ICCBT2008

Modal Testing of a Cantilever Grandstand

Z. Ibrahim*, University of Malaya, ***MALAYSIA***
P. Reynolds, University of Sheffield, ***UNITED KINGDOM***

ABSTRACT

Modern sport stadia designs provide safety in the form of sufficient strength to cater for the weight of the sport spectators. However, lighter materials technology, aesthetical demands, and the requirement for an unobstructed view for spectators, combined with the fact that the capacity of a stadium has to be maximised to ensure business profitability, have resulted in the design of lighter and more slender structures, often including long cantilevers. These structures often have relatively low natural frequencies that can lead to vibration problems.

This paper describes the modal testing carried out to evaluate the dynamic characteristic of one such stadia structure, a grandstand at a football stadium located in Bradford, United Kingdom. The modal testing, performed using an electrodynamic shaker and piezoelectric accelerometers, is described in detail. In parallel with the field measurements, finite element models have been established to model the stand and to analyse the effects of various arrangements of elements on the dynamic characteristics of the grandstand. The results from the modal testing were used to manually update the finite element model of the stand. The performance of the finite element model is evaluated by correlating the natural frequencies and mode shapes from the finite element models and the modal testing. The correlation analysis is also described in this paper. The results generated from this study are expected to be of interest to professionals and researchers involved with the design of civil engineering structures susceptible to vibration problems such as grandstand, bridges and tall buildings.

Keywords: *Modal testing, Grandstand, Stadium, Dynamic Characteristic, Vibration, Finite Element Modelling, Correlation Analysis.*

**Correspondence Author: Dr. Zainah Ibrahim, Civil Engineering Department, University of Malaya, Lembah Pantai, 50603 Kuala Lumpur, Malaysia. Tel: +60379674460, Fax: +60379675318. E-mail: zainah@um.edu.my*

1. INTRODUCTION

With the trends towards increased slenderness of stadia structures and livelier crowd activity, there has been an increase in incidence of excessive vibrations on the structures [1, 2, 3]. Furthermore, the increase in the use of stadia structures for non-sports events, such as pop concerts, where enhanced synchronisation of crowd motion is created by the presence of a musical beat, may cause much more significant dynamic motions. There is a potential for this large dynamic motion to lead to panic of the spectators or collapse of the grandstand. In these circumstances, large numbers of people are at risk due to the inherent nature of stadia being assembly structures that support many thousands of people at a time. This vibration serviceability problem on stadia structures has been recognised and causing a great concerns worldwide [4]. This concern is due to a general lack of understanding of the subject and an increasing number of problems related to crowd-induced vibration of stadia structures during sports and pop concert events.

As part of the investigation to gain better understanding and knowledge on this vibration problem, a permanent cantilever grandstand at a football stadium in Bradford, United Kingdom was recently being the subject of experimental dynamic testing and remote monitoring during sporting events [5, 6]. The two dynamic testing carried out provided a large number of vibration response data during an empty and in-service grandstand for the investigation.

This paper describes the procedures and results of the modal testing (the first part of the two dynamic testing), which was performed within a single working day. In addition, correlation analysis between the results from the modal testing and finite element modelling [7, 8] is also described briefly in this paper.

2. DESCRIPTION OF THE STRUCTURE

The structure under test is the Midland Road Stand which is one of the stands at Bradford City Football Club, United Kingdom. The stand was built in 1996 and consists of a series of steel frames at 7.19 m centres. The seating deck is constructed from L-shaped pre-cast concrete units, which are simply-supported between the steel frames. The stand contains a single tier, with kiosks, toilets and a concourse area located beneath it.

Figure 1: The Midland Road Stand at Valley Parade, Bradford.

The stand is built on sloping ground, with about 6 m difference between the pitch and road levels, along the Midland Road side of the ground. Figure 2 shows a photograph of the side elevation of the stand together with the Midland Road behind it. Figure 3 shows a typical cross section of the stand through one of the steel frames. The stand cantilevers back (about 4 m) towards the Midland Road (see Figures 2). The roof overhangs the entire tier, and is supported by steel frames connected at the top of the stand as shown in Figure 3.

Figure 2: Side elevation of the Midland Road Stand

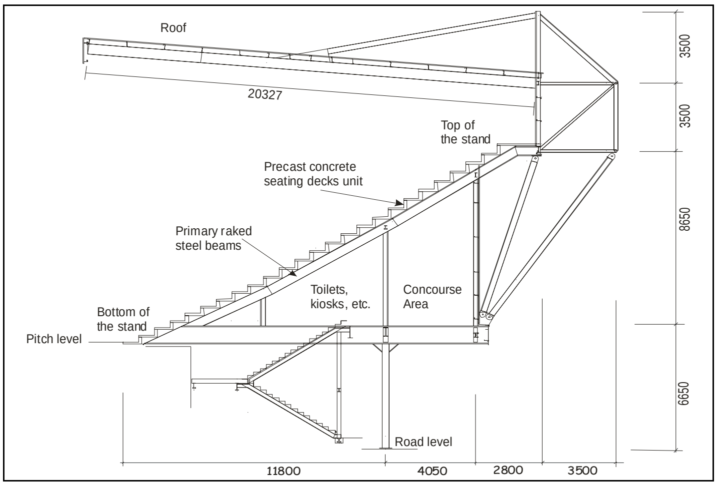


Figure 3: Cross-section of the Midland Road Stand.

