Modal Analysis of Concrete Bridge Decks Subjected to Free Vibration

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ABSTRACT

This paper reports a study on free vibration dynamic analysis for determining vibration parameters such as natural frequencies and mode shapes for two selected bridges in Johor. The vibration parameters for these bridges are studied using finite element analysis software package ANSYS 6.0. A three-dimensional finite element model is developed for the bridges based on design drawing provided by the Public Works Department (PWD). Separate element types with same nodal layer are used as a modeling technique in this finite element analysis. Mode shapes based on natural frequency analysis are obtained for the bridges from the models with and without diaphragms. It is found that a moderately coarse mesh density of 1m for every edge element length would be sufficient for a majority of practical structural applications.

Keywords: *dynamic analysis, monitoring, finite element, vibration parameters*

Introduction

In Malaysia, there are only a few research works related to bridge health monitoring and the area is still new. Although bridge failures in Malaysia are rare, large stocks of bridges are suffering from deterioration and damage at a small fraction of their design life. Monitoring and assessing structural integrity of existing bridges would be very useful in detecting defects and deterioration at very early stage and helping decision-making related to maintenance and rehabilitation. Vibration testing based on dynamic analysis provides one of the effective means of bridge evaluation through the assessment of dynamic properties such as natural frequencies and mode shapes.

Problem Statement

Dynamic testing is performed on bridge structures for the purpose of identification of their in-service structural properties. These properties include the articulation conditions, the effective flexural and torsional rigidities of the deck, the level of damping of principle modes of vibration and also identification of local damages. Identification of these conditions is important to determine support conditions, performing amount of bridge load carrying capacity and condition monitoring of ageing bridge infrastructure.

Purpose and Scope

The objective of the study is to develop a simple model of selected bridges for dynamic analysis to obtain natural frequencies and mode shapes. For this purpose, ANSYS 6.0 program is used as a tool for numerical analysis of dynamic response data.

Two bridges in Johor are modeled as simply supported with slab and beams system in the case study. The bridges comprised of a cast in-situ concrete and pre-cast pre-stressed concrete bearing within linear elastic analysis. All data specifications and detail drawings are based on the document provided by the Public Works Department (PWD).

Literature Review

Dynamic Testing of Bridges

Dynamic testing techniques rely upon structural response measurements, taken over selected grid points of the bridge from a suitable dynamic excitation source to identify the natural frequencies and mode shapes. Excitation can be provided by either controlled vibration (e.g. use of impact devices, hammers and shakers) and random vibration (e.g. from natural traffic vibration).

Finite element analysis models of the bridge can be established and used to perform analysis for evaluating load carrying capacity or investigation of other performance criteria for the bridge.

Free Vibration

The frequency of the free vibration is an important dimension in vibration analysis and monitoring. In practice, vibrations are 'damped' as a consequence of energy loss and, therefore, die out (Collacott 1979).

Based on research carried out on dynamic tests on large cable-stayed bridge, the free vibration test was performed not only to check the main results of the ambient vibration test but essentially to permit an accurate identification of the damping factors associated with the modes of vibration. It gave more significant contribution to the dynamic response of the bridge particularly under wind loading (Cunha, et al. 2001).

Natural Frequency

A structure's dynamic behaviour is defined by a discrete spectrum of an infinite number of natural frequencies and corresponding mode shapes which are determined by geometry, distribution of mass, stiffness and boundary conditions. Within these parameters, changes in stiffness are directly related to changes in the safety condition of the structure. Therefore, it is essential to identify the damage in the structure by comparing the measured natural frequencies and mode shapes (Chen et al. 1995).

Numerous studies have indicated that an increase in damage reflects decreased natural frequencies of a structure (Chen et al. 1995). Morgan and Oesterle (1985) stated that abnormal loss of stiffness could be inferred when measured natural frequencies are substantially lower than expected. Sun and Hardy (1992) reported continual reduction in natural frequencies as the severity of induced deterioration increased. They reported that the original second and fourth modes, at advanced stages of deterioration, were not present. Various authors have quoted how frequencies have changed with ambient conditions. One extreme case was reported by Aktan (1994) where changes in natural frequency exceeding 5% were due to ambient effects within single day.

Mode Shapes

Once the resonance frequencies of a structure are found, the mode shapes at each of these frequencies may be determined. Some studies have suggested that changes in mode shapes may be more sensitive to damage than are natural frequency measurements and also may be able to identify the location. The greatest changes occur in the vicinity of the defect and appear to be more pronounced in the higher modes. In general, the mode shapes of the bridge could be classified as lateral modes, vertical modes, torsional modes and longitudinal modes (Xu et al. 1997). The number of points required to define a mode shape accurately depends on the mode and the number of degrees of freedom in the system.

