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Dynamic Characterization and Damage Detection in Concrete Box Section Bridges of the Middle East

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ABSTRACT: This paper investigates the dynamic behavior of medium- and long-span concrete box girder bridges, commonly used in the Middle East. In addition, the paper examines using these bridges dynamic characteristics for damage detection. A theoretical investigation was conducted to determine the dynamic characteristics of three box girder bridges built in Egypt and Saudi Arabia. The resulting frequencies and vibrational modes were compared to those available in the literature. In addition, they were compared to those extracted experimentally for one of the examined bridges. A damage scenario was introduced to bridge models to examine theoretically its effect on the dynamic characteristics in the form of vibrational frequencies and mode shapes. The results generally show that utilization of dynamic characterization is a viable alternative for significant damage detection.

1 INTRODUCTION

Numerous researchers carried out theoretical and experimental studies to examine the behavior of box girder bridges including actual loading tests. In addition to static load tests, modal tests help in assessing the dynamic behavior of bridges. The goal of modal testing is to obtain a signature of the dynamic behavior of a structure in the form of mode shapes and frequencies. The frequencies of vibration are directly related to the stiffness and the mass of the structure. If the structure deteriorates, its stiffness will decrease resulting in reductions in frequencies and changes in mode shapes. As such, these tests can be used for bridge condition monitoring and damage detection.

The primary objectives of this paper are to: (1) outline the methodology of modal testing and possible excitation methods that can be used for concrete box girder bridges, (2) determine theoretically the dynamic characteristics of three different concrete box section bridges built lately in the middle east, (3) compare between those theoretically extracted properties and the experimentally determined ones for one of the studied bridges, and (4) examine the effect of a defect scenario on the dynamic characteristics of concrete box section bridges.

2 EXCITATION TOOLS OF BOX SECTION BRIDGES

The process of obtaining and processing the modal test data from a bridge involves two steps. The first is to acquire the data in the field. The second step is to combine all data and perform a modal analysis. The first step is performed by exciting the vibration of the bridge and measuring its response. With respect to excitation, two general source categories might be used: (1) tests with measured-input sources; and (2) ambient tests (Farrar et al 1999).

In the measured-input excitation, various forcing techniques are used including: shakers, step-relaxation, and methods of measured impact. Impact excitation offers the advantage of being quick, portable, and able to excite a broad range of frequencies. However, the input has a very high peak energy and low energy content creating signal to noise problems especially with large bridges as the case with concrete box girder bridges. Additionally, the extremely low frequency range encountered in testing concrete bridges requires extremely long sample periods to have reasonable frequency resolution (Maia & Silva 1997). In general, impact excitation is not practical for exciting lateral modes. On the other hand, step-relaxation input involves the sudden release of a static force that has been applied to a point of the structure, for example by using a released tensioned cable. This method can excite a wide range of frequencies, however, with inherent safety issues. Many measured inputs to bridge structures have been applied with electro-dynamic shakers with a considerable amount of infrastructure needed for their operation. They are not very portable and are relatively expensive and their ability to excite box girder bridges is limited.

Ambient excitation is that experienced by a bridge under its normal operating conditions such as that due to traffic and wind. For large bridges, ambient excitation is the most practical means of exciting the structure because of its ability to input significant energy into the structure. A drawback of using ambient excitation is that this type of input is often non-stationary. The varieties of ambient excitation methods that have been reported in the literature are: ambient test vehicles, ambient traffic, wind, or seismic shocks. Frequencies observed while test vehicle are on the bridge are not necessarily those of the bridge, but might be related to the natural frequency of the vehicle suspension system. Resonant frequencies of the bridge are typically calculated from peaks in the power spectral density functions. For bridges that can not be taken out of service, ambient traffic loading, coupled with other excitation sources such as wind, is the primary method for exciting the structure. Random traffic excitation has the limitation that it may not sufficiently excite the lateral modes which are often of interest in seismic studies. The literature review revealed that, in general, tests with measured inputs are conducted on short- to medium-span bridges. For large bridges, however, ambient test are probably the most practical means (Farrar et al 1999). Therefore, it would be advisable to utilize ambient excitation for modal tests of concrete box girder bridges.