3. MODAL TESTING AND PARAMETER ESTIMATION

3.1 Overview

The modal testing of the empty grandstand was carried out to establish modal properties for comparison with those from Ambient Vibration Testing (AVT) [7]. It was also used to plan the installation of the transducers for the Remote Monitoring System (RMS) [5, 6, 7]. A brief description of the theoretical basis of modal testing is given here. More detailed information can be found in other established references such as Ewins (2000) and Maia et al. (1997).

The modal testing on the empty stand was carried out on 4 September 2001. By measuring both the input force to the empty stand and the stand's corresponding vibration responses, frequency response functions (FRFs) were estimated. Multi degree of freedom (MDOF) modal parameter estimation was then applied to determine the modal properties of the empty stand.

The following sections describe the equipment used, testing methodology, data acquisition and analysis for the modal testing.

3.2 The Equipment

The modal testing was performed using an APS Dynamics Model 113 electrodynamic shaker (Figure 4) as an excitation source. The excitations were performed in both vertical (Figure 4(a)) and horizontal (Figure 4(b)) directions.

The shaker force is electrodynamically generated, where the output is directly proportional to the current supplied by an amplifier. The shaker unit employs permanent magnets and is configured such that an electrical coil attached to the armature of the shaker remains in a uniform magnetic field over the entire stroke range. To generate the excitation force to the structure, the shaker was placed at the test point on the structure. The excitation force was generated by the acceleration of a moving mass, which is attached to the shaker armature. An accelerometer was attached to the shaker armature to measure the excitation force applied to the structure.

The structural responses were measured using low frequency and high sensitivity Endevco Model 7754-1000 piezoelectric accelerometers (Figure 5). These accelerometers have a high nominal sensitivity of 1000 mV/g with integral electronics, a noise floor of less than 10 μg and a lower frequency limit of approximately 0.1 Hz. Figure 5 shows two accelerometers (protected by sound insulation cap) mounted on steel base plate and placed at one of the test points on the structure (horizontally and vertically).

Figure 4: APS Dynamic Model 113 Shaker in (a) vertical and (b) horizontal directions

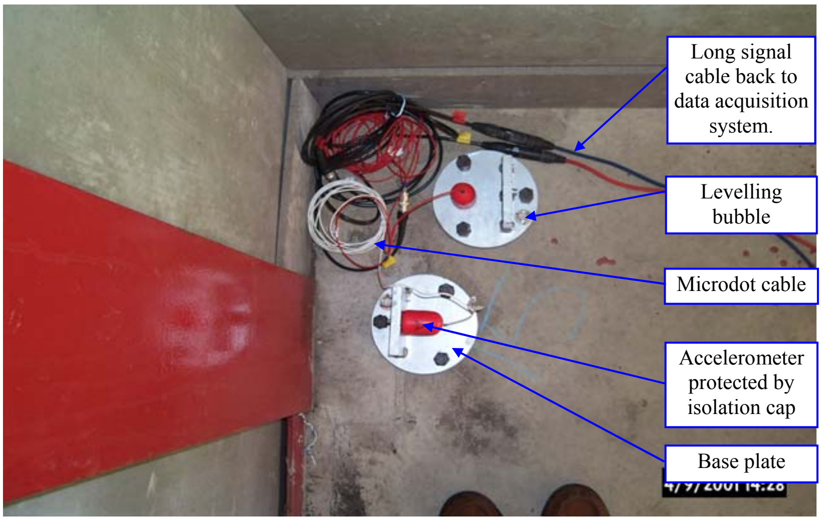


Figure 5: Endevco Model 7754-1000 Accelerometers

The accelerometers were connected to a signal conditioner (Figure 6) that provided their power and amplified the response signals. The signal conditioner used was a 16-channel ISOTRON Signal Conditioner Model 2793 manufactured by Endevco.

A Data Physics DP440 portable spectrum analyser (SignalCalc Mobilizer) as shown in Figure 6 was used in the data acquisition of both excitation and response signals. The spectrum analyser has seven 18-bit input channels and one 16-bit output channel. In this modal testing, the input channels were used to acquire one excitation and six response signals and the shaker excitation signal was provided through the output channel.

In addition to the spectrum analyser, a Racal StorePlus VL analogue instrumentation tape recorder (Figure 6) was used as a backup device. The tape recorder has 16 input channels and was used to store the signals that were also recorded on the spectrum analyser for later re-sampling if required. Figure 6 shows the data acquisition centre with the equipment and test personnel at work. It was set-up beneath the middle of the tier, beside the concourse area.

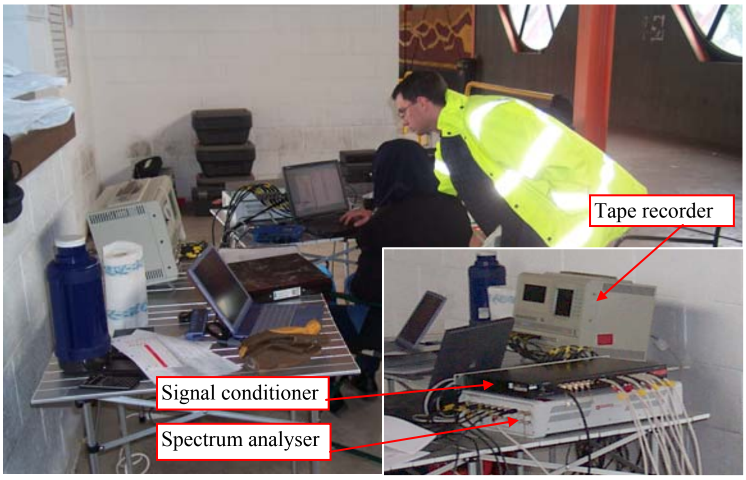


Figure 6: Data acquisition centre at the Midland Road Stand.

