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Ambient Vibration Test of Aswan Cable Stayed Bridge

アスワン斜張橋の振動試験

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The vibration test, which is an estimation of the modal parameter of a bridge on the basis of measuring the vibration of the bridge, was carried on the Aswan Cable Stayed Bridge in south of Egypt. The test was performed using a 300 kN truck traffic load. Eleven positions were used to monitor the bridge response. 3D model was performed for the bridge using finite element program. Fundamental frequencies and mode shapes obtained from the finite element model were compared to the experimentally obtained ones and were found in good agreement for the first modes of vibration. It seem that the obtained data is useful for monitoring based maintenance scheme.

Key Words: *Ambient vibration test, mode shapes, linear power spectra, modal analysis*

1. Introduction

Monitoring of existing structures is important within maintenance strategies. There are several approaches to interpret the mechanical performance of structures with non-destructive and simple procedures. Ambient vibration test is one of the effective approaches to monitor the performance of structures as a non-destructive test, and in addition to its advantages of cost reduction, and simplicity. The vibration test is an estimation of the modal parameter of a structure (frequency, damping ratio, and modal shapes) on the basis of measuring the vibration of the structure. The test results depend mainly on how to excite and vibrate the tested bridge to measure the bridge response for this excitation and then process the obtained data to get the dynamic properties. By surveying the previous works, many different types of excitation methods have been applied to bridge structures[1]. The methods of exciting a bridge can be classified into two categories:

- Measured-input tests: - It depends on forced vibration for a structure with measured input, such as using shaker[2),3)], impact[4),5)], and step relaxation method[6)].
- Ambient tests: - It depends on that the excitation experienced by a structure under its normal operating conditions, such as traffic[7),8)], wind[9),10),11)], and seismic ground motion excitation[12)], or using vehicles for test[13),14),15),16)].

In general, tests with measured-inputs are conducted on smaller bridges. For larger truss, suspension, and cable-stayed bridges, ambient tests become the only practical means of exciting the structure.

This paper represents an effort to assess the vibration test results using ambient excitation. The Aswan Cable-Stayed Bridge over the Nile River, located at Aswan in south of Egypt was selected. The tests were carried out as the construction of the chosen bridge had just been completed to obtain the initial data[17)].

2. Description of The Bridge and its Structural System

2.1 Bridge Super Structure

Aswan Bridge is a prestressed concrete cable-stayed bridge. The bridge connects roads in the East Bank with roads in the West Bank as a part of main new road constructed at the west of Aswan country with length of 120 km. The bridge length is approximately 980 m. It consists of three main parts:

- The eastern approach, which consists of eight prestressed concrete deck spans with a typical span of about 40 m length.
- The navigable part, which consists of a cable stayed pre-stressed concrete with navigation span of 250 m length.
- The western approach, which consists of three prestressed concrete deck spans with a typical span of about 40 m length.

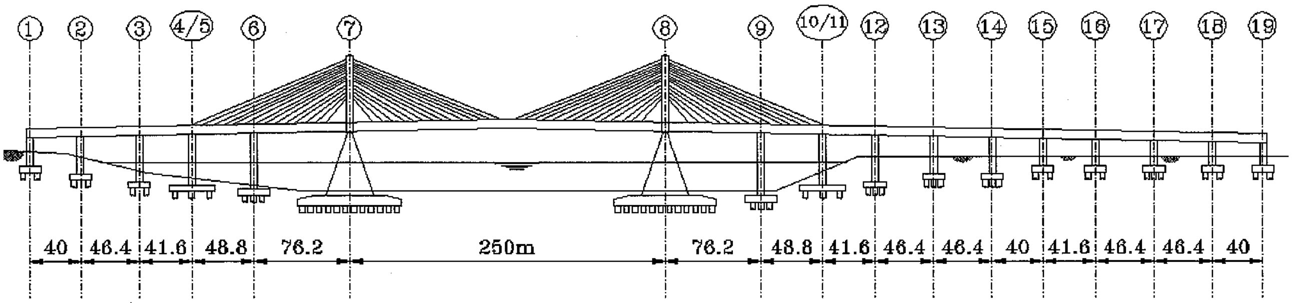


Fig.1 General layout for Aswan Cable-Stayed Bridge over the Nile

Fig.1 shows a general layout for Aswan cable-stayed Bridge. The test was performed on the cable-stayed part between the axes (4/5) and (10/11).

(1) Bridge deck

The deck cross section consists of a prestressed single box section with a trapezoidal shape. The box girder has 200 mm thickness bottom slab and the top slab has variable thickness. The inclined webs have 420 mm thickness. The bridge super elevation of 2% was provided using symmetric inclination of the top slab as shown in **Fig.2.**

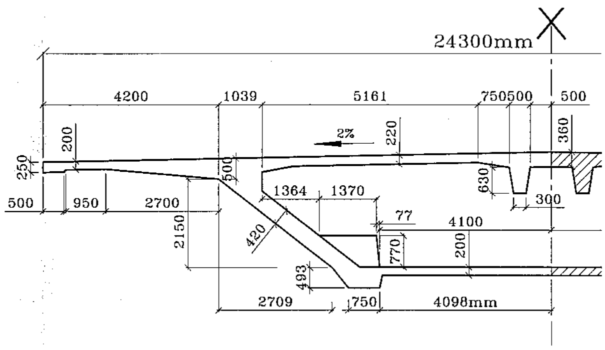


Fig. 2 Deck transverse cross-section details at cable stayed part

(2) Bridge pylon

The bridge pylons have 52 m height above the deck level. The cross section of pylon has an irregular eight-polygon shape. The pylons were prestressed by transverse cables as shown in **Fig.3**.