3 THEORETICAL INVESTIGATION

A theoretical study utilizing the finite element method and a commercial software package was conducted to determine the dynamic properties of three box girder bridges built in the Middle East with span lengths between 23m and 150m. In the following, a description of each bridge is presented, the modeling technique is overviewed, and the results of the dynamic analyses in the form of vibration frequencies and mode shapes are displayed.

3.1 El-Moneeb Bridge

El-Moneeb Bridge crosses the Nile, linking El-Maadi district on the east bank to El-Moneeb district on the West Bank (see Figure 1). It is an 8 spans post-tensioned prestressed concrete segmental box-girder bridge. The bridge construction was completed in 2001. The bridge has two separate structures: one for the westbound traffic and the second for eastbound traffic. The first structure, consisting of twin parts four spans each, was selected for the current investigation. The span lengths are: 85, 150, 150, and 85m, respectively. The bridge is longitudinally prestressed. However, it is conventionally reinforced in the transverse direction.

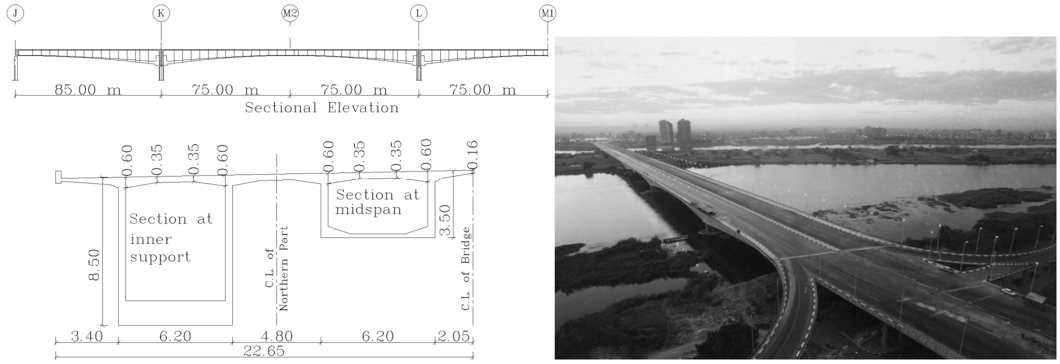


Figure 1. Sectional elevation, cross section, and a photo-El Moneeb Bridge

3.2 Thuwal Interchange Bridge

Thuwal Interchange Bridge carries Thuwal-Rabigh Expressway over Al-Qassim–Rabigh Expressway in Saudi Arabia. The bridge construction was completed in 2004. It is a Four-span post-tensioned prestressed concrete box-girder bridge with conventional reinforcement for the bridge cross section. The bridge is slightly curved in plan with a radius of curvature of approximately 700 m. Figure 2 shows a longitudinal section and transverse cross-section of the bridge. The spans lengths are: 42, 55, 55, and 42m, respectively. The superstructure rests on pot-type bearings supported by the columns and abutments.

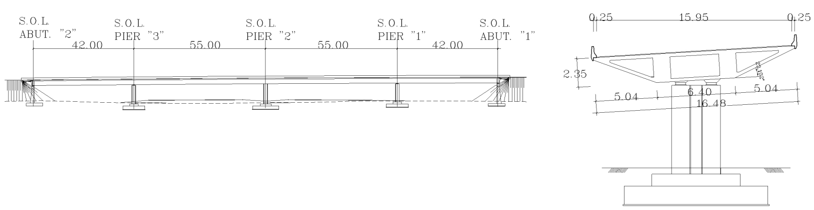


Figure 2. Sectional elevation and cross section-Thuwal Interchange Bridge

3.3 El Matar Bridge

Al-Matar Bridge carries the Northern International Road of Egypt over Al-Matar Road and a drain in Damietta Governorate-Egypt (see Figure 3). The bridge construction was completed in 2003. The bridge has two separate structures: the eastbound bridge and the westbound bridge. The eastbound bridge consists of twelve spans separated into four parts with three intermediate expansion joints. Different structural systems were used in this bridge. Composite concrete slabs and steel plate girders were used in the spans over the drain. In the remaining three sections, reinforced concrete box girders were utilized. The portion, between expansion joints, under consideration in the current study, has four spans with centerline lengths of 29, 29, 45, and 27m, respectively. The bridge is conventionally reinforced in the longitudinal and transverse directions.

