Chapter 15
System Identification and Displacement Profiles of Multi-Span Skewed Bridges with Seat Type Abutments

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Abstract Skewed bridges are classified as irregular structures due to the geometry of the deck and bents. The evaluation of their dynamic response is challenging as it requires a combination of several modes of vibration. In this study, the results of ambient vibration tests performed on four bridges in British Columbia, Canada are used to identify the dynamic properties and the displacement profiles of multi-span skewed bridges with seat type abutments. The frequencies of vibration, the modes of vibrations and the modal dampings are identified using frequency and time domain techniques. In addition, the directionality in the transverse and longitudinal response for skewed bridges with different levels of lateral restraint and deck flexibility is discussed. This paper improves the understanding of the dynamic response of skewed bridges, in particular their lateral response to seismic loads. This understanding contributes to having a better assessment of the seismic demands that skewed structures will undergo and to the development of displacement based design methods for these structures.

Keywords Skewed bridges • Ambient vibration tests • Displacement profiles • Seat type abutments

15.1 Introduction

Skewed bridges are irregular structures due to the geometry of the deck and bents (Fig. 15.1). A good understanding of the dynamic properties and the lateral displacement demands is needed in the current displacement-based design procedures for skewed bridges [1], in which the displacement demand is directly compared with the provided displacement capacity to ensure the desirable seismic performance. This is particularly important in skewed bridges with seat type abutments, in which, given their support details, pounding between the deck and its abutments is more likely to happen in many cases leading to the unseating of the superstructure.

Skewed bridges have different stiffnesses and strengths depending upon the orientation of the axes along which these properties are determined. An accurate estimation of the transverse and longitudinal demands is connected to a proper identification of the so called "preferred response directions". The preferred response directions are the directions in which the critical transverse and longitudinal demands respectively occur [2, 3]. These directions are given by the predominant directions of the transverse and longitudinal modes of vibration. A number of authors have conducted experimental and analytical studies to identify the dynamic parameters of skewed bridges with integral abutments [4–7]. However, a better understanding of the dynamic properties and the displacement profiles of skewed bridges with seat type abutments is required, and will improve the evaluation of the maximum displacement demands for these structures.

The University of British Columbia (UBC) and the Ministry of Transportation (MoT) have undertaken a study to evaluate the seismic response and the effects of Soil-Structure-Interaction (SSI) on skewed bridges. In this study, the whole soil-foundation-structure and embankment-abutment-structure systems are simulated using 3D finite element and simplified numerical models. The results are complemented with ambient vibration tests conducted at typical skewed bridges. This paper discusses the results for four multi-span skewed bridges with seat type abutments.

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Fig. 15.1 Typical multi-span skewed bridge

Fig. 15.2 Highway 99 and 24th avenue underpass (HWY 24th)

15.2 Description of Bridges

15.2.1 Highway 99 and 24th Avenue Underpass (HWY 24th)

The structure was built in 2006 and is located along Highway 99 in Surrey, British Columbia, Canada (Fig. 15.2). The bridge is 48 m long, 19 m wide, and has two continuous spans with seat-type abutments. The superstructure consists of a concrete deck slab supported on 0.8 m deep precast concrete box stringers. The substructure consists of 0.8 m diameter, 3.3 m high multi-column frames with concrete cap beams. The abutment and pier foundations consist of strip footings.

Fig. 15.3 Annacis highway and Highway 10 underpass (HWY 10th)

Fig. 15.4 Highway 1 and Lougheed highway underpass (LHH-EB underpass)

15.2.2 Highway 10 Underpass (HWY 10)

The structure was built in 1985 and is located along Annacis Highway in Surrey, British Columbia, Canada (Fig. 15.3). The bridge is 71 m long, 22.1 m wide, and has two spans with seat-type abutments. The superstructure consists of a concrete deck slab supported on nine 1.9 m deep, concrete I-girders. The superstructure is discontinuous and fixed-connected to the cap beam at midspan. The substructure consists of a multicolumn frame with a set of five concrete columns which are 1 m in diameter. The foundations consist of steel pipe piles filled with concrete.

15.2.3 Highway 1 and Lougheed Highway Underpass (LHH-EB Underpass)

The underpass was built in 2012. It is located in Burnaby, B.C. at Highway 1 and Lougheed Highway. The three-span bridge is approximately 135 m long and 26 m wide. Its construction consists of a concrete deck slab supported on 2.2 m deep steel girders, which are supported by multicolumn frames with a set of eight columns which are 1.22 m diameter. Both ends rest on bent abutments, and are connected by approach slabs. There are also expansion joints on all four spans. The foundation consists of 1.22 m diameter steel pipe piles (Fig. 15.4).