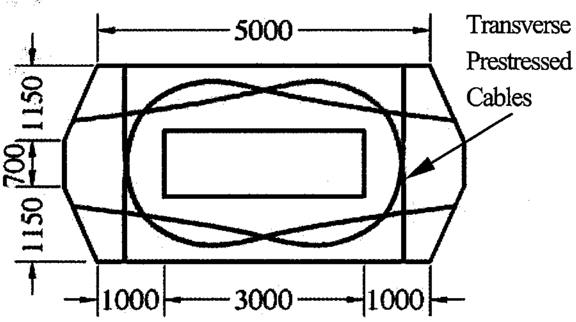


Fig. 3 Pylon cross-section and transverse prestressed cables

(3) Stay cables

14 stay cables were used to support the deck on each side of the pylon. The arrangement of the stay cables was fan stay cable arrangement.

2.2 Bridge Sub-Structure

The piers are divided into two main categories:

- On shore piers have been made of reinforced concrete. Pier heights range from 2.55 m to 11 m. On shore piers have been executed by climbing forms.
- Off shore piers -pylons carried- have been made of reinforced concrete. Their heights range from 10.5 to 18.5 m.

All piers are supported on piles. The used piles were bored piles with diameter 110 cm, and depth ranging from 21m to 23.15m for pile caps of on-shore piers, and from 20.7m to 30.3m for pile caps of off-shore piers.

3. Experimental Program

3.1 Excitation Method

The typical ambient excitation used in the current study was carried out using a single 300 kN truck running at an average speed of 30 km/hr across the bridge. The bridge has 4 lanes, totally, and the truck passed on the 2nd lane (near center of the deck). Several researchers such as Jine-Wen Kou[14] and Talha et al.[16] used this type of ambient excitation before. Jine-Wen Kou[14] discussed the influence of the vehicle velocity and weight on the dynamic behavior of a bridge. So the truck speed and weight was fixed along the test.

3.2 The Data Acquisition System

The dynamic responses of the bridges were measured using five Kinemetrics 0.25g EpiSensor force balance accelerometers placed at various locations on the structure[18]. Since the vertical deck accelerations were only measured, bending and torsional mode shapes could be detected. Due to the physical limitation of the available number of sensors and the length of the bridge,

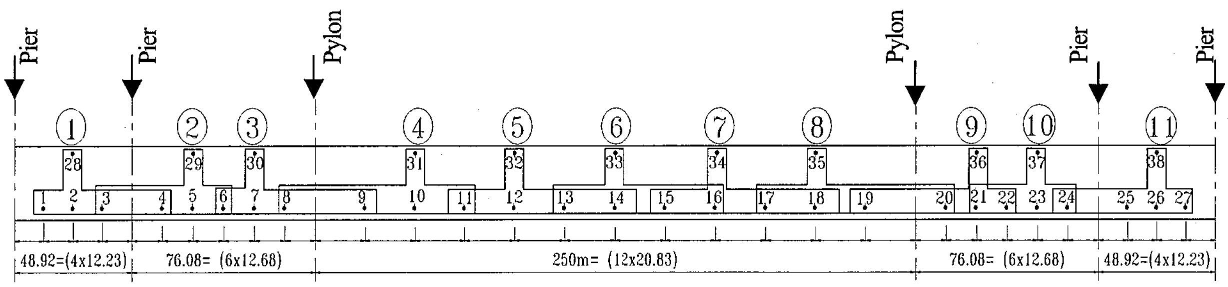


Fig. 4 The reading points at each position

eleven positions were used to monitor the bridge response. Measuring of vibration at each position was run two times to check repeatability of the results. Measurements were recorded for about two minutes during and after the truck pass. Each position consists of five recording points; four on the same side and the fifth on the opposite side of the bridge to capture any torsional modes of vibration. **Fig.4** shows the positions of recording, and **Table 1** shows the reading points at each position and the reference stations. The recorded data were obtained in waveforms as a time domain. **Fig.5** shows a sample of the recorded response in the time domain obtained during Run 1-P-6 (first run at accelerometers numbers 13,14, 15, 16-Position 6).

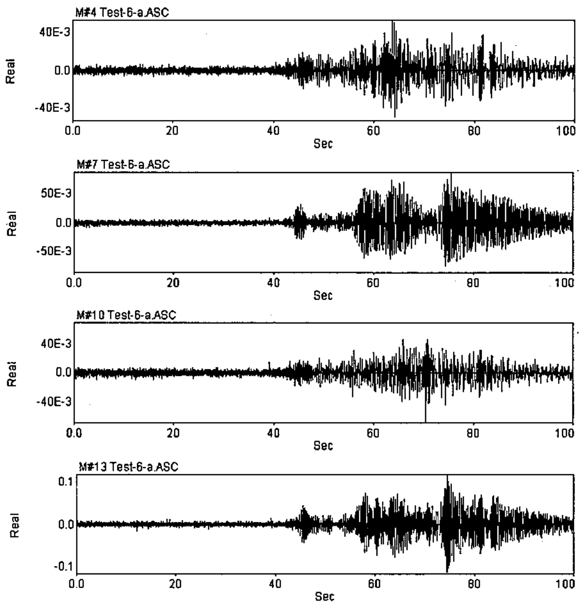


Fig. 5 Sample of the recorded response obtained during Run 1-P-6 in the time domain

