FINITE ELEMENT MODELLING FOR EVALUATING THE DYNAMIC CHARACTERISTIC OF A GRANDSTAND

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ABSTRACT

This paper describes the finite element modelling for evaluating the dynamic characteristic of a grandstand located in Bradford, United Kingdom. Field measurements have been conducted to investigate the dynamic characteristics of the grandstand. 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 such as horizontal and vertical bracings on the dynamic characteristics of the grandstand. Finally, the performance of the finite element model is evaluated by correlating the natural frequencies and mode shapes from the finite element models and the field measurements. 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: *finite element modelling, dynamic characteristic, grandstand, vibration*

INTRODUCTION

With the trends towards increased slenderness of stadia structures and more lively 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 grandstand 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. However, since one of the objectives of this research is to provide design guidelines with respect to the vibration serviceability criteria, an appropriate model of the structure that can predict the dynamic behaviour of the structure prior to the construction need to be modelled and proposed.

With a better understanding, backed up by a large number of vibration response data, the engineers/designers can build predictive computer simulation models that can guide future structural designs. Finite Element (FE) modeling was carried out as part of the research prior to the modal testing and manually updated to correlate well with the results obtained from the experimental dynamic testing. The modeling process with various arrangement procedure up to the final model is describes in this paper.

The Midland Road Stand at Valley Parade, Bradford, UK

The Midland Road Stand (Figure 1) is one of the permanent grandstands at the Valley Parade Stadium. This stadium, home to Bradford City AFC, is currently officially titled the Bradford & Bingley Stadium following a sponsorship agreement. The stand is situated on the east side of the stadium (Figure 1) and can accommodate

4,500 spectators at one time. This is about 18% of the total capacity of the whole stadium, which is 25,136 spectators. About half of the stand (bays E, F and G) is usually reserved for visiting supporters whereas the remainder is usually occupied by home supporters.

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

MATERIALS AND METHODS

Structural Description

The existing Midland Road Stand is the fourth stand built at the location. It 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.

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

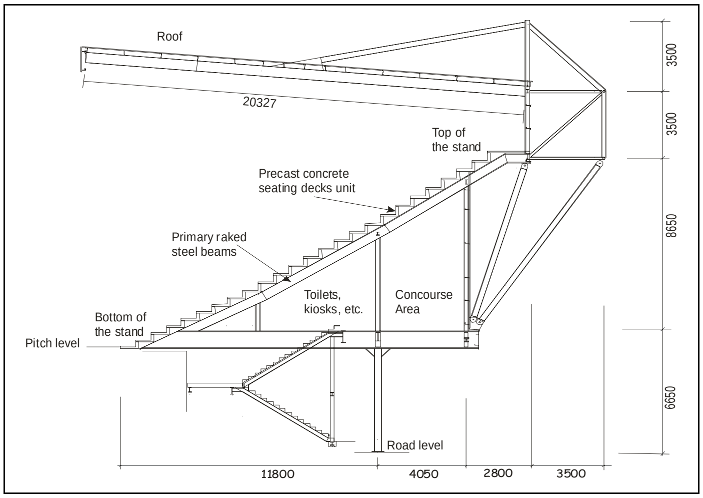


Figure 3: Cross-section of the Midland Road Stand.

Modal Parameters from Modal testing

Figure 4 shows the modal parameters (natural frequencies, damping ratios and mode shapes) obtained from the modal testing. It shows the first 6 modes which consist of a family of modes involving mainly the cantilevered back section of the stand. All these modes had maximum response on the top landing of the stand (seating deck), hence were considered to be important in this research as they might produce significant response under crowd occupation. These modal parameters will be used in the correlation analysis to update and validate the FE model of the stand.