Fig. 15.5 Douglas road underpass (Douglas Rd)

Table 15.1 Summary of bridge characteristics

Structure	Length (m)	Spans No.	Spans Lengths (m)	Width (m)	Clearance (m)	Skew angle (degrees)	Substructure Type	Substructure Abutments	Superstructure type
HWY 24th	48	2	23-23	19	4.9	37	Multi-column-frames ($\phi = 0.8$ m)	Seat type	Continuous—concrete box girders
HWY 10th	71	2	36-36	22.1	9.1	31	Multi-column-frames ($\phi = 1.0$ m)	Seat-type	Discontinuous—reinforced concrete I-girders
LHH-EB Underpass	135	3	37-58-37	26	5.0	54–57	Multi-column-frames ($\phi = 1.22$ m)	Bent seat-type	Continuos—concrete steel girders
Douglas Rd	83	4	12-22-21-21	17	4.6	28	Multi-column-frames ($\phi = 0.6$ m)	Seat-type	Disontinuous—concrete box girders

15.2.4 Douglas Road Underpass (Douglas Rd)

The underpass, built in 1962, is located at Highway 1 and Douglas Road. It is four spans with a total length of 83 m and a width of 17 m (Fig. 15.5). The superstructure consists of a concrete slab deck with precast post-tensioned box girders. The substructure has multicolumn frames with four columns, which are 0.6 m in diameter. Pad footings are used for the piers. The abutments are seat-type; and the slab is discontinuous at midspan, whereas the girders are discontinuous at all supports. At the internal piers, expansion bearings exist; but at the abutments there are fixed bearings.

The following table summarizes the characteristics of the structures tested (Table 15.1).

15.3 Field Testing

Ambient Vibration Testing involves measuring a structure's response to typical forces that it is subjected to every day. These ambient forces can be wind, traffic, human activities, etc. This method of testing provides a cheap, non-invasive, and non-destructive method for obtaining modal parameters of large structures. With Ambient Vibration Testing you avoid having to physically excite the structure with heavy equipment, which results in the disruption of the structure's typical operation. The response that you obtain from these tests is characteristic of the true operating conditions of the structure. To obtain the modal parameters of the structure, Modal Operational Analysis algorithms are used to process the data [4, 9].

Ambient vibration testing is typically carried out by using sensitive accelerometers or other types of sensors, along with a multi-channel data acquisition system. Some inconveniences in using the sensors involve cable handling, sensor balancing, signal clipping, and power supply issues. The Earthquake Engineering Research Facility (EERF) at the University of British Columbia (UBC) carries out ambient vibration tests with its nine wireless Tromino sensors. These instruments were set to

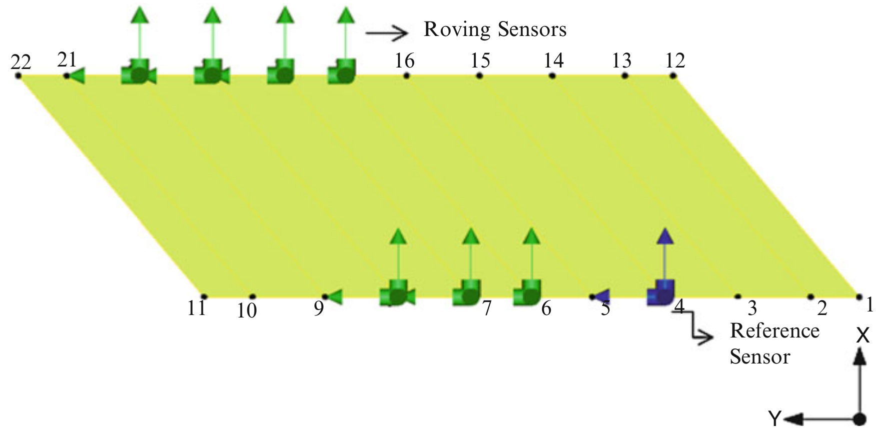


Fig. 15.6 Typical test setup for HWY 24th

record high gain velocities, low gain velocities and accelerations at 128 samples per second. The Trominos are equipped with GPS and radio antennas for time synchronization.