A Fast Fourier Transform (FFT) was applied to each acceleration time history using modal analysis software, where the linear power spectra were obtained (response in the frequency domain) as shown in **Fig.6.** From the power spectrum, the first peak was at frequency 0.486 Hz. So it indicates that there is a fundamental mode at frequency 0.486 Hz. In order to know whether the peaks obtained at points represents these points moving in the same direction or in opposite direction, the phase angle of each motion at the specified frequency (0.486 Hz) was checked. If the phase difference is 180 degree, it indicates opposite direction of motion, while 0.0° or 360° phase difference indicates the same direction of motion[15].

Table 1 Reading and reference points at each position

Position Number	Reading Points		Reference Station
	Measuring Side	Opposite Side	
1	1 , 2 , 3 , 4	28	---
2	3 , 4 , 5, 6	29	3 , 4
3	6 , 7 , 8 , 9	30	6
4	8 , 9 , 10 , 11	31	8 , 9
5	11 , 12 , 13 , 14	32	11
6	13 , 14 , 15 , 16	33	13 , 14
7	15 , 16 , 17 , 18	34	15 , 16
8	17 , 18 , 19 , 20	35	17 , 18
9	19 , 20 , 21 , 22	36	19 , 20
10	21 , 22 , 23 , 24	37	21 , 22
11	24 , 25 , 26 , 27	38	24

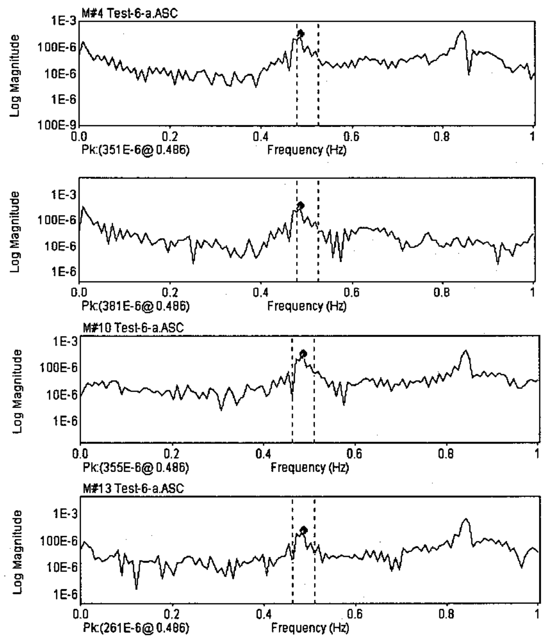


Fig. 6 Sample of response in the frequency domain (Power Spectrum) obtained during Run 1-P-6

Fig.7 shows that the phase angle of points 13, 14, 15, and 16 are 88.5°, 88.9°, 88.1°, and 86.1° respectively. It indicated that the four points was moving in the same direction. The mode shapes were computed from ratios of the peak amplitudes, taking into consideration the relative phase angle, at various points of the structure[15], as shown in **Fig.8**.

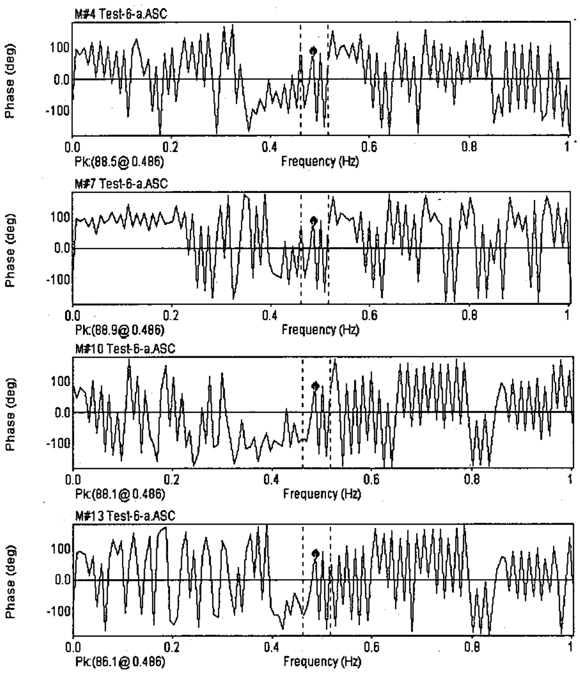


Fig. 7 Phase Angle of Run 1-P-6 (Black Spot at frequency 0.486 Hz)

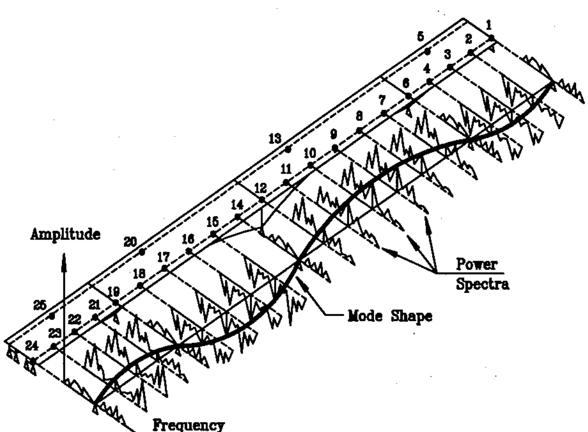


Fig. 8 Determining the mode shape using the peak amplitude method

By plotting the values of normal mode shape versus the distance along span, one can get the mode shape at each frequency. The seven mode shapes got from vibration test compared to the matched mode shapes gotten from modal analysis are shown at the end of study.