3.4 Modelling

The three bridges superstructures were modelled using the finite element method. Sap 2000, a finite element software package, was used in the current investigation (1997). Shell elements were utilized to model the different elements of the box girders. To ensure reasonable analysis results, element sizes and lengths were selected following the requirements of AASHTO Standard Specifications (1998).

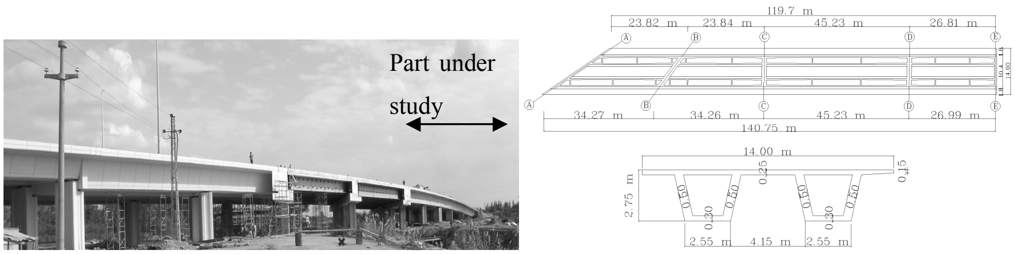
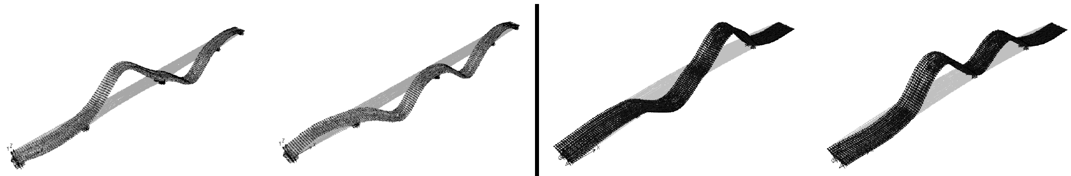


Figure 3. El-Matar Bridge- Damietta Governorate

In El-Moneeb Bridge, the resulting finite element model contained 5502 active nodes and 5850 elements with 33012 degrees of freedom. To verify the model, the theoretical model own weight, which is 303820 kN, was compared to that computed based on the geometrical dimensions of the bridge, which is 300970 kN. This clearly demonstrates the resemblance of the finite element model to the real bridge. The weight of the asphalt layer and other superimposed dead loads were not included in the model because the experimental dynamic test data available was for the actual bridge before adding these elements (Talha et al 2003). For Thuwal Interchange Bridge, the mass of the deck was modified to account for the presence of the super imposed dead loads. The model was verified by comparing the total dead load reactions to those in the calculation sheet of the bridge design with the difference being less than 2%. The maximum aspect ratio of the finite elements was 1.34. A similar approach was followed with respect to the Al-Matar Bridge. The mass of the deck was modified to account for the presence of the super imposed dead loads. To account for cracking in Al-Matar Bridge, a reinforced concrete bridge, the shell elements were assigned a reduced stiffness (75% of the crack-free stiffness) (Fayed et al 2002). El-Moneeb and Thuwal Interchange Bridge bearings are free, guided and fixed pot bearings. Due to their high stiffness, the bearings were replaced with restrains in the directions of movement restriction. Due to the flexibility of the elastomeric bearings used in El-Matar Bridge, the model was supported on elastic springs with equivalent stiffness to those of the bearings.

4 RESULTS AND DISCUSSION

The theoretical investigation yielded the dynamic characters of the investigated bridges in the form of vibrational frequencies and mode shapes. Figure 4 (a) and (b) show the first two bending modes of El-Moneeb Bridge. Figure 4 (c) and (d) show the first two bending mode shapes of Thuwal Interchange Bridge. Comparing the results of the two bridges, it is interesting to note that increasing the span length resulted in decreasing the fundamental frequency. This means that the fundamental vertical frequency is inversely proportional to the maximum span of the bridge structure. Figure 5 (a) shows the first mode of El-Matar Bridge. Due skewness, the first vertical mode was a coupled bending-torsional mode with a frequency of 3.71 Hz. As depicted in Figure 5 (b), the second mode was a pure bending mode with a frequency of 5.97 Hz.