Methodology

Developing an interactive methodology for constructing a reliable finite element models of the bridges involved a number of phases.

1. Development of a simple bridge model as a preliminary modeling to accommodate the requirement of dynamic analysis and, thus, sequential analysis steps. In this paper, ANSYS 6.0 software package is used in the modeling and this program permits the input of parameters to define bridge geometry and loading while retaining vast capability of a commercial code for both static and dynamic analysis.
2. Development of finite element models for typical and actual bridge structures to identify vibration parameters and determine the best method to represent these features in a finite element model.

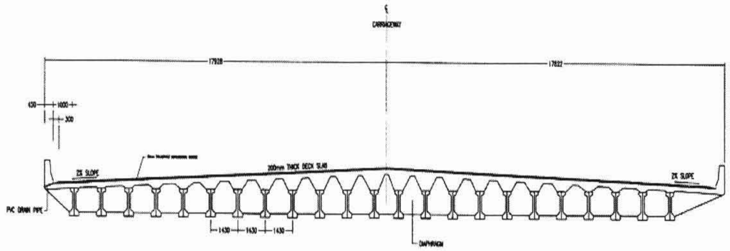
Bridge Case Studies

Two bridges around Johor Bahru have been selected in this study. The data for modeling is based on drawings provided by the PWD. The main objective of this study is to develop a simple model for the selected bridges to obtain natural frequencies or resonant frequencies and mode shapes. Modal analysis is selected to accomplish the objective. Block Lanczos method in ANSYS is applied to extract the eigenvalue and eigenvector of the models that finally gave eigenfrequencies.

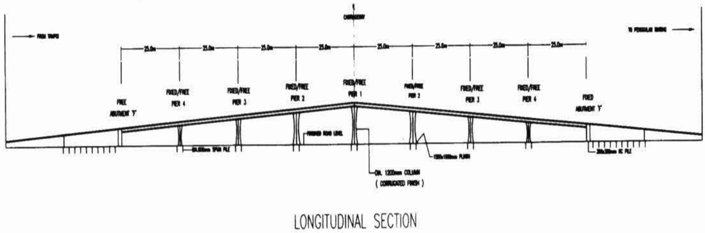
Description of Bridge 1

Bridge 1 is the Persimpangan Bertingkat of Persimpangan Jln. Persekutuan 1, Jln.Tampoi/Jln.Pengkalan Rinting, Johor Bahru, Johor. It is an eight-span simply supported bridge and has three lanes with double carriageway which crosses the main road Kuala Lumpur-Johor Bahru. The bridge has 23 pre-cast I Beam spaced at 1.43 m c/c, tied by 4 pre-cast concrete diaphragms 152 mm thick, spaced at 5 m c/c and two end diaphragms 305 mm thick for each span. The bridge supports a 200 mm thick cast in-situ concrete slab with 50 mm thick asphaltic concrete wearing course. Each span is 25 m and 35.75 m wide. There are concrete crash barriers on either side of the concrete slab. The pre-cast concrete beams are supported by elastromeric bearing pads. These beams are fixed on one end and free at the other end. The bridge is supported on concrete abutments at the end supports and on concrete piers at the inner supports as shown in Figure 1.

