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Full-scale dynamic testing of the second Bosporus suspension bridge

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ABSTRACT: Full-scale measurements of ambient vibrations were made on the second Bosporus Bridge in order to determine natural frequency, mode shape and damping ratio for vertical, lateral, torsional and associated modes in the deck and tower up to a maximum of 2Hz. Agreement between experimental and theoretical modes was acceptable for vertical modes below 1Hz, and for torsional modes, but it was difficult to identify the lateral modes due to low levels of response and lateral stiffness of the wide deck.

1 BACKGROUND, DESCRIPTION OF THE BRIDGE AND OBJECTIVES

The first Bosporus (Bogazici) bridge, opened in 1973, carried up to 180,000 vehicles a day until the second Bosporus Bridge (full name Fatih Sultan Mehmet) was opened in 1989, as part of a second peripheral highway around Istanbul.

Fig. 1 gives details of the Fatih Bridge. The 8-lane box deck is 39.4m wide, 3m deep and 1090m long and is suspended by vertical hangers. There are no sidespans and the steel towers rise from their foundations 8m below deck level to a height of 110m above ground level.

The testing of Fatih bridge was the third in a series of ambient vibration surveys (Brownjohn et al. 1987, 1989) of major European box-girder suspension bridges by the Earthquake Engineering Research Centre (EERC) at Bristol University. The objectives of the measurements have always been to validate the mathematical models used for seismic response analyses of these bridges (e.g. Dumanoglu and Severn 1987, 1990), although latterly the Humber bridge has been the subject of an extended study of the response to wind loading (Diana et al. 1991). For Fatih the objectives were to determine vertical plane, lateral and torsional modes of the deck and towers in the range 0-2Hz to validate asynchronous and stochastic response analyses (Dumanoglu et al. 1989) and to make measurements of hanger and main cable response and of wind conditions.

2 EQUIPMENT

The accelerations were sensed by servo-type accelerometers and amplified by power supply/conditioner units. Signals were recorded on a four channel FM tape recorder and some signals were processed on site in real time using a spectrum analyser to determine the Fourier spectra of the acceleration signals and to compute the amplitudes and phases of the signals. These spectra together with spectra obtained from the recorded signals were used to determine the natural frequencies and damping ratios of the Bridge and to determine the mode shapes from relative phases and amplitudes.

A cup and vane weather monitor was used to provide wind speed and direction data and as an exercise in using digital techniques for monitoring and as complement to the analog measurements, digital data acquisition equipment consisting of anti-alias filters and an analogue to digital converter was used to record acceleration and wind signals on a micro-computer; this was also used to store Fourier spectra from the analyser.

3 TEST PROGRAM

The Bridge was tested between the 6th and 15th June 1989.

A reference accelerometer was set up at a strategic point inside the deck and some of the other ('traveller') accelerometers were placed at positions throughout the deck. The accelerometers were in turn oriented to measure lateral and vertical accelerations, and by moving the travellers from one end of the deck to the other and up and down a tower, acceleration spectra for 28 positions were determined. These positions were located at every second hanger location in the European half span from mid-span to tower connection to obtain fine resolution of the mode shapes, and at every fourth hanger location in the Asian half span to confirm the symmetry of the mode shapes. Measurements were made at five levels in the European tower; the uppermost position in the top portal was also used as a secondary reference for measurements of response of the tower.

Resolution of vertical and torsional response was achieved using accelerometers at opposite sides of the deck and at the top of the tower and taking sum or difference signals.

In addition to the measurements made to map out deck and tower mode shapes, measurements were made of the longitudinal motion of the deck to check the performance of the deck bearings, of the vertical and lateral motion of the cable to check for the prolific cable modes predicted by the three-dimensional finite element analysis, and of vibrations in the hangers to estimate the tensions.

Extended recordings of up to 12 hours were made for increased accuracy of estimates of frequency and damping ratio, and some values were obtained from 610 RMS averages obtained by running the spectrum analyser 60 hours over a weekend. The damping values given here were estimated from this data.

4 PRESENTATION OF RESULTS

For brevity, only modes up to 1Hz are discussed here; the full set of modes is given by Brownjohn et al. (1990). In the mode shape plots the circles indicating the experimental mode shapes have diameters proportional to the value of transfer function coherence between the reference and the appropriate travelling accelerometer.