4. Finite Element Model

A three-dimensional finite element model was performed using general-purpose program SAP2000 version 8.01[19]. The model was used to perform the modal analysis of the bridge. The main box girder and the supporting pylons were modeled using the 3-D solid element. The shape of elements were chosen to meet these geometric conditions:

• The inside angle at each corner of the faces was in the rang of 45° to 135°.

• The ratio of the longest dimension of the element to its shortest dimension was in the range of 1 to 4.

The exact geometry of the bridge was precisely simulated in the model taking into consideration the deck super-elevation and the longitudinal slope of the bridge. The elastomeric bearing was modeled as a real hinge. Foundations were not added to model assuming that the pylons are fixed in the off shore piers and the deck is simply supported on on-shore piers, as shown in **Fig.9**.

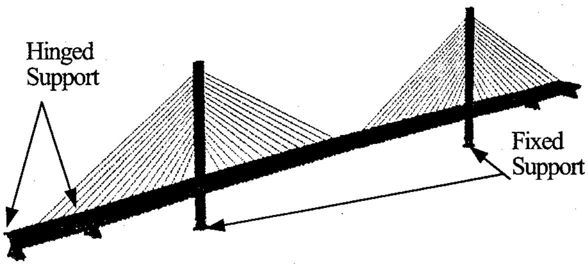


Fig. 9 3D finite element model

4.1 Detailed Model

(1) Material properties

The material properties of concrete and steel implemented in the finite element model are shown in **Table 2**. The used stiffness values of materials in analysis were equal to those of experimental material property.

Table 2 Material properties

Material	Unit Weight (kN/m^3)	Strength (MPa)	Moduls of Elastisity (MPa)	Poisson Ratio
Concrete	25	45	29500	0.2
Stay Cables Steel	87	1767	195000	0.3

(2) Main box girder model

A precise 3D model was performed for the box girder of the bridge using solid elements. The transverse cables at each end-block of stayed cables were modeled using steel frame element. **Fig.10** shows a typical segment of the bridge deck model. The bridge transverse super elevation of 2% was provided through the top cord slab of the box girder. The bridge longitudinal super elevation of 8:1000 was also provided to the total length of the bridge.

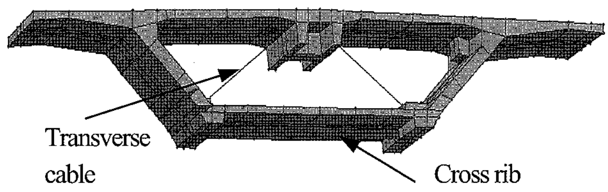


Fig. 10 The main box girder model

(3) Stay-cables modeling

The stay cables were modeled as cable elements. The cable element is a frame element with a compression limit equal zero.

(4) Pylons model

The pylons were modeled using solid element. The transverse prestressing was neglected in modeling. An equivalent rectangular box section was used.

4.2 Modal Analysis

A dynamic modal analysis was carried using program "SAP-2000 Ver. 8.01" to obtain the fundamental frequencies and mode shapes of the bridge. The analysis was based on the following equation [19),20)]:

$$[M]\{\ddot{X}\}+[C]\{\dot{X}\}+[K]\{X\}=0 \qquad (1)$$

Where [M] is the mass matrix, [C] is the damping matrix, [K] is the static stiffness matrix, and the vectors $\{\ddot{X}\}$, $\{\dot{X}\}$, and $\{X\}$ are the absolute node accelerations, velocities, and displacements, respectively.

When proportional damping is assumed, equation (2) turns to the simple form:

$$[M]\{\ddot{X}\}+[K]\{X\}=0 \qquad (2)$$

The resulting eigenvalues and eigenvectors, corresponding to the fundamental frequencies and mode shapes of the structure, are thus a unique property of the structure and depend solely on its mass and stiffness properties. They are actually considered as the "Dynamic Signature" of the structure.

5. Correlation between Modal Analysis and Ambient Vibration Test Results

The initial data obtained from existing structures, such as mode shape, and frequency is quite important for monitoring based maintenance scheme. Because these were very sensitive to the modulus of elasticity Ec, which can represent deterioration of used material itself or structural damage due to external loads. However, estimated stiffness values through numerical analysis are not similar to those of experiment generally. For instance, the convenient modification factor for the modulus of elasticity Ec was in the range of 0.4 to 0.6 Ec[15),17)] for beam bridges. As mentioned before, the used values of materials stiffness in this analysis were as well as those of experimental material property. Further data are needed for discussion[17)].

The dynamic response (Dynamic Signature) of the bridge got from the vibration test does not change as soon as there is no change in the structural performance of the bridge. If the structure has damage due to external loads or deterioration of used material itself, the mode shapes and frequency will be changed, as described before. So, further data acquisition is needed periodically to keep monitoring the bridge structural performance.

