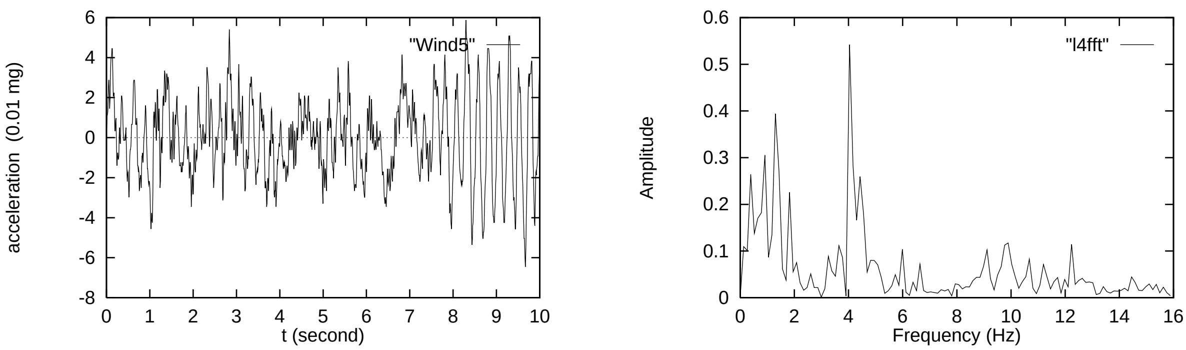

Figure 10: Measured longitudinal acceleration and amplitude spectrum at location 4

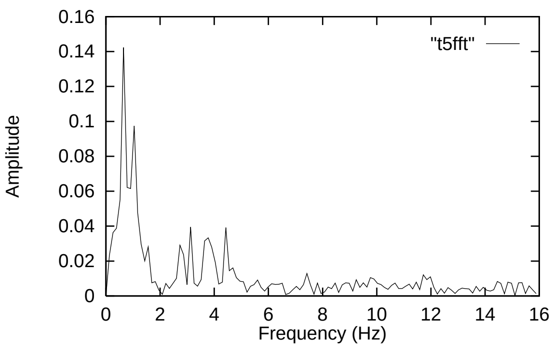

Figure 11: Amplitude spectrum of transverse acceleration at location 5