4.1 Vertical modes

A check on the auto power spectrum of vertical acceleration of the deck at the reference in the range 0-6Hz, showed strong response between 2Hz and 4Hz indicative of dynamic loading due to vibration of vehicle bodies on their suspension systems and weaker response below 1Hz, partly due to the traffic and partly due to wind. Fig. 2 is the auto power of vertical and torsional response in the range 0-1Hz, from the sum and difference of accelerometer signals either side of the deck. Vertical modes (fig. 2a) were in general very well defined and easy to identify.

Table 1 summarises the 12 vertical deck modes in the range 0-1Hz obtained from the vertical deck accelerations and fig. 3 shows matching of vertical experimental mode shapes for V1-V6 with theoretical mode shapes obtained from a 3-dimensional mathematical model in which one of the deck end bearings is hinged and the other is free to hinge and slide. The overestimation of natural frequencies by the model increases with frequency, reaching 6% (overestimate) for mode V12; the error accelerates for higher modes.

Table 1 Vertical deck modes

Mode		Modal frequency /Hz		Damping %
no.	type and symmetry	experimental	Theoretical	
V1	V asym	0.125	0.125	1.33
V2	V sym	0.155	0.159	1.27
V3	V sym	0.208	0.212	0.80
V4	V asym	0.244	0.251	0.69
V5	V sym	0.317	0.325	0.44
V7	V asym	0.389	0.400	0.38
V8	V sym	0.470	0.485	0.65
V9	V asym	0.555	0.576	0.29
V10	V sym	0.645	0.673	0.31
V11	V asym	0.741	0.787	0.63
V12	V sym	0.839	0.907	0.28
V13	V asym	0.942	1.037	0.28

4.2 Torsional deck modes

Fig. 2b is the auto power spectrum of torsional response at the reference and Table 2 summarises the torsional modes (labelled T). The acceleration difference signals were weak and modes T3 and higher were usually difficult to resolve. Apart from the lowest mode, the model underestimates all the theoretical torsional mode frequencies by the same percentage (about 4.4%).

Table 2 Torsional deck modes

Mode		Modal frequency /Hz		Damping %
no.	Type and symmetry	Experimental	Theoretical	
T1	T sym	0.296	0.243	0.70
T2	T asym	0.352	0.333	0.77
T3	T sym?	0.529	0.501	1.37
T4	T asym	0.692	0.661	0.64
T5	T sym	0.867	0.828	0.54

4.3 Lateral deck modes

Fig. 4 is the auto power spectrum of lateral response at the reference. Apart from a strong response around 0.3Hz the general level of response is at least an order of magnitude less than for vertical motion in this bridge and lateral motion in Humber and Bogazici. Examination of spectra such as this led to the

Examination of spectra such as this led to the identification of 8 possible lateral modes up to 1Hz and these are summarised in Table 3. Below 0.1Hz the signal is dominated by static rotation but the weak first lateral mode at 0.77Hz can still be identified. In the range 0.2-0.27Hz the acceleration spectra appear to show several modes; modes L2 and L3 appear in most of the individual measurements. There is strong mechanical cross-coupling with torsional acceleration at 0.297Hz, but mode L4 appears to be a distinct lateral mode. Estimation of damping is particularly difficult for modes L1-L3.

Table 3 Lateral deck modes

Mode	Experimental frequency /Hz	Theoretical frequency /Hz	Damping %
L1	0.077	0.073	-
L2	0.239	0.218	-
L3	0.250		-
L4	0.287	0.288	0.97
L5	0.315	0.303	3.51
L6	0.432	0.421	1.39
L7	0.466		0.90
L8	0.504	0.543	0.78

Fig. 5 shows the experimentally determined shapes for modes L1-L4. As for torsional modes, the lateral modes are so weak that even with the most sensitive accelerometers the signal to noise ratio (related to coherence) is low; mode L1 is afected by the static torsion. The shapes do not follow the same sort of progression as the vertical modes and the correspondence with theoretical modes is not clear except for modes L1 and L2.

4.4 Longitudinal tower modes

By using one accelerometer in each pylon of the European tower it was possible to take the sum of the signals as the pure longitudinal response and the difference as the pure torsional response.