3.3 Test Procedure and Data Acquisition

Before the test could be carried out, it is necessary to develop a grid of test points at which FRF measurements are to be made to capture the complete ‘picture’ of the modes of vibration of the stand. The locations of the test points were determined from observation made from the pre-test FE modelling [7] carried out prior to the modal testing. The test points location were selected in such away that all the modes of interest should be excited in the measurements. In addition, the number of channels of instrumentation and the amount of time available for the testing are important factors for the size of this test grid.

This modal testing used a grid of 15 test points. The test grid is illustrated in Figure 7. The test points were distributed along the top landing of the stand because the tip of the cantilever is at the back of the stand where the maximum modal ordinates were expected to occur. These optimised locations were determined from the pre-test 3D FE model as described in details in Ibrahim (2006) [7] and Ibrahim and Reynolds (2007) [8]. Both vertical and horizontal excitations were applied on all 15 test points but responses were measured only at reference locations. Six reference accelerometers (TP4V, TP4H, TP7V, TP7H, TP15V and TP15H) were selected as indicated in Figure 7. All the six response signals together with the input signal from the shaker were sampled by the spectrum analyser and recorded by the analogue tape recorder. Three additional accelerometer response signals were recorded using the analogue tape recorder and were not digitised. One test point was at the roof level (TP4H-R) and another two test points were at concourse level (TP8V-C and TP4V-C).

Initially, the shaker was placed in the vertical direction at TP1 to TP15 in turn. For each test point, FRF measurements were made between that point and all reference accelerometer locations. The process was repeated for the shaker in the horizontal direction. A total of 30 sets of FRF measurements were therefore made for this test. The measurements took about three hours to be completed.

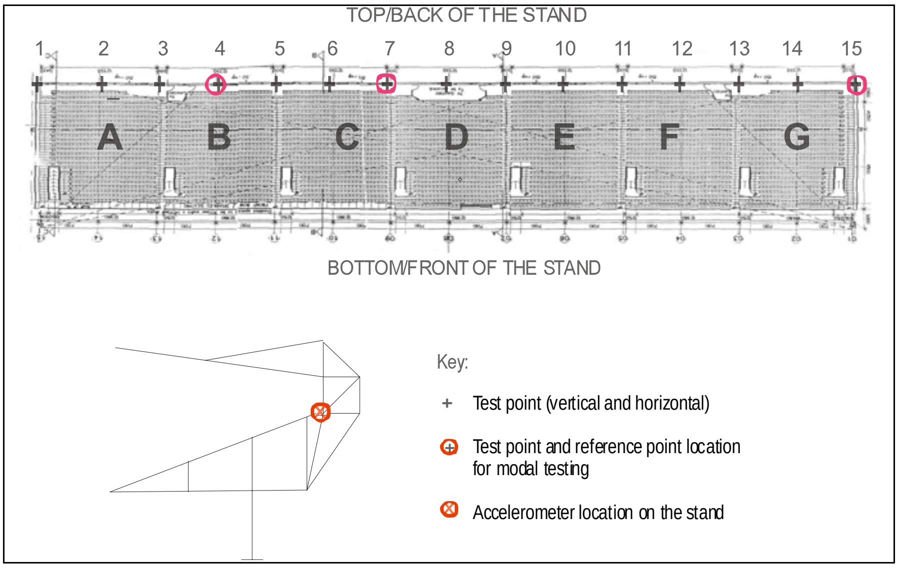
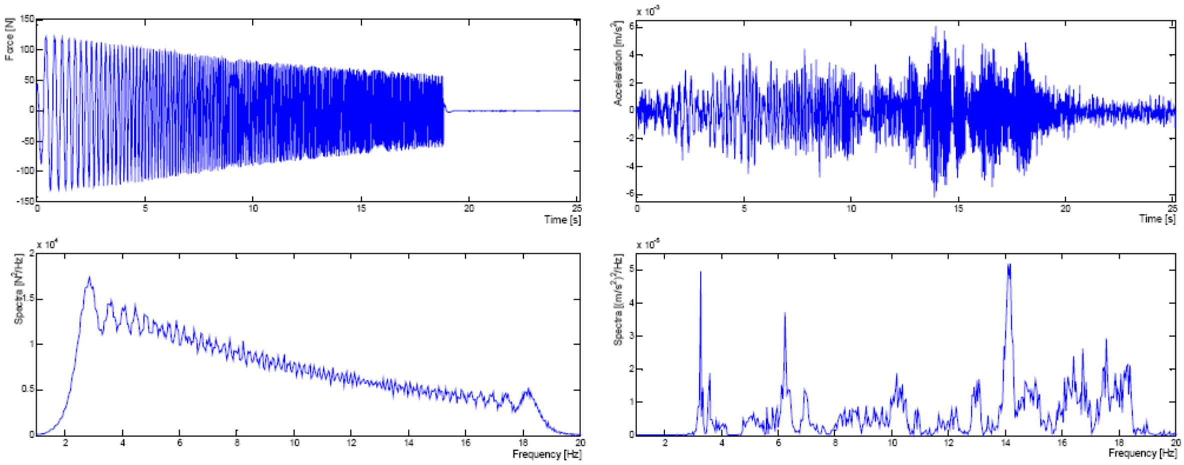


Figure 7: The Stand layout - location of the test points for modal testing.