Table 3 shows the analytical and experimental mode shapes and their types and frequencies. By comparing between the frequencies of mode shapes detected from the ambient vibration test and those obtained from the finite element model, the ambient vibration test results showed a good agreement with the analytical ones. The differences between the experimental frequencies and the analytical ones are in rang of ±10%. This was attributed to the difference between the actual bridge mass and the simulated one in the finite element model without

Table 3. The analytical and experimental mode shapes and their frequencies

Analytical Mode No.	Mode Type	Analytical Frequencies (Hz)	Detected Experimental Modes	Experimental Frequencies (Hz)	Analytical Freq. /Experimental Freq.
1	Pylon Bending	0.421	Not Detected	--------	--------
2	Pylon Bending	0.460	Not Detected	--------	--------
3	Deck Bending	0.535	Detected	0.486	1.100
4	Lateral Deck Bend.	0.823	Not Detected	--------	--------
5	Deck Bending	0.854	Detected	0.842	1.014
6	Deck Torsion	1.345	Detected	1.310	1.027
7	Deck Bending	1.360	Detected	1.420	0.958
8	Deck Torsion	1.900	Not Detected	--------	--------
9	Deck Bending	1.908	Detected	2.010	0.949
10	Deck Bending	2.012	Not Detected	--------	--------
11	Deck Bending	2.025	Detected	2.210	0.916
12	Deck Torsion	2.424	Not Detected	--------	--------
13	Deck Torsion	2.536	Not Detected	--------	--------
14	Deck Bending	2.609	Detected	2.940	0.887

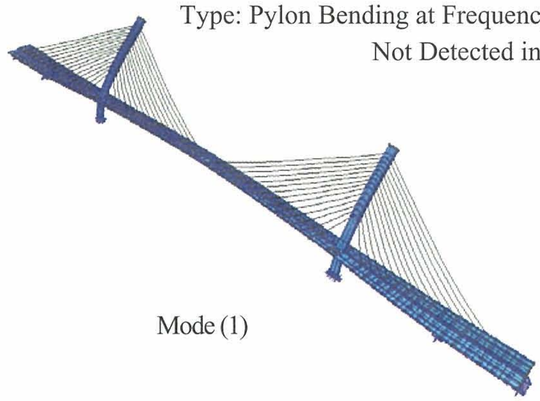
non-structural components.

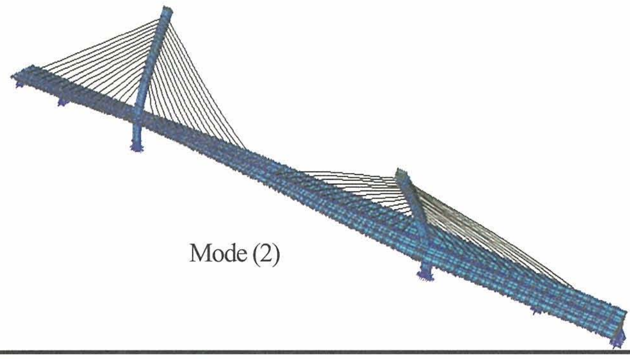
Fig. 11 shows the mode shapes obtained from the finite element model compared to experimentally ones. Bending mode shapes can be observed in most cases. The mode shapes, which were obtained from the ambient vibration test, were similar to those of analytical ones. The analytical mode shapes which related to the movement of pylons, like mode 1 and 2, and the lateral movement of bridge deck couldn't be detected in this study as measuring of the vertical movement of the bridge deck was only carried out. Seven mode shapes could be detected from the ambient vibration test; one of them was bridge deck torsional mode and the others were deck-bending modes.

(a) Mode No. 1 and 2

Type: Pylon Bending at Frequency = 0.421 Hz and 0.4604 Hz respectively

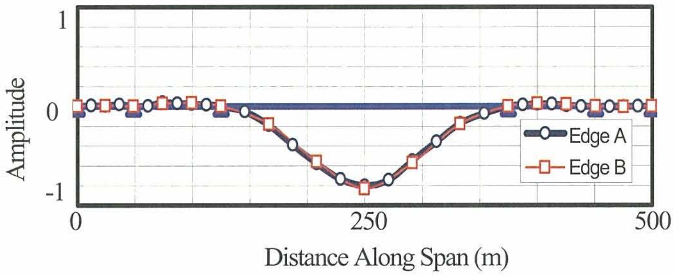
Not Detected in Measured Frequencies

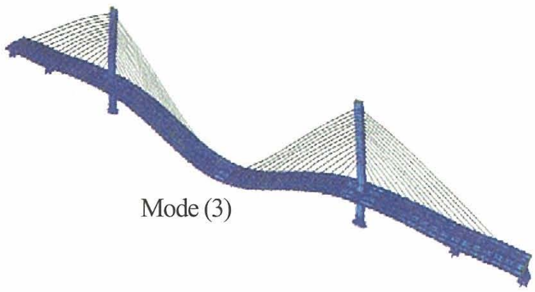




(b) Mode No. 3

Type: Deck Bending at Frequency = 0.5347 Hz. Detected at Measured Frequency = 0.486 Hz





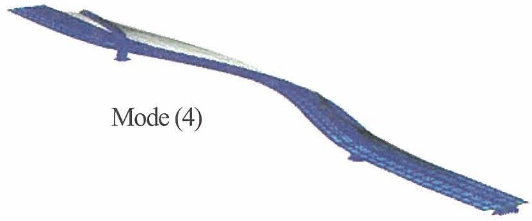
Experimental Mode Shape ***Analytical Mode Shape***