Apart from participation in some of the lower vertical deck modes, the strongest tower modes occur above 1Hz and all but three of the measured modes in the range 1-2Hz correspond to a deck mode. The mode shapes are similar (e.g. Fig. 6a) and reflect the stiffness of the back stay cables. By contrast the participation of the towers in the lowest vertical deck modes, up to 0.3Hz is characterised by a cantilever type of mode shape (6b).

4.5 Lateral tower modes

Fig. 7 is the auto power spectrum of lateral acceleration at the tower tip and Table 4 summarises the identifiable lateral tower modes up to 1Hz. The acceleration levels are higher than for either lateral deck response or longitudinal tower response and the modes are clearly identifiable from the spectra and are unambiguous. Below 1Hz the experimental mode shapes have the simple cantilever form of fig. 6b, but above 1Hz they progress towards the type of mode shape shown in Fig. 6a. A high proportion of measured lateral tower modes do not involve deck participation.

Table 4 Lateral tower modes

Mode	Participation	Experimental frequency /Hz	Damping %
TL1	tower + deck	0.287	1.40
TL2	tower + deck	0.295	1.07
TL3	tower + deck	0.432	1.19
TL4	tower + deck	0.464	0.65
TL5	tower + deck	0.503	0.97
TL6	tower	0.520	1.03
TL7	tower	0.630	0.98
TL8	tower	0.673	0.15
TL9	tower	0.691	0.30
TL10	tower	0.753	0.24
TL11	tower	0.802	0.20
TL12	tower + cable	0.866	0.07
TL13	tower	0.937	1.03

4.6 Cable modes

An accelerometer was placed on the lowest part of the main cable at centre span to investigate the participation of the cable in deck modes or otherwise.

All the peaks in the main cable vertical acceleration auto power spectrum coincide with vertical or torsional deck modes, but the cable lateral acceleration spectra are harder to interpret, showing a multiplicity of modes, consistent with the high proportion of cable modes in the two- and three-dimensional mathematical models. The frequency of the strongest lateral cable mode at 0.866Hz corresponds with that of the strongest lateral tower mode below 2Hz but there is no strong lateral response in the deck at this frequency. A significant proportion of the lateral modes do not correspond with any measured or theoretical lateral deck or tower mode and without having simultaneous data from measurements in the towers, the deck and several points in the main cable it is not possible to be certain about the nature of all the cable modes.

4.7 Hanger response

The auto power spectrum of longitudinal acceleration of a hanger close to the reference showed strong response at 2nd and higher harmonics of a fundamental mode which was not actually measured ($\approx$3.45Hz for the instrumented hanger) . This absence of a fundamental mode contrasts with measurements on the Bogazici Bridge. A further difference is that the peaks are clear and sharp, despite RMS averaging over several records during which traffic loads (hence cable tension) would be expected to vary. By simple analysis, hanger frequency varies with tension and these values suggest modest variations in the hanger stress levels at Fatih by comparison to Bogazici. At the time of these measurements there were less than 24,000 vehicles per day crossing Fatih Bridge.

4.8 Digital recordings of wind and response data

A number of digital recordings were made of wind speed and direction concurrent with acceleration signals.

The wind speeds on the bridge were generally fairly low, with maximum instantaneous values of about 8m/second, but the wind direction was usually along the Bosporus, perpendicular to the deck.

The limited range of wind speeds and limited quantity of data prevented analysis of the relationship between response amplitude or modal parameters and wind speed, but observations during the stronger gusting suggested increased response levels for the lower modes of vibration.

The digital recordings were useful mainly as a check on the analog data and as an practice exercise in digital data acquisition for this type of structure. Two lessons were learnt from this exercise:

1) The data acquisition equipment employed has been expensively used for in laboratory and is suitable for field work with minimal modifications. For simplicity and to reduce software overheads, all input signals should be supplied in analog form.

2) The selection of appropriate anti-aliassing filters is particularly important. For this application they need to have cut-off frequencies as low as 1Hz, which for some types of filter can lead to instabilities. The filters should be high-order for a sharp roll off since the high levels of acceleration due to traffic occur start just above 2Hz and must be completely filtered out.

5 CONCLUSIONS

1) The measured vertical natural frequencies and mode shapes match the predicted values for a mathematical model featuring bearings fixed at one end and free to slide at the other.
2) The vertical modes of the deck are clearly defined, while the lateral modes are weak and poorly defined, probably due to the very wide deck.
3) The traffic loading for the bridge was low at the time of the test since only four of the eight carriageways were open. Even so, traffic was the main source of dynamic loading.
4) The hanger measurements suggest that the stress fluctuations in the hangers are small.