3.4 Measurement of an FRF

Each FRF was measured by sampling both the excitation and response signals. A chirp signal was used as the input excitation through the shaker. A chirp signal is a sinusoidal signal with a frequency that increases linearly as a function of time between two prespecified frequency limits. For these tests, a frequency range of 2 to 19 Hz was selected. **Error! Reference source not found.**Figure 8 (top) shows typical excitation and response signals measured when applying a chirp excitation and Figure 8 (bottom) shows their linear spectra respectively. It can be seen in the excitation spectra (Figure 8(a)) that there is excitation energy at all frequencies of interest between 2-19 Hz. Similarly, the response spectrum has peaks at frequencies likely to correspond to the natural frequencies of the stand.



(a) Typical chirp excitation and it's spectrum

(b) Response and it's spectrum to chirp excitation at TP7 (point mobility).

Figure 8. Excitation and It's Spectrum

To determine the optimum data acquisition parameters, several trial and error measurements were performed. It was decided that 8 averages provided Frequency Response Functions (FRFs) of sufficient quality. To avoid leakage (signal energy smearing out over a wide range of frequency range), exponential window is used. The exponential window applies an exponential decay that forces the response data to zero by the end of the time frame. This guarantees a periodic signal, hence avoiding leakage.

For a frequency span of 20 Hz and number of frequency lines of 500, provide a frequency resolution of 0.04 Hz. This frequency resolution is sufficient to ensure that two (or more) closely spaced modes to be accurately determined, at the same time minimized the time needed for measurement. Time span of 25.17 s and number of sample of 2048 gives a sampling frequency of 81.37 Hz. Table 1 shows the main digital data acquisition parameters used for FRFs measurement of this modal testing. A typical averaged FRF is presented in Figure 9, which is zoomed between 1 and 10 Hz for clarity.

Table 1: Main digital data acquisition parameters adopted for FRFs measurements

Parameter description	**Parameter value**
Data acquisition time	25.17 s
Excitation frequency limits	2-19 Hz
Frequency span	20 Hz
Number of frequency lines	500
Frequency resolution	0.04 Hz
Total number of samples	2048
Number of averages	8
Window	Exponential ($\lambda = 1$)

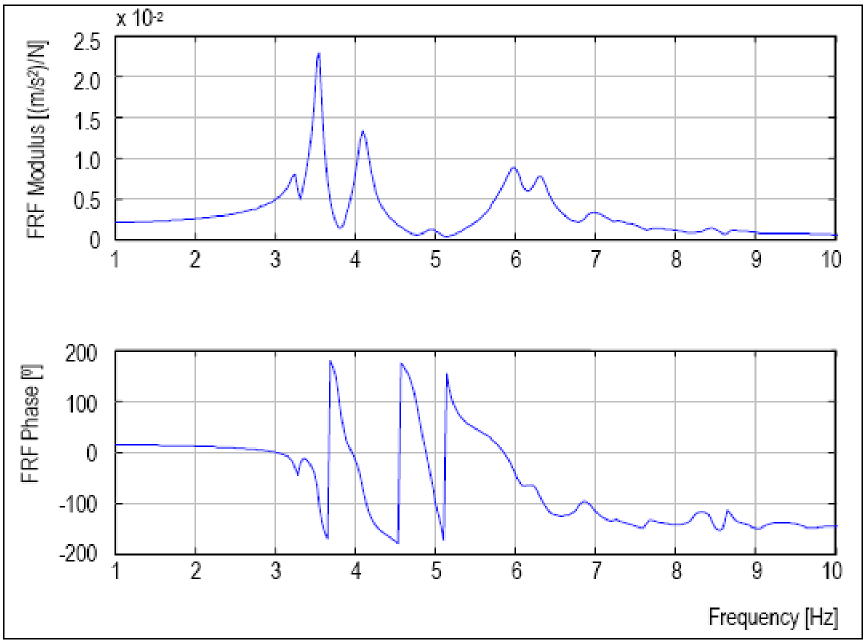
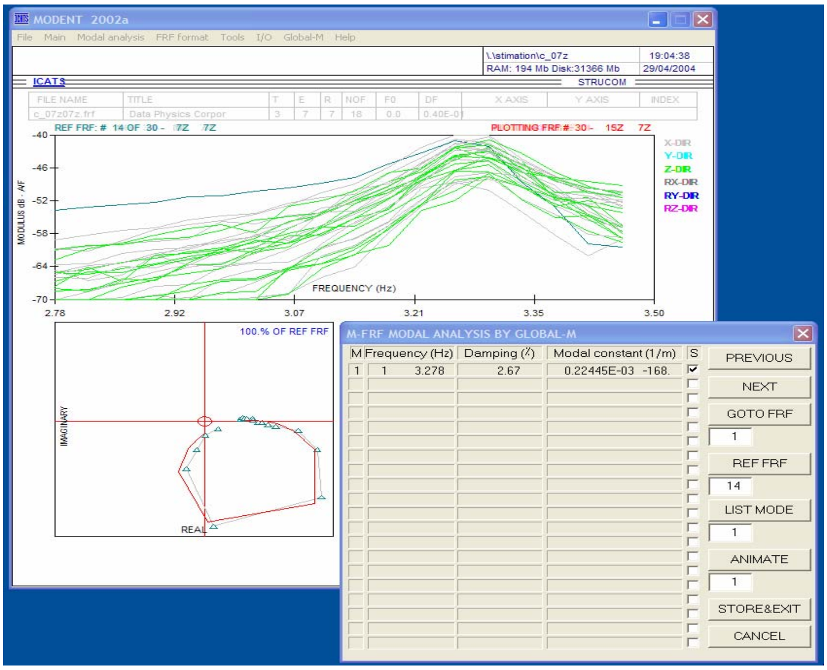