(c) Mode No. 4

Type: Lateral Bending for Deck

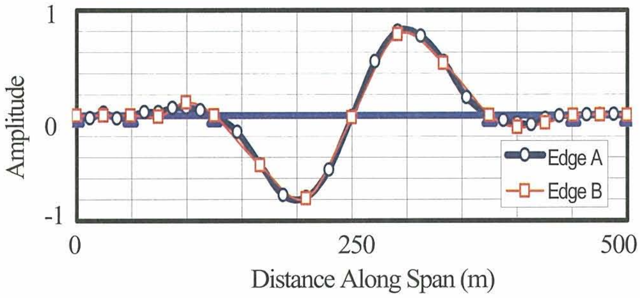
at Frequency = 0.823 Hz

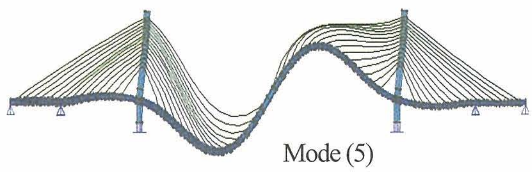
Not Detected in Measured Frequencies



(d) Mode No. 5

Type: Deck Bending at Frequency = 0.854 Hz. Detected at Measured Frequency=0.8417 Hz



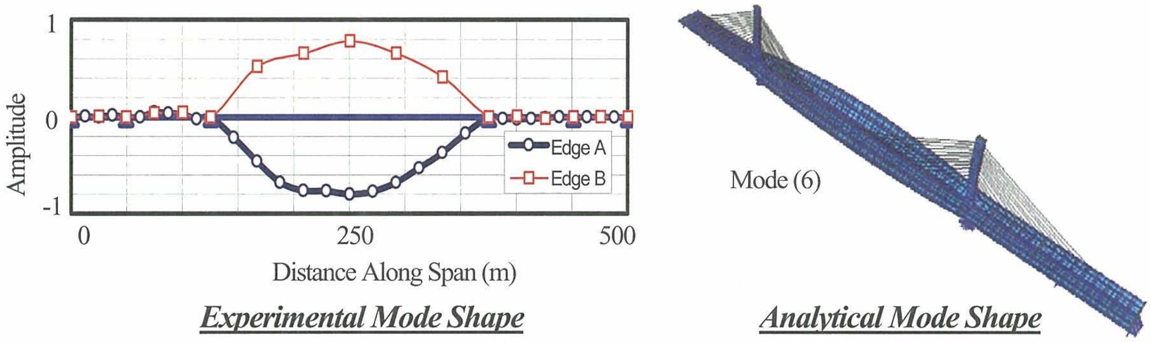


Experimental Mode Shape ***Analytical Mode Shape***

Fig. 11 Analytical mode shapes compared to the experimentally obtained from ambient vibration test

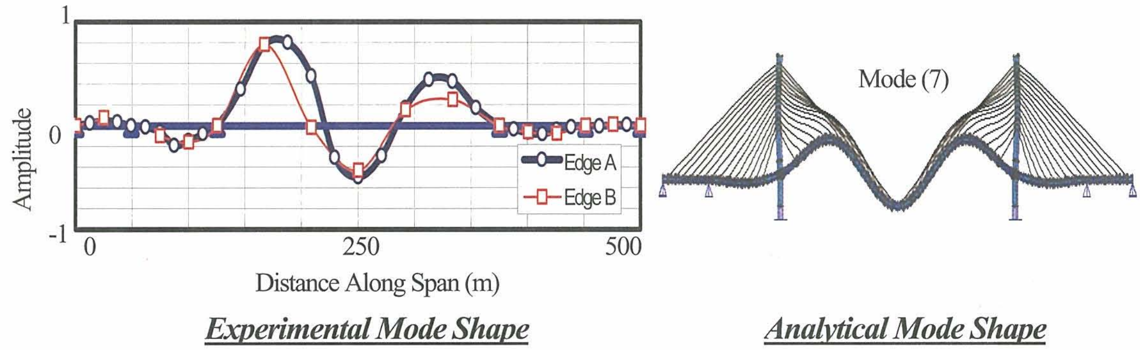
(e) Mode No. 6

Type: Deck Torsion at Frequency = 1.345 Hz.   Detected at Measured Frequency = 1.31 Hz.



(f) Mode No. 7

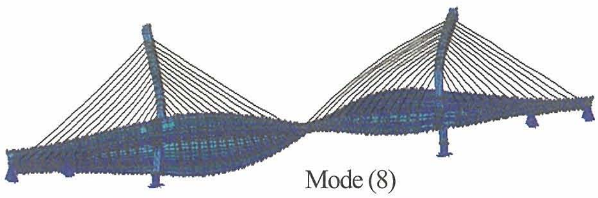
Type: Deck Torsion at Frequency = 1.360 Hz.   Detected at Measured Frequency = 1.420 Hz.