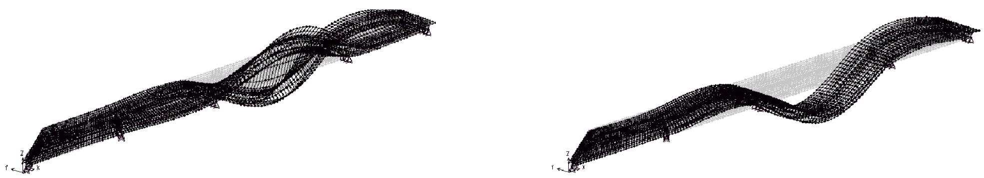
(a) Mode 1 - 1.37 Hz

(b) Mode 2 - 1.54 Hz

(c) Mode 1 - 2.39 Hz

(d) Mode 2 - 2.96 Hz

Figure 4. (a) & (b) are El Moneeb Bridge's first and second bending modes; (c) & (d) are Thuwal Interchange Bridge's first and second bending modes



(a) Mode 1: Coupled mode – 3.71 Hz

(b) Mode 2: Bending mode – 5.97 Hz

Figure 5. El Matar Bridge's first mode and second mode

In order to assess the results, they were compared to those available in the literature. Figure 6 shows the fundamental natural frequency as a function of bridge span for approximately ninety bridges tested by the Swiss Federal Institute of Technology (Hassan et al 1993) based on over 200 dynamic load tests of Swiss bridges. The regression line in the figure was proposed by (Cantieni et al 1984). On that figure, the fundamental frequency of the three bridges in the current study are marked by an oval for El-Moneeb Bridge, a square for Thuwal Interchange Bridge and a circle for El-Matar bridge. The theoretically determined frequencies lay in proximity of the regression line. It should be noted, however, that El-Matar Bridge has a fundamental frequency higher than that anticipated by regression line, probably because of its low span-depth ratio. On the other hand, Thuwal Interchange Bridge lies directly on the regression line and El-Moneeb Bridge lies outside and slightly below the regression line. Being above the regression line means that El-Matar Bridge is stiffer than the average bridge with a similar span length. On the contrary, El-Moneeb Bridge is more flexible than similar bridges with the same span length. Adding the superimposed dead loads would have caused increased flexibility of the bridge and would have caused the circle representing the bridge on Figure 6 to move further lower on the graph.

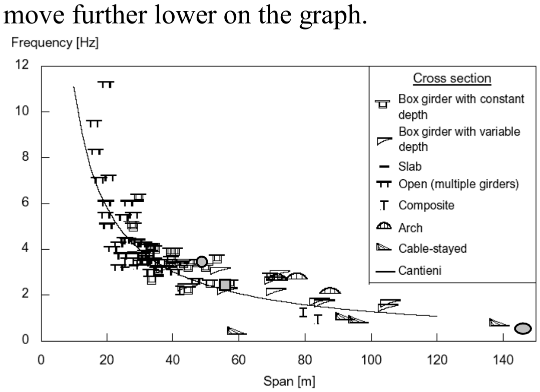


Figure 6. Fundamental frequency as a function in span length

5 COMPARISON WITH MODAL TEST DATA

Talha et al (2003) conducted a modal test on El-Moneeb Bridge. The excitation mean was either a concrete mixer filled with water or a mobile crane mounted on a truck, both travelling along the bridge at a speed of approximately 30 km/hour. The acceleration response of the bridge was collected at numerous locations.

In the current investigation, the test data were reanalyzed utilizing Origin 6, a commercial Windows-based spread sheet package (2001). Table 1 lists and describes the experimentally determined frequencies of vibration of the six detected modes. Moreover, the table lists the corresponding frequencies from the current theoretical study. The first detected mode has a frequency of 1.37 Hz.