Figure 9: Typical FRF from experimental data

3.5 Modal Parameter Estimation

At the end of the full measurement of FRFs, a total of 30 x 6 FRFs were collected. Then, using the FRFs, modal parameter estimation was performed to estimate the modes of vibration of the structure. To determine if re-measurement of any test points was required, a quick estimation was performed briefly on site to confirm the adequate quality and completeness of the acquired data. A more comprehensive analysis was then performed following return from site.

The ICATS suite of software developed by Imperial College was used for the analysis of the modal test data. A MDOF method of modal parameter estimation called Global-M, which is available in the MODENT module of ICATS, was utilised. This method analyses all FRFs corresponding to a single reference point simultaneously (Single Input Multiple Output (SIMO)). Figure 10 shows a screenshot from the analysis procedure in ICATS.



\.\stimation\c_07z 19:04:38
RAM: 194 Mb Disk:31366 Mb 29/04/2004

FILE NAME	TITLE	T	E	R	NOF	F0	DF	X AXIS	Y AXIS	INDEX
c_07z07z.frf	Data Physics Corpor	3	7	7	18	0.0	0.40E-01			

M	Frequency (Hz)	Damping (%)	Modal constant (1/m)	S
1	1 3.278	2.67	0.22445E-03 -168.	☑
				☐
				☐
				☐
				☐
				☐
				☐
				☐
				☐
				☐
				☐
				☐
				☐
				☐
				☐
				☐
				☐
				☐
				☐
				☐

Figure 10: MDOF modal parameter estimations in ICATS

4. RESULTS AND DISCUSSIONS

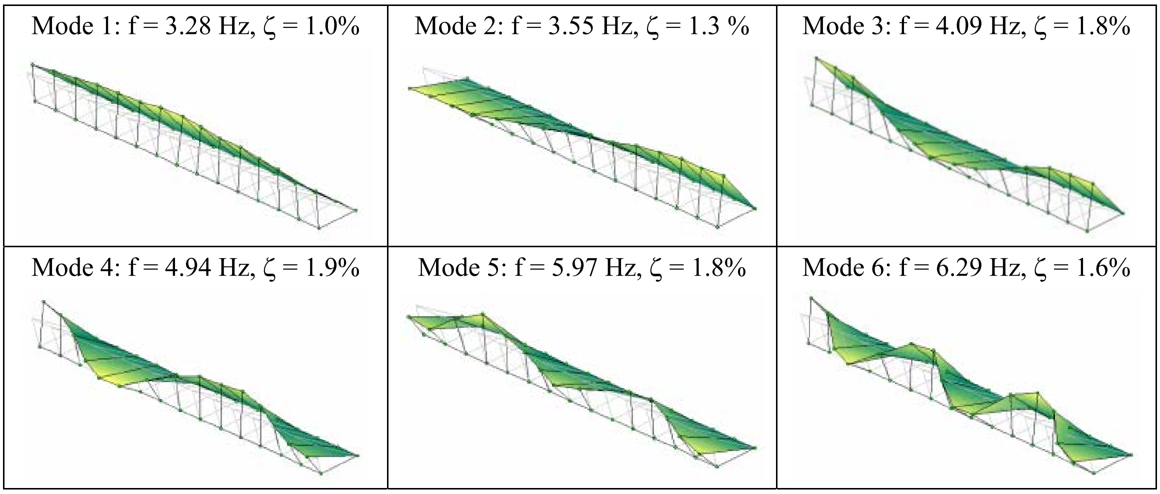
4.1 Modal Parameters from Modal testing

The modal parameters of the first six lowest modes of vibration, which were estimated from the measured FRF data, are presented in Figure 11. The Figure shows the modal parameters (natural frequencies, damping ratios and mode shapes) obtained from the modal testing.

A single line of measurement points was utilised along the back of the stand as described in Section 3.3 and, for ease of visualisation, another two lower rows are included as zero points.

As expected, it was found that the lowest modes of vibration engaged primarily the back of the stand. It is also clear that there is a family of modes that engage primarily the back of the stand. The first mode of vibration (at 3.28 Hz) comprised a single half-sine shape along the entire length of the stand. Higher modes exhibited an increasing number of half-sine shapes along the length of the stand, which is typical behaviour for a strongly orthotropic system. It should be noted that the ends of the stand were not fully restrained (i.e. the modal ordinates were not zero).