6 ACKNOWLEDGEMENTS

The authors would like to thank NATO and SERC for financial support and the Turkish State Highway Directorates for their assistance.

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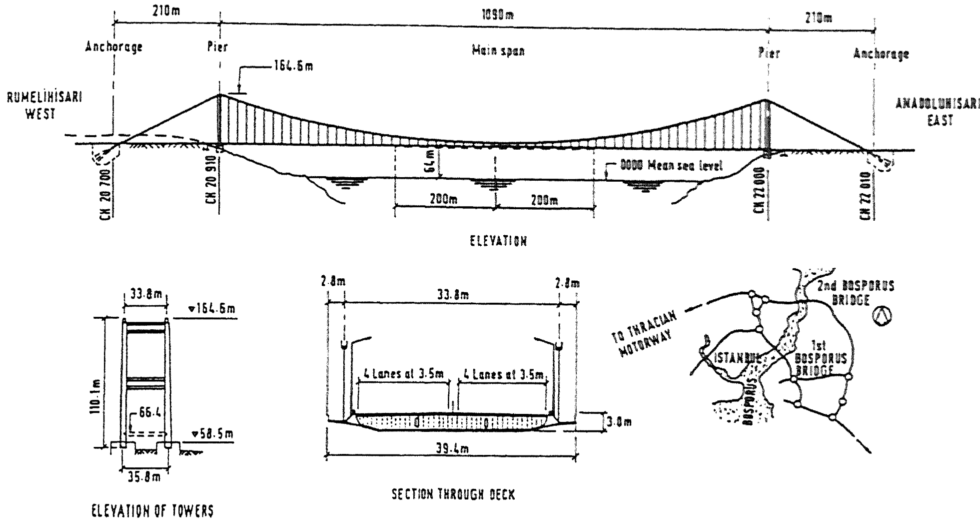


Fig. 1 Second Bosporus (Fatih Sultan Mehmet) Bridge

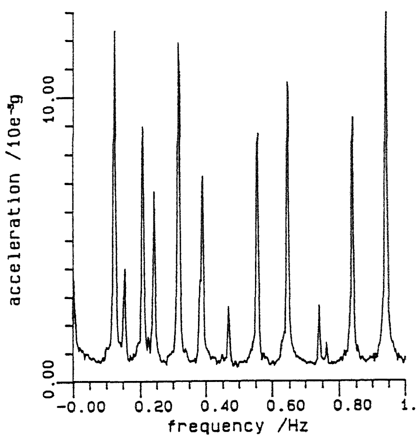


Fig. 2a Deck vertical response auto-power

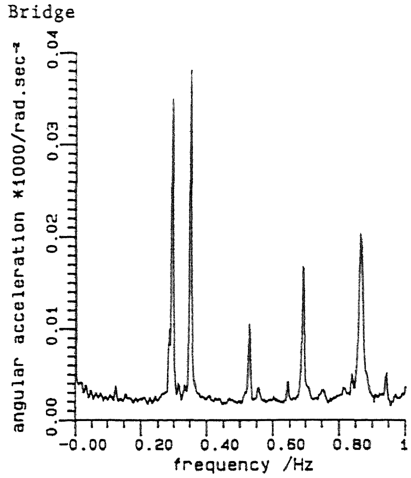
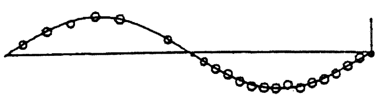
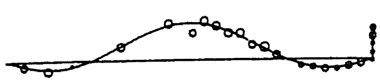