On the other hand, for the second and the third bending modes, the actual bridge has a slightly lower frequency than the theoretical model. These modes have frequencies of 1.53 and 2.45 Hz, compared to 1.70 and 2.55 Hz from the theoretical model. Nevertheless, the close match between the theoretical and experimental results clearly indicates that the theoretical model is capable of representing the actual bridge structure after the simply adjustment. For the fourth bending mode and the second coupled bending and torsional mode, the experimentally determined frequencies were 3.10 Hz and 4.15 Hz, respectively. These were 22% and 18% less than the theoretically determined frequencies. It should be noted that this discrepancy might be attributed to the fact that the bridge is conventionally reinforced in the transverse cross section, and hence, its stiffness characteristics might be affected by the anticipated inertia loss due to cracking. Such phenomenon was not incorporated in the theoretical model. Being expressive of the actual bridge, the theoretical model may be used for evaluating changes in the dynamic behavior of the real bridge in the future.

Table 1. Vibration frequencies from current investigation and the theoretical study

Extracted frequency (Hz)	Theoretical model frequency (Hz)	Vertical Mode Description
1.37	1.37	First bending mode
1.53	1.70	Second bending mode
2.45	2.55	Third bending mode
3.10	3.96	Fourth bending mode
3.50	4.15	Second coupled bending and torsional mode
5.07	-	Vertical fourth bending

6 DAMAGE DETECTION USING DYNAMIC TESTING

In this section, the capability of dynamic testing as a damage detection tool for concrete box girder bridges is examined. To fulfil this objective, a theoretical parametric study to examine the influence of damage presence on the natural frequencies of box girder bridge models was conducted. Four bridge models were considered: (1) a one span simply supported single vent box girder, (2) a two-span single vent box girder, (3) a double vent simply supported box girder, and (4) a two-span double vent box girder. The span length of each of the investigated bridges is 30 meters. The bridge cross section is shown in Figure 7. The four bridges were modelled in SAP 2000 utilizing shell elements. Concrete cube compressive strength was 45 MPa and its Young's Modulus was 30000 MPa.

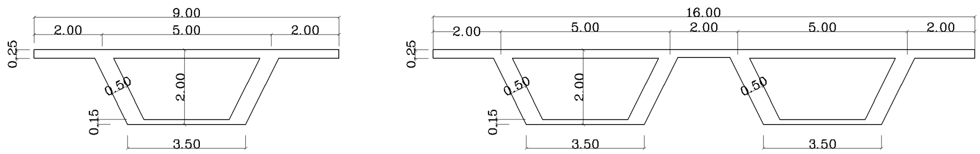


Figure 7. Cross sections of the bridge models

In this paper, only one damage scenario is introduced as shown in **Error! Reference source not found.**. The scenario simulates a flexural crack initiating in the inclined web at the mid span section of both simple and continuous bridges at the interface with the soffitt slab and is extending vertically and horizontally in the webs and in the soffitt until reaching the bottom of the deck slab. The damage progress was intended to model successive stiffness loss due to cracking rather than the crack propagation process. Cracking is represented in the theoretical model by reducing the modulus of elasticity of the shell elements neighbouring the crack to one-tenth its value. The damage index shown in Figure 8 represents the ratio of the length of crack at the shown damage stage to the length of crack at the end of Stage 7 of crack propagation. The dynamic analyses yielded the dynamic characteristics in the form of frequencies of vibration and mode shapes.

Several dynamic related methods can be used to detect and locate damages including natural frequency based methods, mode shape based methods, mode shape curvature methods, strain mode shape based methods, dynamically measured flexibility based methods, and matrix update based methods (Catbas & Aktan 2002). In the current study, damage is identified by shifts in natural frequencies and changes in mode shapes. Damage adversely affects the bridge stiffness, and hence, caused reduction in the vibration frequencies. In Figure 9, shifts in the fundamental frequency of vibration for each of the four bridge models are plotted versus the damage index. For 100% damage index, the frequency shifts were 13.3% and 7.4% for the simple span box girder bridges of single and double vents, respectively. For the same damage index, the frequency shifts were lower in the continuous bridges (6.3% and 3.3% for two-span single vent and two-span double vent bridges, respectively). As such, it can be concluded that frequency shifts are higher in simply supported bridges than in continuous bridges and are higher in single vent boxes compared to multi-vent boxes. From the graph, it is clear that bridges with alternative load paths would yield lower frequency shifts in response to the same damage. In other words, frequency shifts are lower in bridges with higher redundancy.