The visual observation of mode shapes from modal testing fit well with the trends observed in the pre-test FE analysis [7, 8]. However, the experimental natural frequencies were significantly higher than those predicted from the model, particularly for higher modes. Clearly, the structure under test had additional stiffness that was not included in the FE model. Accordingly, the modal parameters identified in the modal testing were used in the correlation analysis to update and validate the FE model of the stand [7, 8]. These comparisons and manual model updating were explained and described in details in Ibrahim (2006) [7] and Ibrahim and Reynolds (2007) [8]. The final (manually updated) modal parameters from the finite element modelling are shown in Figure 12. The correlation analysis between the results from FE model and modal testing is described in the next section.



Mode 1: f = 3.28 Hz, ζ = 1.0%

Mode 2: f = 3.55 Hz, ζ = 1.3 %

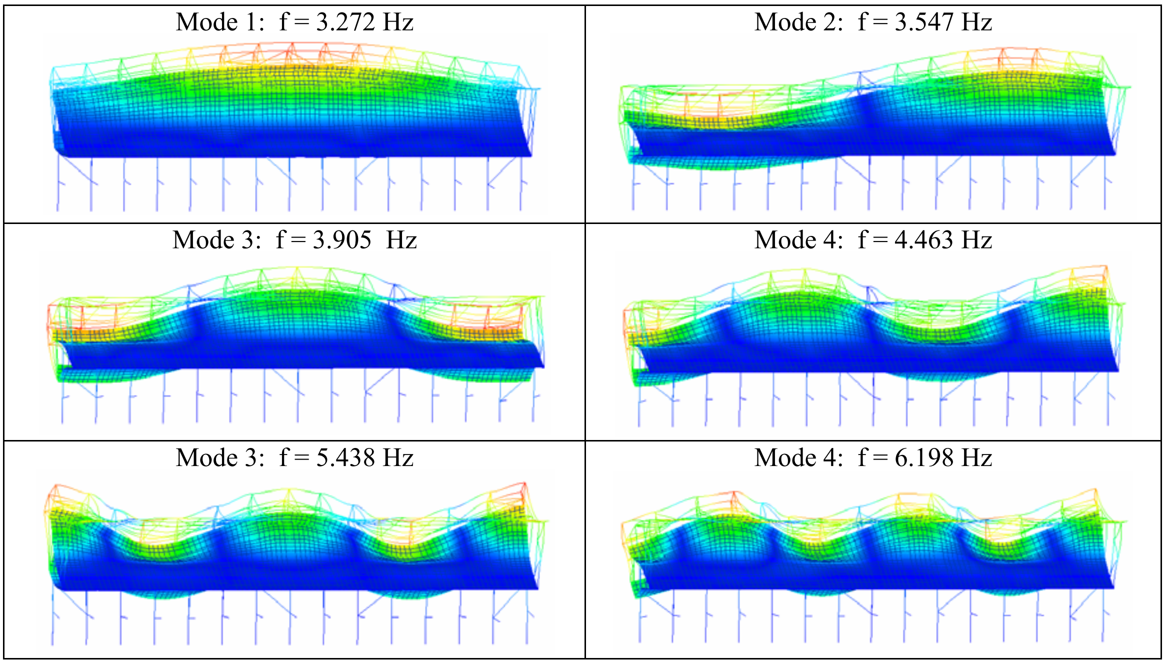
Mode 3: f = 4.09 Hz, ζ = 1.8%

Mode 4: f = 4.94 Hz, ζ = 1.9%

Mode 5: f = 5.97 Hz, ζ = 1.8%

Mode 6: f = 6.29 Hz, ζ = 1.6%

Figure 11: Mode shape estimates from modal testing



Mode 1: f = 3.272 Hz

Mode 2: f = 3.547 Hz

Mode 3: f = 3.905 Hz

Mode 4: f = 4.463 Hz

Mode 3: f = 5.438 Hz

Mode 4: f = 6.198 Hz

Figure 12: Mode shapes from the updated FE model of the Midland Road Stand

4.3 Correlation Analysis

In correlation analysis, the modal properties for the final FE model were compared with those estimated from shaker modal testing. The comparison was made in order to verify the FE modal properties were suitable for use in the analytical crowd-structure simulations [6, 7]. The FEMtools software was used for this comparison purposes because it has in-built functions for correlation analysis. Initially, the final FE model developed in ANSYS FE code was imported into FEMtools. The model was analysed in FEMtools by specifying a range of natural frequencies between 3.2 to 6.3 Hz, so that, only the first 6 vertical modes (excluding the sway mode) are estimated. This was necessary to have a compatible pairing of analytical modes with the relevant modes from the modal testing. Note that the results for natural frequencies in FEMtools were the same with those results in ANSYS FE.