(g) Mode No. 8

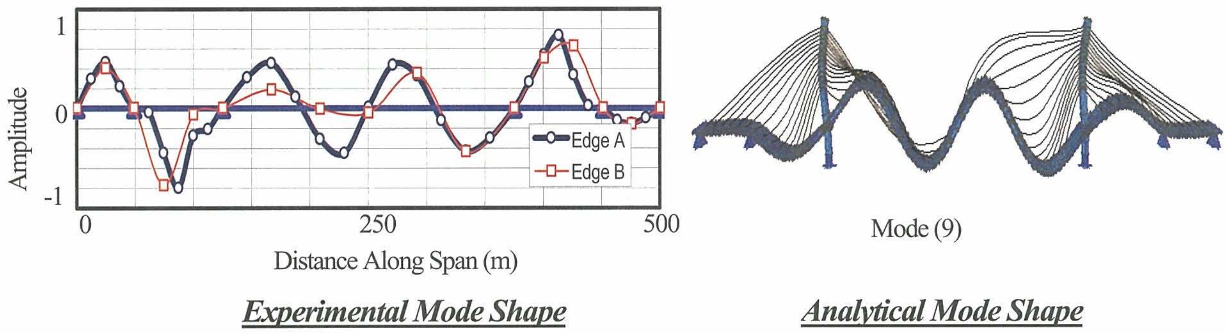
Type: Deck Torsion at Frequency = 1.90 Hz

Not Detected in Measured Frequencies



(h) Mode No. 9

Type: Deck Bending at Frequency = 1.908 Hz.   Detected at Measured Frequency = 2.01 Hz



(i) Mode No. 10

Type: Deck Bending at Frequency = 2.012 Hz

Not Detected in Measured Frequencies

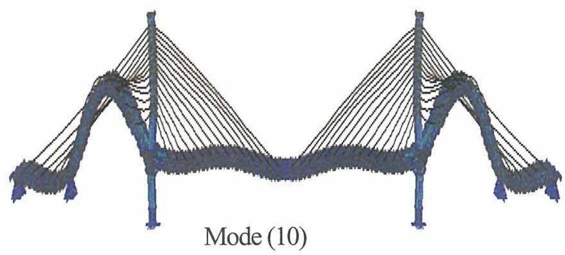
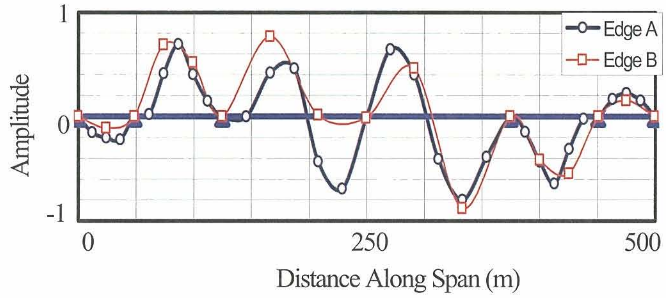


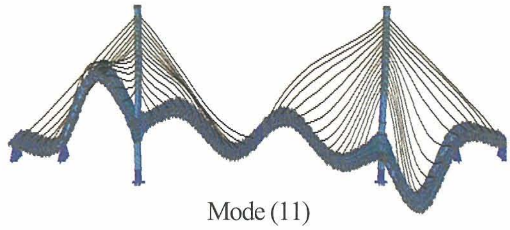
Fig. 11 Analytical mode shapes compared to the experimentally obtained from ambient vibration test

(j) Mode No. 11

Type: Deck Bending at Frequency = 2.025 Hz.

Detected at Measured Frequency = 2.210 Hz.





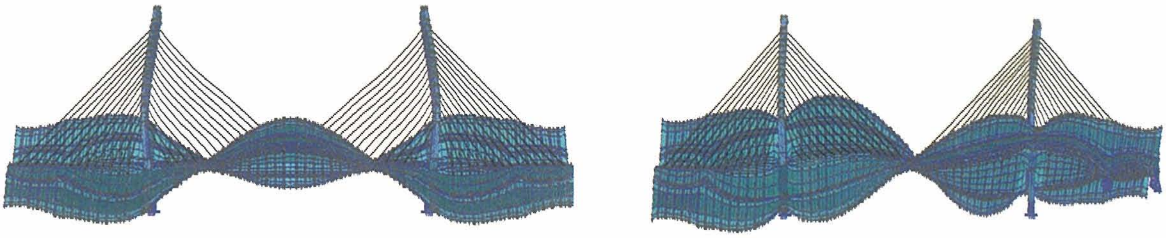
Mode (11)

Experimental Mode Shape ***Analytical Mode Shape***

(k) Mode No. 12 and 13

Type: Deck Torsion at Frequency = 2.424 Hz and 2.536 Hz respectively

Not Detected in Measured Frequencies

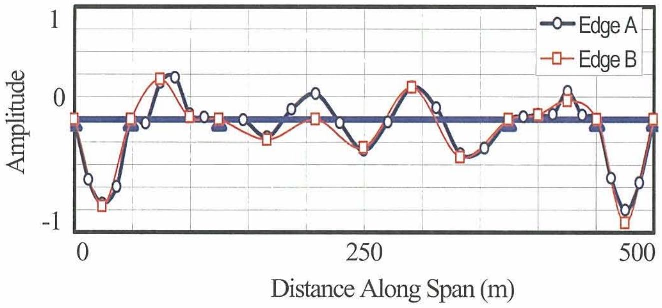


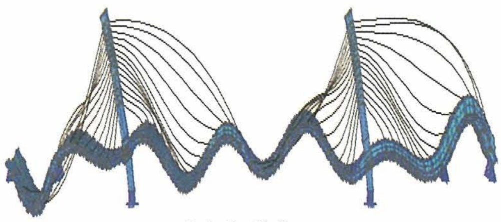
Mode (12) Mode (13)