Description of Bridge 2



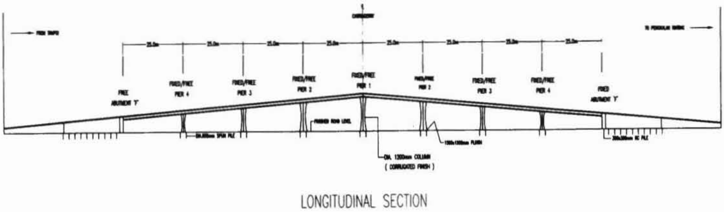
(a) Bridge Cross-sectional Section



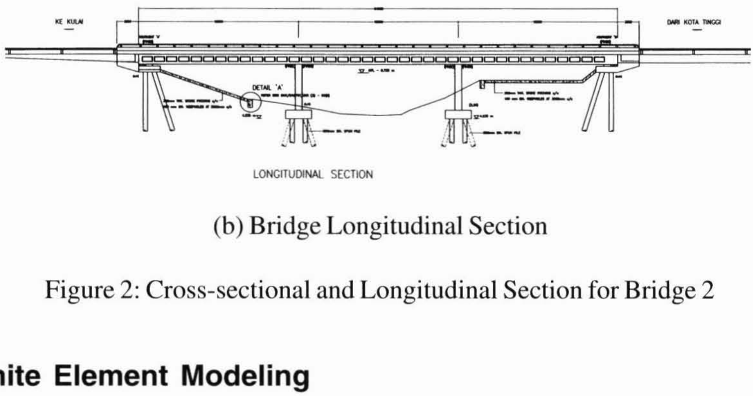
(b) Bridge Longitudinal Section

Figure 1: Cross-sectional and Longitudinal Section for Bridge 1

Bridge 2 is the Jambatan Sungai Skudai of Laluan F0094, Jln. Kulai/ Kota Tinggi, Johor. It is a three-span simply supported bridge and has two-lanes with double carriageway which crosses the Sungai Skudai. The bridge has 8 pre-cast I Beam spaced at 1.50 m c/c, tied by 3 pre-cast concrete diaphragms 152 mm thick, spaced at 4.36 m c/c and two end diaphragms 381 mm thick for each span. The bridge supports a 200 mm thick cast in-situ concrete slab with 50 mm thick asphaltic concrete wearing course. Each span is 18.3 m and 11.45 m wide. There are concrete crash barriers on either side of the concrete slab. The pre-cast concrete beams are supported by elastromeric bearing pads. These beams are fixed on one end and free at the other end. The bridge is supported on concrete abutments at the end supports and on concrete piers at the inner supports as shown in Figure 2.



(a) Bridge Cross-sectional Section



(b) Bridge Longitudinal Section

Figure 2: Cross-sectional and Longitudinal Section for Bridge 2

Finite Element Modeling

For the purpose of this study, a complete 3D FE model has been developed. This model is used in the dynamic analysis and consists of one layer of node which is assigned to the beams and deck with separate element type.

Element Type

Since all the modeling performed in this study is linear elastic, a selection of linear elements is made in order to model various aspects of the structures under consideration. These are:

- SHELL63. A 4-noded linear elastic shell element with both bending and membrane capabilities and 6 DOFs at each node. This is for use in the modeling of cast in-situ concrete slab considered in this study.
- BEAM4. A 2-noded linear elastic beam element with 6 DOFs at each node. This element is chosen typically for the modeling of elements which do not require their centroid to be offset from the location of the FE nodes. In this study, pre-cast I Beam and diaphragms is used this element type. This element type is used for the pre-cast pre-stressed I-Beam and diaphragms.

Material and Cross-Section Properties

Basic materials used in these two bridges are pre-cast concrete and cast in-situ concrete. The Young's modulus for the pre-cast prestress I-Beam is $34 \times 10^9 N/m^2$ while a value of $31 \times 10^9 N/m^2$ is assumed for other structural members including the end diaphragms, intermediate diaphragms and the deck slab. All members have a Poisson's ratio of 0.2 and a mass density of 2400 kg/m^3. The dimensions and sections properties of the pre-cast prestressed I-Beams are shown in Table 1 and the dimensions of the model structures are summarised in Table 2.

Table 1: Dimensions and Section Properties of Pre-Cast I-Beam

Description		Bridge 1	Bridge 2
Span range	L(m)	25.0	18.3
Depth	D(mm)	1245	1040
Weight	W (kN/m)	8.934	6.91
Sectional Area	A (mm^2)	372237	283875
Neutral Axis	Yt(mm)	697	579
	Yb(mm)	547	461
Moment of Inertia	Ixx (mm^4)	6.947×10^{10}	34.46×10^{10}
	Iyy (mm^4)	6.779×10^9	3.191×10^9
Section Moduli	Zt (mm^3)	99.84598×10^6	59.56×10^6
	Zb (mm^3)	126.49×10^6	74.76×10^6

(Source: HUME Industrial (M) Sdn. Bhd. and Freyssinet PSC (M) Sdn.Bhd.)

Table 2: Dimensions for Model Structures

Component	Dimensions
Concrete deck slab	200mm
Pre-cast I-Beam	As in Table 1
Intermediate Diaphragm	
Bridge 1	152 mm x 1067 mm
Bridge 2	152 mm x 710 mm
End Diaphragm	
Bridge 1	305 mm x 1067 mm
Bridge 2	381 mm x 710 mm

Finite Element Discretisation

In this study, the model is discretised by one metre at the edge length where the number of element divisions is 25 for Bridge 1 and 18 for Bridge 2. In order to check the accuracy of the selected mesh density, the models are refined by using 0.5 meter at the element edge.

Loading and Boundary Condition

Both bridges are modeled as having pinned support assigned at one end of the beam whereas the other end is specified as roller support. The pinned support is constrained in the x, y and z directions whereas the roller support is constrained in the x and y directions based on the global coordinate system.