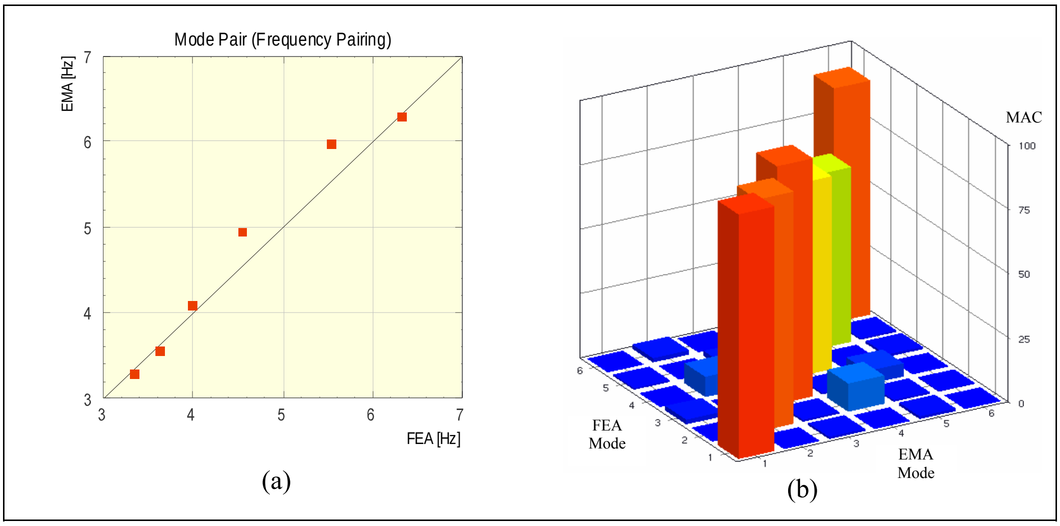
The correlation analyses were carried out using Modal Assurance Criterion (MAC) [10] and Coordinate MAC (COMAC) [10]. MAC is a tool to check the correlation between two sets of vibration mode shapes (measured/measured, theoretical/theoretical, or theoretical/measured). COMAC indicates the correlation at selected measurement points on the structure.

Initially, the correlation of frequencies pairing (Figure 13(a)) and the reduced mode shapes pairing (Figure 14) were carried out. The natural frequencies of the FE model for modes 1, 2, 3, 6 and sway mode are within reasonable values to those from experimental measurement. However, the natural frequencies of the model for modes 4 and 5 are lower, up to 0.5Hz (9.6 % errors) compared to experimental measurement. All the first 6 modes had MAC values greater than 68% (Table 2) which indicates good correlation of mode shapes (Figure 13(b)) between FE model and experimental results. The COMAC is illustrated in Figure 15. The high values of COMAC (82.5 - 87.5%) indicate good correlation over the range of the 6 selected modes.

A reasonably good agreement has been obtained for modal properties of the FE model to those identified in modal testing (Experimental Modal analysis, EMA) as shown in Table 2. As can be seen, the maximum difference of the FEA natural frequencies is only 9.62% which is small considering that all six modes are modelled and compared simultaneously.

Table 2: Comparison of modal properties identified by EMA and final FEA

Mode	**EMA Natural Frequencies [Hz]**	**FEA Natural Frequencies [Hz]**	**Difference in Frequencies [Hz]**	**Errors in Frequencies [%]**	**MAC Values [%]**
1	3.28	3.275	0.005	0.15	95.1
2	3.55	3.549	0.001	0.03	90.3
3	4.09	3.908	0.182	4.45	92.6
4	4.94	4.465	0.475	9.62	75.0
5	5.97	5.441	0.529	8.86	67.9
6	6.29	6.200	0.090	1.43	91.0



(a)

(b)

Figure 13: Plots of (a) Frequency Pairing and (b) Modal Assurance Criterion (MAC) between experimental modes and modes from the final FE model

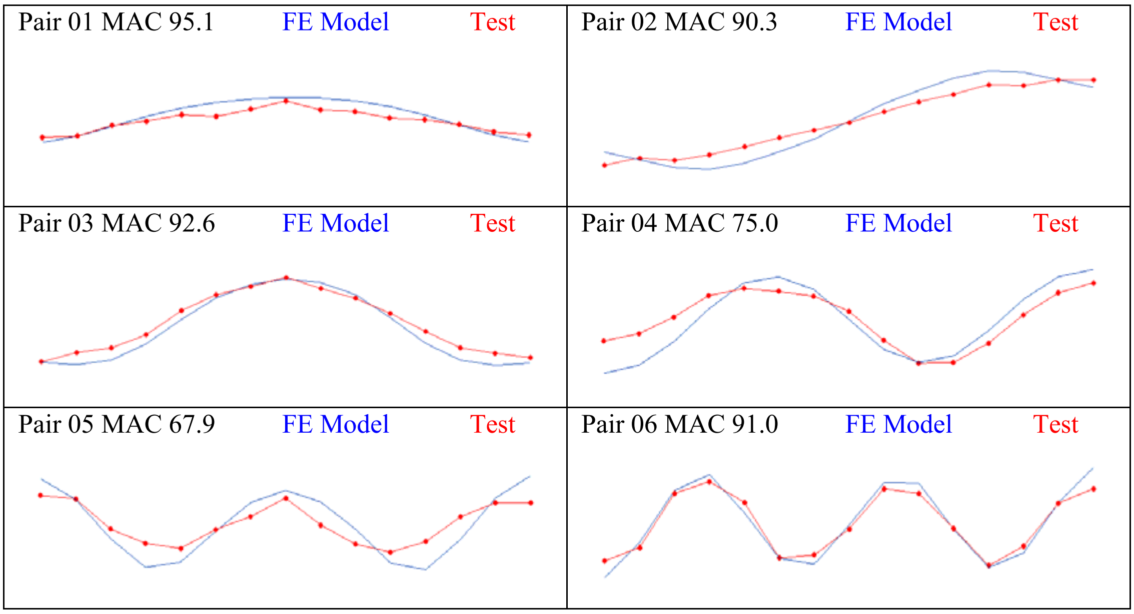


Figure 14: Reduce Mode Shapes Pairing (measurement points)