In 2012, members of the EERF-UBC team carried out ambient vibration tests on the HWY 24th, HWY 10th, LHH-EB Underpass and Douglas Rd bridges. During the tests, one unit stayed at the same location and is called a reference sensor, while the others are moved along the bridge to cover different testing locations and are called roving sensors. Figure 15.6 shows a typical test setup for HWY 24th. All the bridges were open to traffic. There were 20 testing locations along the sidewalks of HWY 24th, 32 along HWY 10th, 59 along LHH-EB Underpass and 38 along Douglas Rd. In addition to this, there were two testing locations at each approach and at least one free field measurement for all the bridges. All measurements were taken for 30 min in each setup.

It is important to point out that LHH-EB underpass was partially open to traffic, and did not have sidewalks. As a result, the test could only be conducted on the two southbound lanes that were closed to traffic.

15.4 Data Analysis and Results

The natural frequencies, mode shapes and dampings of the bridges were identified using the ARTeMIS Extractor [8].

For convenience, the presentation of results is divided into the identification of the dynamic properties in the vertical direction and the identification of the in-plane dynamic properties.

15.4.1 System Identification in the Vertical Direction

The Enhanced Frequency Domain Decomposition (EFDD) technique was used to undertake the modal identification analysis. For the Highway 99 and 24th Avenue Underpass seven modes of vibration in the vertical direction were clearly identified. For this two span continuous structure, Fig. 15.7 displays well-defined vertical antisymmetric, vertical symmetric and torsional modes. The system identification in the vertical direction undertaken for all the bridges is summarized in Table 15.2.

15.4.2 In-plane System Identification and Lateral Displacement Profiles

As traffic was the main excitation on the bridges, mainly the vertical modes are excited during the test and the identification of the in-plane motions (transverse, longitudinal and rotation) becomes more challenging. In order to identify the in-plane modes of vibrations, which are fundamental for seismic assessment, the Stochastic Subspace Identification (SSI) technique [9] was used, in addition to the Enhanced Frequency Domain Decomposition (EFDD) technique.

The frequencies and modes of vibration obtained using both techniques are similar (Tables 15.3 and 15.4). The frequencies are consistent with the boundary conditions of the bridges in each direction. For instance, HWY 24th has strong shear keys at abutments in the transverse direction and is seated on expansion bearing in the longitudinal direction. Consistently, the