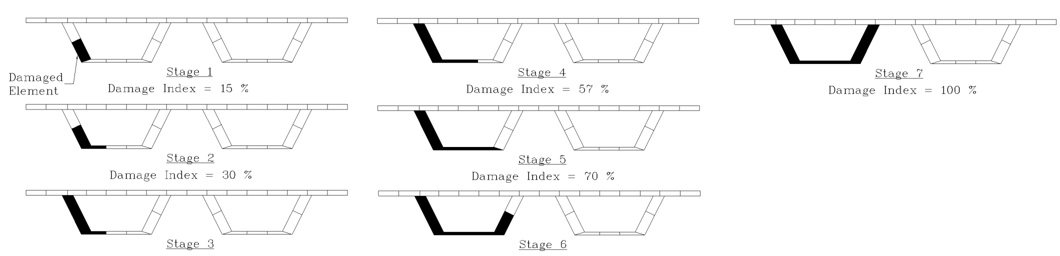


Figure 8. Crack progress in the box section bridge

It should be noted that previous research concluded that frequency variations due to incidental/ambient and environmental effects can be as high as 5–10% (Khalil et al 1998). It might be argued that lower frequency shifts would not necessarily be useful damage indicators.

However, environmental effects of air temperature, humidity, rain, wind speed were monitored for several bridge types and it was demonstrated that their effects might be filtered out. Accordingly, it was justified that stiffness degradations could be detected if the corresponding frequency shifts were more than 1.5% (Khalil et al 1998). As such, 28%, 35%, 36% and 56% damage index can be judged as detectable for single-vent simple, single vent continuous, double-vent simple, and double-vent continuous box girder, respectively as shown in Figure 9. In other words, it would be possible to detect a flexural crack propagating at the mid span section of a simple single vent box girder when it extends to mid heights of the webs.

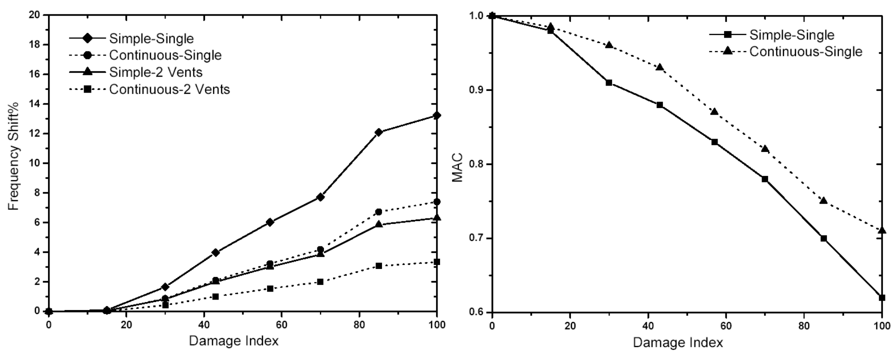


Figure 9. Damage index, frequency shift, and MAC value for Mode No. 8

Literature indicates that comparison of mode shapes is a more robust technique for damage detection than shifts in natural frequencies Salawu (1997). A common method to compare two mode shapes is the Modal Assurance Criterion, MAC (Allemang & Brown 1982). The MAC value can be considered as a measure of the similarity of two mode shapes and is given by:

$$MAC(\{\phi_i^X\},\{\phi_j^Y\}) = \frac{(\{\phi_i^X\}^T\{\phi_j^Y\})^2}{(\{\phi_i^X\}^T\{\phi_i^X\})(\{\phi_j^Y\}^T\{\phi_j^Y\})} \tag{2}$$

with $\{\phi_i^X\}$ = shape vector of Mode i of the structure in State X, $\{\phi_j^Y\}$ = shape vector of Mode j of the structure in State Y. A MAC value of 1 is a perfect match and a value of zero means they are completely dissimilar. Thus, the reduction of a MAC value may be an indication of damage. Previous research indicated that a MAC value less than 0.90 is a sign of damage presence. In Figure 9 the MAC value of Mode 8, the most affected mode by the present damage, for single-vent simple and continuous box girders before inducing the damage and with various damage stages is plotted versus the damage index. Clearly, the figure shows that 30% and 50% damage index is easily detectable for the case of simple and continuous bridges, respectively. This example clearly shows that modal testing may be used for significant damage detection.