The mechanical loadings involved in this modeling are pressure loading and self weight loading. Parapets (9978.4 N/m) is assigned as line loading to the structure and distributed uniformly along the edge of the deck slab. Finally, the gravitational loading (9.81 m/s^2) acts as a mass density of the structural models.

Analysis Type

Modal Analysis is the analysis procedure employed in this study. It is used to determine the natural frequencies and corresponding modes of free vibration for the structure. For this analysis, master degree of freedom and the number of modes to expand must be specified. The basic equation is solved in a typical undamped modal analysis. A shifted Block Lanczos method in ANSYS is chosen to extract the eigenvalue and eigenvector pairs. It uses the Lanczos algorithm where the Lanczos recursion is performed with a block of vectors.

Modal Analysis

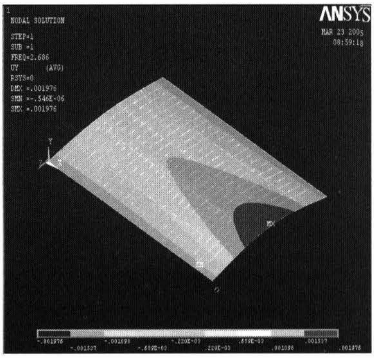
An ANSYS modal analysis is performed on the models of Bridge 1 and Bridge 2 to determine the fundamental frequencies and mode shapes of these structures. The results are shown in Table 3 for Bridge 1 and Table 4 for Bridge 2 while the forms of mode shapes for these bridges are shown in Figures 3 and 4.

Table 3: Natural Frequencies for Bridge 1 with Diaphragm and without Diaphragm

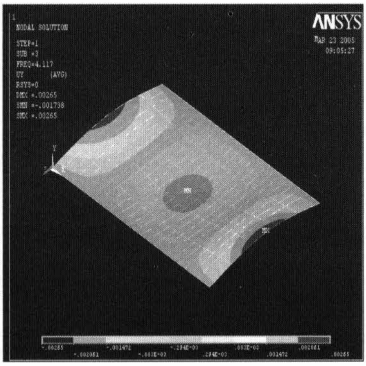
Mode Number	Natural Frequency (Hz)	Nature of mode shapes	Natural Frequency (Hz)	Nature of mode shapes
	With diaphragms		Without diaphragm	
1	2.69	Bending with single curvature	2.81	Bending with single curvature
2	3.00	Torsional	3.01	Torsional
3	4.12	Coupled mode	3.59	Coupled mode
4	6.02	Coupled mode	4.41	Coupled mode
5	8.81	Coupled mode	5.44	Coupled mode
6	9.91	Bending partially with double curvature	6.70	Coupled mode
7	10.94	Bending partially with double curvature	8.24	Coupled mode
8	11.91	Bending with double curvature	8.46	Bending partially with double curvature
9	12.54	Coupled mode	10.03	Coupled mode
10	13.62	Coupled mode	11.47	Bending partially with double curvature

Table 4: Natural Frequencies for Bridge 2 with Diaphragm and without Diaphragm

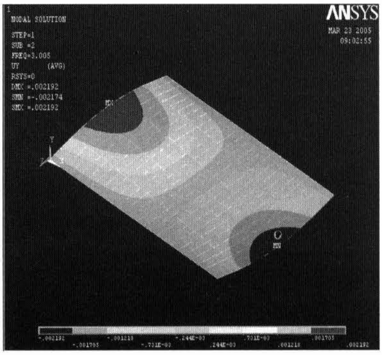
Mode Number	Natural Frequency (Hz)	Nature of mode shapes	Natural Frequency (Hz)	Nature of mode shapes
	With diaphragms		Without diaphragm	
1	4.04	Bending with single curvature	4.15	Bending with single curvature
2	6.26	Torsional	5.60	Torsional
3	11.97	Coupled mode	9.27	Coupled mode
4	16.12	Bending with double curvature	15.28	Coupled mode
5	18.52	Torsional	16.53	Bending with double curvature
6	21.65	Coupled mode	18.11	Torsional
7	24.78	Coupled mode	22.08	Torsional
8	33.11	Lateral	24.03	Coupled mode
9	34.80	Torsional	28.35	Torsional
10	35.77	Coupled mode	33.37	Lateral