Fig. 2b Deck torsional response auto-power

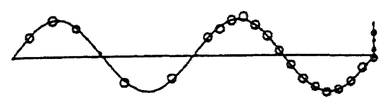


mode V1 fn = 0.125 Hz ζ ∽ 1.33%

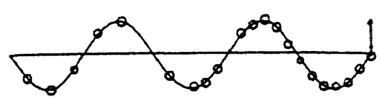


mode V2 fn = 0.155 Hz ζ ∽ 1.27%

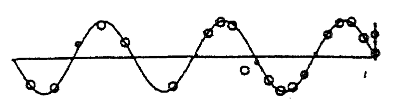
mode V3 fn = 0.212 Hz ζ ∽ 0.80%



mode V4 fn = 0.244 Hz ζ ∽ 0.69%



mode V5 fn = 0.317 Hz ζ ∽ 0.44%



mode V6 fn = 0.389 Hz ζ ∽ 0.38%

Fig. 3 Vertical plane mode shapes and experimental modal parameters

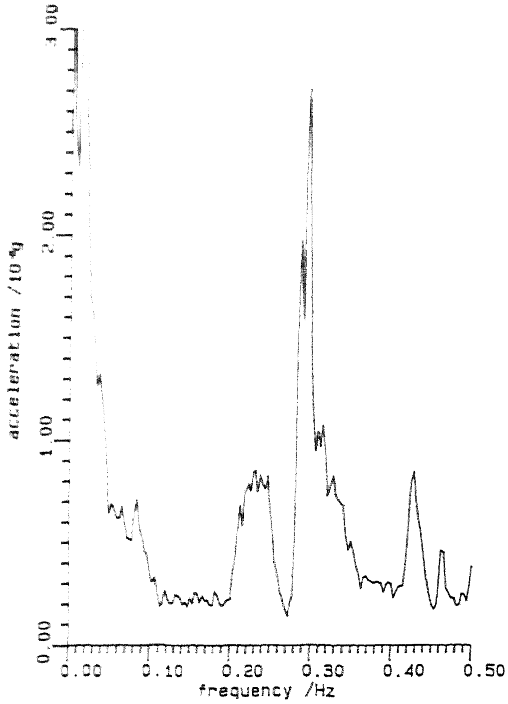


Fig. 4 Deck lateral response auto power

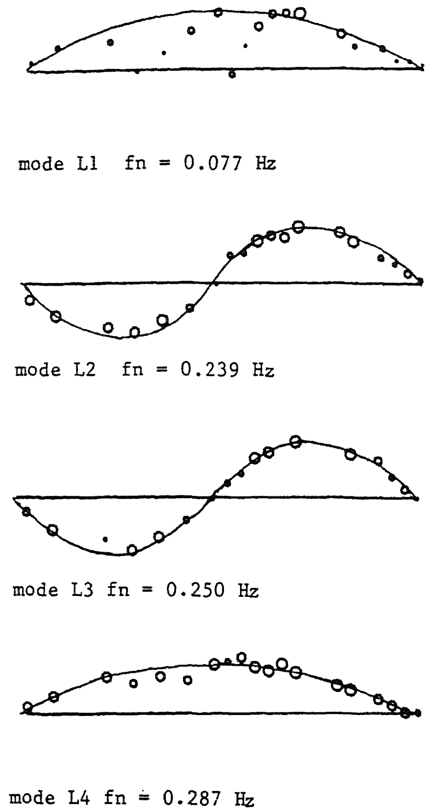


Fig. 5 Deck lateral modes

Fig. 6a Longitudinal tower mode shape at 1.42 Hz

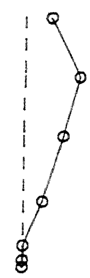
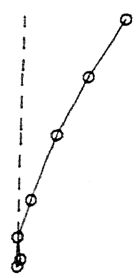


Fig. 6b Longitudinal tower mode shape at 0.208 Hz



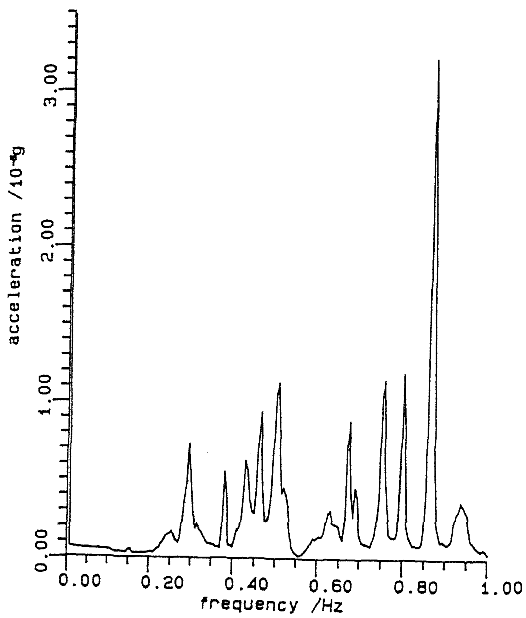


Fig. 7 Tower lateral response auto power