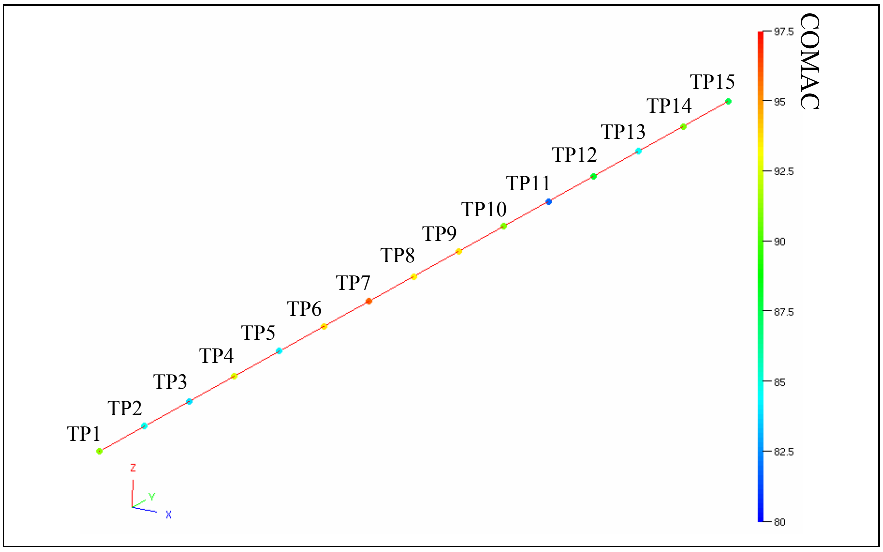


Figure 15: Plot of COMAC over all test points and corresponding nodes from FE analysis.

5. CONCLUSIONS

This paper demonstrated that the modal testing performed by an electrodynamic shaker was successfully utilised to estimate the relevant modal properties of the grandstand, a medium size civil engineering structure. The first 6 vertical modes with a range of natural frequencies between 3.2 to 6.3 Hz were estimated successfully. The natural frequencies and modeshapes estimated from measurements were used in the model updating of the finite element modelling.

A good correlation of natural frequencies and mode shapes from the experimental results and FE modelling was also described in this paper. The good correlation indicates that the FE model of a grandstand structure is fairly accurate. The percentage errors in natural frequencies vary from 0.15 % to 9.62 % and the values of the natural frequencies are generally lower than those from modal testing. Similarly the MAC values are generally high (slightly lower for modes 4 and 5) which indicates a good correlation in mode shapes.

REFERENCES

[1]. Bolton, A. (1992), *Fatal mix caused stand fall*, New Civil Engineer, May 14, 1992, pp. 18.

[2]. Reid, W. M. (1999), "Football stadia", In *Behaviour and Design of Structures for Serviceability Conditions*, IABSE, British Group, IStructE, London, pp. 53-58.

[3]. Littler, J. D. (1996), "Measuring the dynamic response of temporary grandstands", In *proceeding of Structural Dynamics Eurodyn '96*, Florence, Italy, June 5-8, 1996, A. A. Balkema, Rotterdam, The Netherlands, pp. 907-913.

[4]. SCOSS (2002), *Dynamic Behaviour of Grandstand*, SCOSS Bulletin, pp. 1-4.

[5]. Reynolds, P., Pavic, A. and Ibrahim, Z. (2003), "A remote monitoring system for stadia dynamics", *Structures and Building,* Vol. 157, No. SB6, pp. 385-393.

[6]. Ibrahim, Z., Reynolds, P. and Pavic, A. (2004), "The effects of crowd occupation on the dynamic performance of a grandstand", In *proceeding of ISMA 2004 - International Conference on Noise and Vibration Engineering*, Katholieke University, Leuven, Belgium, pp. 797-810.

[7]. Ibrahim, Z. (2006), "The effects of crowds on dynamic characteristic of stadia structures", PhD Thesis, University of Sheffield, United Kingdom.

[8]. Ibrahim, Z. and Reynolds, P. (2007), “Finite element modelling for evaluating the dynamic characteristic of a grandstand”, *In: 2nd. International Engineering Convention (INTEC 2007),* Jeddah, Saudi Arabia.

[9]. Reynolds, P. and Pavic, A (2002), “Modal testing of a sport stadia”, in *Proceedings of the 20th. International Modal Analysis Conference (IMAC XX)*, Los Angeles, California, USA, February 4-7, 2002, Society for Experimental Mechanics, pp. 1037-1043.

[10]. Ewins, D. J. (2000), *Modal testing: Theory, practice and application,* 2nd edition, 0862802184, Research Studies Press Ltd. & John Wiley and Sons Inc., Taunton, Somerset, England.

[11]. Maia, N. M. M., Silva, J. M. M., He, J., Lieven, N. A. J., Lin, R. M., Skingle, G. W., To, W-M. and Urgueira, A. P. V. (1997), *Theoretical and Experimental Modal Analysis*, ed. Maia and Silva, Taunton, UK: Research Studies Press Ltd.