(l) Mode No. 14

Type: Deck Bending at Frequency = 2.609 Hz

Detected at Measured Frequency = 2.941Hz





Mode (14)

Experimental Mode Shape ***Analytical Mode Shape***

Fig. 11 Analytical mode shapes compared to the experimentally obtained from ambient vibration test

6. CONCLUSIONS

From the finite element analysis and experimental work presented in this paper, the following conclusions were obtained:

1. The dynamic parameters such as mode shapes and frequency were identified through the ambient vibration test and numerical analysis for Aswan Cable Stayed Bridge, as an initial data of a monitoring. Any change in the stiffness of the bridge due to external loads or deteriorated of material itself will affect on these dynamic parameters of the bridge.
2. The used stiffness values of materials in analysis are as well as those of experimental material property. So, it seems that the constructed structure does not have initial defects such as

shrinkage cracking.

The initial data obtained from existing structures is quite important for monitoring based maintenance scheme. Further data acquisition is needed periodically.

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REFERENCES

1) Farrar, C.R., T.A. Duffey, P.J. Cornwell, S.W. Doebing, "Excitation Methods for Bridge Structures," Proceedings of the 17th International Modal Analysis Conference, Kissimmee, FL, Feb. 8-11, 1998.

2) Salane, H. J., J. W. Baldwin, "Identification of Modal Properties of Bridges," *ASCE Journal of Structural Engineering*, 116(7), 2008-2021, 1990.

3) Shelley, S. J., K, L. Lee, T. Aksel and A. E. Aktan, "Active-Control and Forced-Vibration Studies on Highway Bridge," *ASCE Journal of Structural Engineering*, 121(9), 1306-1312, 1995.

4) Farrar, C.R., P.J. Cornwell, S.W. Doebling, E.G. Straser, "Variability of Modal Parameters Measured on the Alamosa Canyon Bridge," Proceedings of the 15th International Modal Analysis Conference, Feb. 3-6, 1997, Orlando, FL.

5) Pavic, A., Hartley, M. J., Waldron, P., "Updating of the Analytical Models of Two Footbridges Based on Modal Testing of Full-Scale Structures," Proceeding of ISMA23, Vol.3, 1111-1118, 1998.

6) Eberhard, M. O., Marsh, M. L., "Lateral-Load Response of a Reinforced Concrete Bridge," *ASCE Journal of Structural Engineering*, 123(4), 451-460, 1997.

7) Wilson, J.C. & Liu, T., "Modelling of a Cable Stayed Bridge for Dynamic Analysis," *Earthquake Engineering & Structural Dynamics*, Vol. 20, pp. 707-721, 1991.

8) Wilson, J.C. and Liu, T. "Ambient Vibration Measurements on a Cable–Stayed Bridge," *Earthquake Engineering and Structural Dynamics*, Vol. 20, pp. 723-747, 1991.

9) A. M. Abdel-Ghaffar & R. H. Scanlan, "Ambient Vibration Studies of Golden Gate Bridge: I. Suspended Structure," *ASCE Journal of Mechanical Engineering*, 111, 463-482, 1985.

10) A. M. Abdel-Ghaffar & R. H. Scanlan., "Ambient Vibration Studies of Golden Gate Bridge: II. Pier-Tower Structure," *ASCE Journal of Mechanical Engineering*, 111, 483-499, 1985.

11) Main, J. A. and Nicholas P. Jones, "Full-Scale Measurements of Stay Cable Vibration." Proc. 10th International Conference on Wind Engineering, Copenhagan, Denmark, June 1999.

12) Wilson, J. C. and B. S. Tan, "Bridge Abutments - Assessing Their Influence on Earthquake Response of Meloland Road Overpass," *ASCE Journal of Engineering Mechanics*, 116, 1838-1856, 1990.

13) Karoumi R., 'Dynamic Response of Cable-Stayed Bridges Subjected to Moving Vehicles', Licentiate Thesis, TRITA-BKN Bulletin 22, Dept. of Structural Eng., Royal Institute of Technology, Stockholm, 1996.

14) Kou, J. W., DeWolf, J. T. , "Vibrational Behavior of Comtinuous Span Highway Bridge-Influencing Variables" *ASCE Journal of Structural Engineering*, 123(3), 333-344, 1997.

15) El-Attar, A. G., "Ambient Vibration Testing of a Composite Steel Bridge," *Engineering Research Journal*, Helwan University, Faculty of Engineering, Mataria Cairo, 83, 56-77, 2002.

16) Talha, M.A., El-Attar, A.G., Khalil, A.H, "Dynamic Monitoring of a Long Span Bridge," *Journal of Engineering and Applied Science*, Faculty of Engineering – Cairo University, 2003.

17) Abd-ElZaher, A. K. "*Assessment of Vibration Test Results of Concrete and Steel Bridges*," Master Thesis, Structural Engineering Department, Faculty of Engineering, Cairo University, 2004.

18) EpiSensor Force Balance Accelerometer Model FBA ES-T and Kinemetrics Model VSS-3000 Vibration Survey System Catalogs.

19) SAP2000 Manual, Static and Dynamic Finite Element Analysis of Structures Plus, Version 8.01, Computers and Structures, Inc. Berkeley, California, USA, 2003.

20) Paz, M. "*Structural Dynamics Theory and Computation*," Second Edition, Van Nostrand Reinhold Company, NewYork, 1985.

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