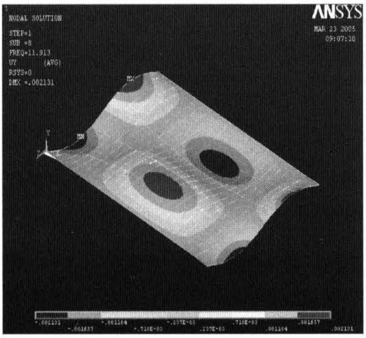
(a) Mode 1, 2.69 Hz



(b) Mode 2, 3.00 Hz



(c) Mode 3, 4.12



(d) Mode 8, 11.91 Hz

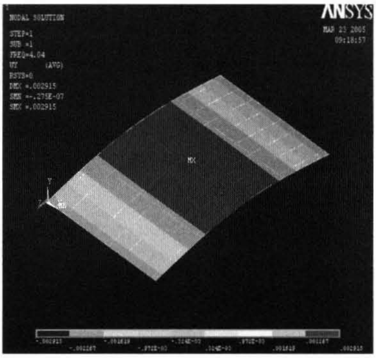
Figure 3: Nature of Mode Shapes for Bridge 1 (with diaphragms)

(a) Bending Mode with Single Curvature

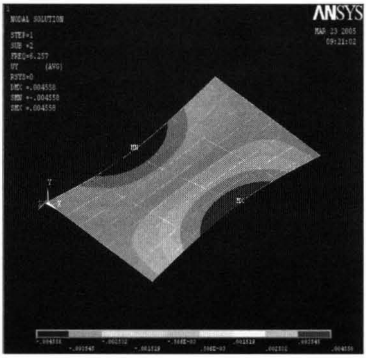
(b) Torsional Mode

(c) Couple Mode

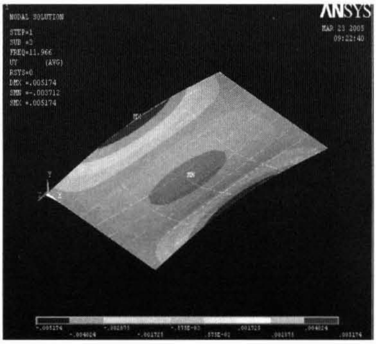
(d) Bending Mode with Double Curvature



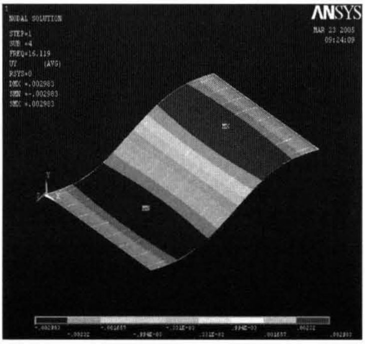
(a) Mode 1, 4.04 Hz



(b) Mode 2, 6.26 Hz



(c) Mode 3, 11.97 Hz



(d) Mode 4, 16.12 Hz

Figure 4: Nature of Mode Shapes for Bridge 2 (with diaphragms)

(a) Bending Mode with Single Curvature

(b) Torsional Mode

(c) Couple Mode

(d) Bending Mode with Double Curvature

Conclusion

The vibration parameters such as natural frequencies and mode shapes for two bridges in Johor are studied and obtained through finite element analysis. Generally, from these case studies several observations have been made as follows.

The difference between natural frequency for the model with diaphragms and the model without diaphragm is not significant. Both methods can be used as modeling techniques based on analysis purposes. If the actual configurations are needed, the model with diaphragms is more suitable to be used. However, for preliminary analysis, the model without diaphragm provides better results. In actual case, the natural frequencies model with diaphragms is mostly used when the field measurement is done. Barefoot (1997) found that diaphragms should be included in the finite element modeling of bridges for reliable dynamic response, particularly when torsional response is desired.

The aspect ratio between the length of span and the width of the bridge is important in determining the natural frequencies and mode shapes. In this study, it is found that when the ratio between length and width is bigger, the natural frequencies obtained are higher.

The nature of mode shapes for fundamental natural frequencies is normal in the bending mode as shown from this study for both bridges. Bending mode is subsequently followed by other nature of mode shapes such as torsional mode, coupled mode and later repeated with bending mode in double curvatures.

The accuracy of the model normally depends on the element type selected and FE discretisation. In this case SHELL63 and BEAM4 are selected as element types to analysis 3-D modeling. Results of previous research have proven that these element types are the most sensitive element in linear elastic model in order to predict the response. For FE discretisation, Hitchings (1992) stated that for dynamic analysis with displacement response and first few natural frequencies required the coarse mesh can be considered. It is shown in this study that the mesh density for 1m and 0.5 m for every edge length give similar natural frequencies for the first five modes. This indicates that a coarse mesh of 1m is sufficiently accurate for most practical applications, giving an advantage of a reduced computer time compared to finer mesh density.

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