7 SUMMARY AND CONCLUSIONS

The paper investigated the dynamic behaviour of concrete box girder bridges and examined using their dynamic characteristics for damage detection. The paper reviewed the available methods for modal testing and explored their use for box girder bridges. A theoretical investigation to determine the natural frequencies and the mode shapes of three box girder bridges was presented. A damage scenario was introduced to bridge models to examine its effect on the dynamic characteristics in the form of vibrational frequencies and mode shapes. The following conclusions may be drawn:

– Using ambient traffic excitation is viable for conducting modal tests on concrete box girder bridges.

– Dynamic analysis might be a means of determining differences in the signatures of different bridges. Further, dynamic response might be a means of identifying and characterizing box girder bridges

– Significant damages might be recognized using either frequency shifts and/or mode shape changes.

8 REFERENCES

American Association of State Highway and Transportation Officials, *Standard Specifications for Highway Bridges*, Sixteen Edition, Washington, DC, American Association of State Highway and Transportation Officials, 1998.

Allemang, RJ and Brown, DL. 1982. Correlation Coefficient for Modal Vector Analysis. Proceeding of the 1st International Modal Analysis Conference, 110-116, Florida, USA.

CANTIENI, R. 1984. Dynamic Load Testing of Highway Bridges. IABSE Proceedings, Zurich, 75-84.

Catbas, FN and Aktan, AE. 2002. Condition and Damage Assessment: Issues and Some Promising Indices. Journal of Structural Engineering, Vol. 128, 8: 1026–1036.

Farrar, CR, Duffey, TA, Cornwell, PJ, and Doebling, SW. 1999. Excitation Methods for Bridge Structures. *Proceedings of the 17th International Modal Analysis Conference* Kissimmee, Florida.

Fayed, MN, Mourad, S, Khalil, AH, and Bassyouni, G. 2002. Diaphragm Effect on Live Load Distribution Factors in Skew Steel Plate Girder Bridges. The Proceedings of Regional Conference on Civil Engineering, ASCE-Egyptian Section, Cairo, Egypt.

Hassan M., Burdet, O., and Favere, R. 1993. Interpretation of 200 Load Tests of Swiss Bridges. IABSE Colloquium: Remaining Structural Capacity, Copenhagen, Denmark.

Khalil, AH, Wipf, TJ, Greimann, LF, and Wood, D. 1998. Modal Testing for Nondestructive Evaluation of Bridges: Issues. The Proceedings of Crossroads 2000, 109-112, Iowa State University, Ames, USA.

Maia, NM, and Silva, JM. 1997. *Theoretical and Experimental Modal Analysis*. New York: John Wiley & Sons, Inc.

Ministry of Communications, Highway Design Manual: Volume 3-Structural Design Specifications, Kingdom of Saudi Arabia, 1992.

Microcal Origin, Microcal Software Inc., Version 6.0, Northampton, MA, USA, 2001.

Permanent Committee for Preparing the Bases of Computing Loads and Forces in Structural Works and Buildings, The Egyptian Code for Computing the Forces in Structural Works and Building, Center for Building and Housing Research and Urban Planning, Ministry of Housing and Utilities, Egypt, 1993.

Salawu, OS. 1997. Detection of Structural Damage through Changes in Frequency: a Review. Engineering Structures, Vol. 19, 9: 718–723.

SAP2000, Integrated Finite Element Analysis and Design of Structures Package, Computers and Structures, Version 7.40, California, 1997.

Talha, M, El-Attar, A, and Khalil, AH. 2003. Dynamic Testing of a Long Span Bridge. Journal of Engineering and Applied Science, Faculty of Engineering, Cairo University, Egypt.