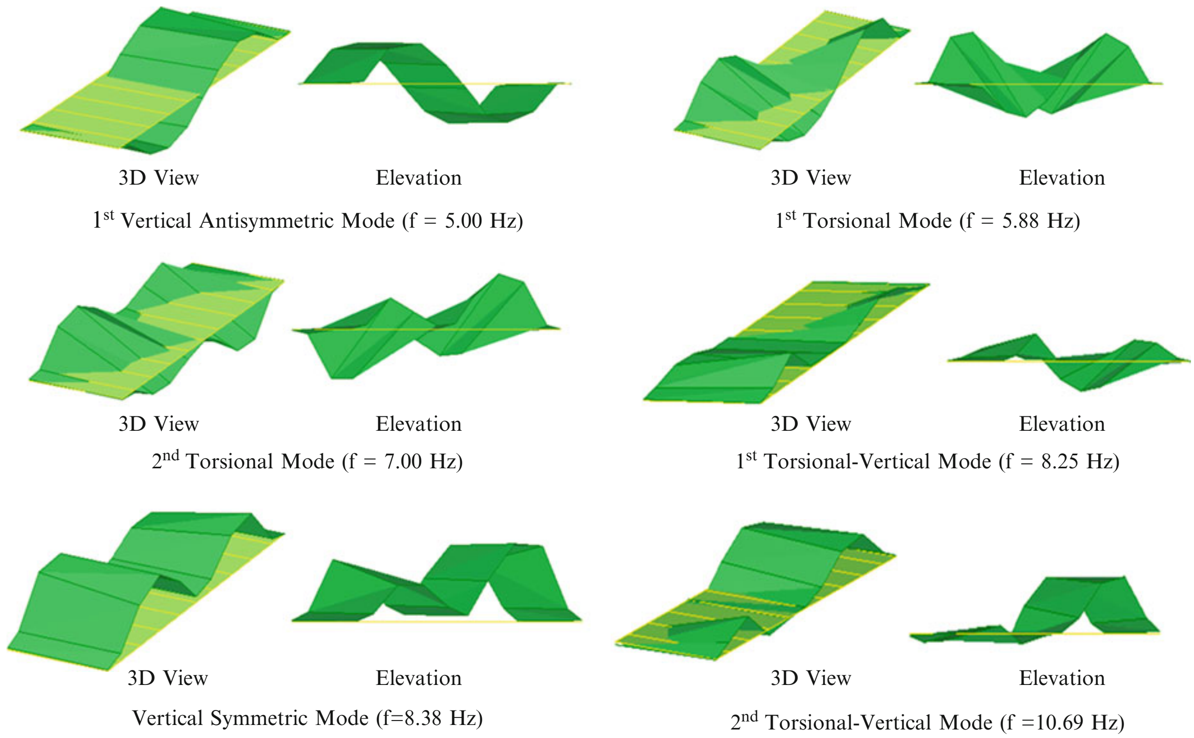


Fig. 15.7 Vertical and Torsional modes of vibration for HWY 24th

transverse frequency of vibration is 10.66 Hz, and the longitudinal 0.97 Hz. Similarly, HWY 10th, which is also a two span bridge seated on expansion joints but with weaker shear keys, has a transverse frequency of 4.76 Hz, and a longitudinal frequency of 1.09 Hz. The consistency observed between the frequency of vibration and the level of lateral restraint in each direction, also suggests that the modal response of skewed bridges could be uncoupled in each direction.

The frequency of vibration for in-plane rotation could only be identified for the HWY 24th (Table 15.3). The value obtained (11.72 Hz) is considered high, and is close to the transverse frequency identified (10.66 Hz). The damping ratios of the bridges tested are also similar in both techniques, EFDD and SSI. The estimated modal dampings vary from 0.24 % to 3.63 % (Tables 15.3 and 15.4). These in-plane damping ratios are similar to the values reported for straight bridges using ambient vibration tests [10].

The transverse and longitudinal modes of vibration are used to study the lateral displacement profiles of skewed bridges for different configurations and boundary conditions. As presented in Table 15.2, the transverse and longitudinal displacement profiles of a two span skewed bridge with seat type abutments and continuous deck as HWY 24th, is in agreement with a rigid deck assumption. In the same way, the transverse displacement profile of a three span skewed bridge with bent type abutments, expansion bearings, and continuous deck as LHH-EB Underpass, is consistent with a rigid deck profile.

In contrast, the transverse displacement profiles of a two span skewed bridge with discontinuous deck as HWY 10th, has a parabolic shape more in agreement to what is expected for a flexible deck. A similar flexible transverse profile is observed for Douglas Rd which is a four spans skewed bridge with discontinuous deck.

The transverse and longitudinal modes of vibration are also used to study the directionality in the lateral response of skewed bridges. The predominant direction of the mode is defined as the azimuth in which the mode tends to move. The predominant direction for each mode was estimated by comparing at abutments and at mid-span, the nodal coordinates of the undeformed geometry with respect to the nodal coordinates of the mode of vibration. The evaluation of the predominant direction of response for the bridges tested illustrates that the predominant direction of the transverse response occurs in the azimuth of the skew bents, whereas the predominant direction of the longitudinal response is perpendicular to the azimuth of the skew bents (Tables 15.3, 15.4 and 15.5).

Table 15.2 Summary of system identification in the vertical direction

Order	Freq. (Hz)	Mode characteristic
HWY 24		
1	5	1st Vertical Antisymmetric
2	5.88	1st Torsional
3	7	2nd Torsional
4	8.25	3rd Torsional
5	8.34	2nd Vertical Symmetric
6	10.69	4th Torsional
HWY 10		
1	5.406	1st Vertical Antisymmetric
2	5.688	2nd Vertical Symmetric
3	7.406	1st Torsional
4	7.781	2nd Torsional
5	10.41	1st Torsional-Vertical
6	10.78	2nd Torsional-Vertical
7	13.97	Torsional-Longitudinal
LHH-EB Underpass		
1	2.31	1st Vertical
2	2.77	1st Torsional
3	4.05	2nd Torsional
4	4.20	Torsional
5	5.06	Vertical
6	6.34	Vertical-Torsional
7	6.84	Vertical-Torsional
8	8.69	Torsional
9	9.59	Torsional
10	10.44	Vertical
11	11.63	Vertical
12	12.52	Vertical
Douglas Rd		
1	1.938	1st Torsional (Third Span)
2	2.625	1st Vertical
3	3.625	Longitudinal-Vertical
4	4.625	Longitudinal-Vertical
5	4.875	2nd Vertical Symmetric
6	5.313	3rd Vertical
7	6.688	Torsional
8	8.0	Vertical-Transverse
9	8.813	Vertical Antisymmetric-Transverse
10	9.063	Vertical Symmetric-Transverse
11	9.375	3rd Vertical
12	9.813	Vertical-2nd Transverse

15.5 Conclusions

The traditional approach for the assessment of the lateral demand of multi-span skewed bridges with seat type abutments considers that the transverse and longitudinal responses are coupled. In contrast, the result of the ambient vibration tests conducted in this research for bridges with different level of transverse restraint indicate that the lateral response can be uncoupled by using the transverse and longitudinal modes of vibration and their predominant directionalities. The results illustrate that the predominant direction of the transverse mode occurs in the azimuth of the skew bents; whereas the predominant direction of the longitudinal mode is perpendicular to the azimuth of the skew. These results were validated using analysis with the EFDD and the SSI methods.

In addition, the lateral displacement profile of the skewed bridges with continuous deck studied is in good agreement with the profile described by a rigid deck motion. On the other hand, the lateral displacement profile of the bridges with discontinuous deck seems to be more in agreement to the profiles described by flexible decks. Finally, in the vertical direction, the ambient vibration study captured the frequencies and modes of vibration below 13 Hz for all the bridges tested.

Table 15.3 Summary of in-plane system identification using the EFDD technique

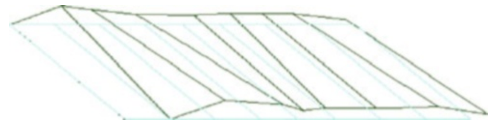
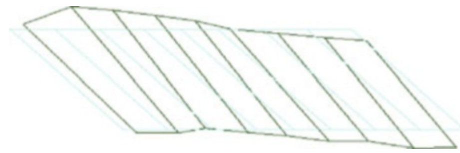
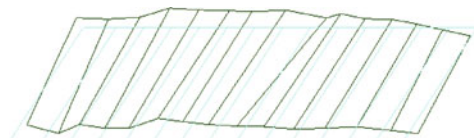
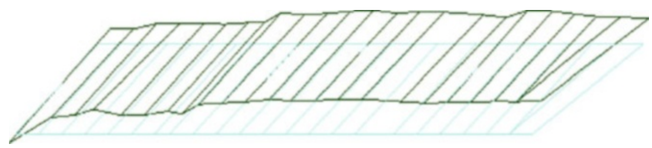
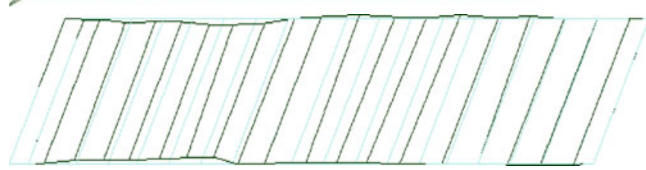
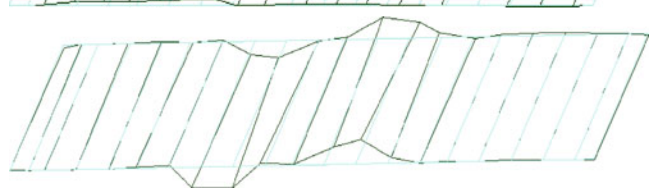
	Mode of vibration	Freq. (Hz)	ξ (%)	Description (plan view)
HWY 24th	1st Longitudinal	0.97	1.96	
	1st Transverse	10.66	1.53	
	In-plane Rotation	11.72	0.51	
HWY 10th	1st Longitudinal	1.09	0.57	
	1st Transverse	4.67	1.71	
LHH-EB Underpass	1st Transverse	1.72	3.05	
Douglas Rd	1st Longitudinal	2.31	2.36	
	1st Transverse	0.42	0.90	

Table 15.4 Summary of in-plane system identification using the SSI technique

	Mode of vibration	Freq. (Hz)	ξ (%)
HWY 24th	1st Longitudinal	–	–
	1st Transverse	10.52	2.15
	In-plane Rotation	12.44	3.63
HWY 10th	1st Transverse	4.69	1.96
LHH-EB Underpass	1st Transverse	1.96	1.90
Douglas Rd	1st Transverse	0.42	0.75
	1st Longitudinal	2.32	0.24

Table 15.5 Predominant direction of transverse response

	Azimuth of transverse mode (degrees)	Skew angle, ϕ (degrees)
HWY 24th	39 to42	37
HWY 10th	32 to 34	31
LHH-EB Underpass	54 to 56	54–57

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