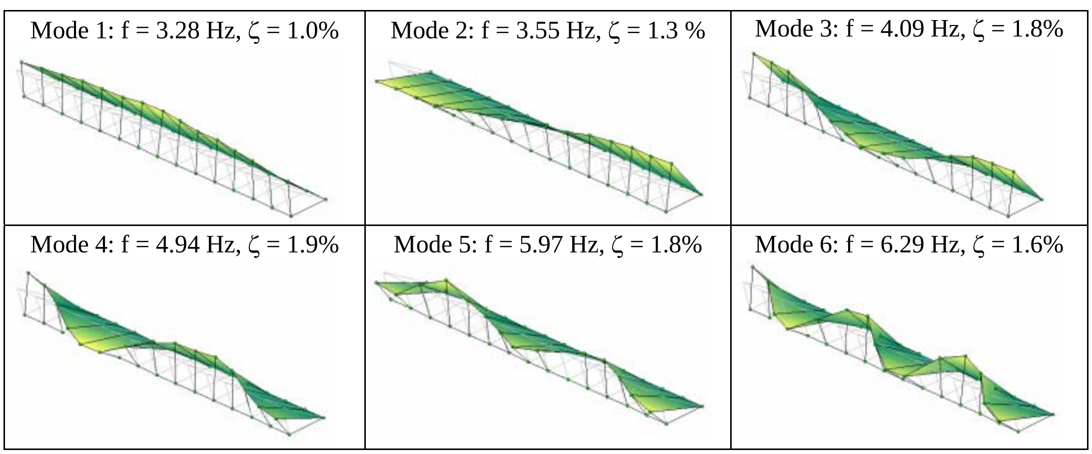


Figure 4: Mode shape estimates from modal testing

FE Modelling

Two FE models of the Midland Road Stand were created prior to the modal testing. Since 3D FE model provides a complete representation of the stand, the pre-test 3D FE model was developed further and manually updated to match as closely as possible the modal properties of the empty stand determined from measurements. The pre-test FE modelling of the Midland Road Stand was carried out as part of the test-planning phase prior to the modal testing. Observing the mode shapes of the stand in the pre-test FE model, help to select transducer and exciter locations for the modal testing to describe all modes of vibration of interest. This selection can increase the efficiency of the modal testing by optimising the number of test points required and therefore reduce measurement time. It also enables better identification of the significant modes and enhances the mode shape display.

The two-dimensional (2D) and three-dimensional (3D) FE models of the empty Midland Road Stand were developed using the ANSYS FE code. The models were created based on parameters from design drawings and specifications. Table 1 shows the material properties for concrete and steel in the FE modelling.

Table 1: Parameters used in FE modelling

Parameters	**Values**
Concrete Young's Modulus, $E_{concrete}$	38 GPa
Concrete's Density, $\rho_{concrete}$	2400 kg/m^3
Concrete Poisson's Ratio, $\eta_{concrete}$	0.2
Steel Young's Modulus, E_{steel}	205 GPa
Steel's Density, ρ_{steel}	7850 kg/m^3
Steel Poisson's Ratio, η_{steel}	0.3

2D Frame Model

A 2D frame model is a simple and typical representation of any one of the frames in a grandstand. Even though a 2D frame is normally believed to oversimplify an actual structure, it can be a quick and simple way to sufficiently examine the behaviour of a grandstand in the vertical and front-to-back direction [7]. Moreover, it is much simpler to recognise an error in a 2D model and correct it [8] compared with a 3D model.
Figure 5 shows a 2D FE model created of the Midland Road Stand. The model consisted of a single 2D frame, which means that the movement of the stand in sway direction was constrained. The beams and columns were modelled using ANSYS BEAM44 elements. ANSYS BEAM44 element is used because it permits the end nodes to be offset from the centroidal axis of the beam (this feature is needed in the 3D model). The first 2 modes of this 2D model engaged mainly the cantilever at the back of the stand with some motion of the roof structure. These modes engaged significantly the seating decks, and therefore were considered important and were investigated further in the 3D model. The third mode clearly engaged primarily the roof. The natural frequencies of the two vertical modes are tabulated in Table. Note that, in this 2D frame model, the loads from concrete slabs, lateral beams, the roof and other non-structural elements were transferred to the frame as equivalent masses at appropriate nodal points using ANSYS MASS21 elements.

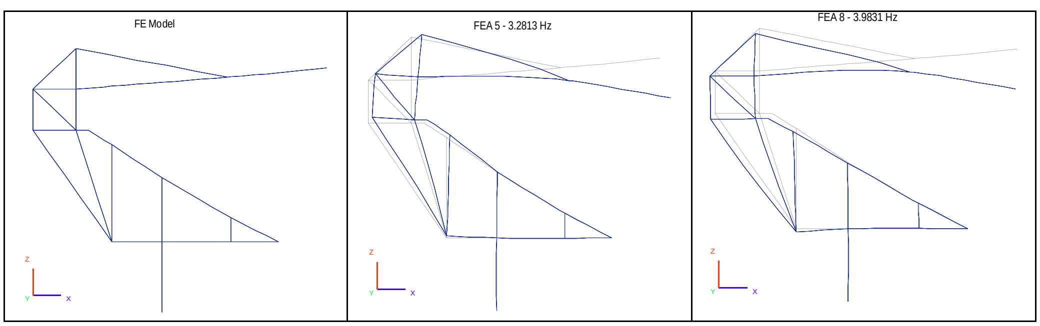


Figure 5: 2D frame model showing typical modes

3D Frame Model

A 3D frame model may provide a more complete representation of a grandstand. The model is more appropriate to represent a complete stand, as it is capable of simulating the dynamic behaviour in all three directions. This includes the sway (side-to-side) direction, which could be critical in vibration serviceability of some stadia structures.

The Midland Road Stand consists of 15 frames at an interval of 7.19 metres. The pre-test 3D FE model of the stand consists of 15 frames (as in the 2D FE model), connecting by lateral beams. The model also includes concourse floor and seating deck slabs and gable end columns. All the beams and columns were modelled using ANSYS BEAM44 and the slabs using ANSYS SHELL63 elements. Similarly, the loads from roof cladding and other non-structural elements were transferred to this 3D FE model as approximate equivalent masses on nodal points using ANSYS MASS21 elements.

Table 2 shows the natural frequencies of the first 7 modes identified from the pre-test 3D FE model of the Midland Road Stand. The lowest mode identified is a sway mode, whereas the remaining 6 modes are a family of modes involving mainly the cantilevered back section of the stand similar to those of modes from the modal testing.

Note that the natural frequency of 3D model mode 1 is higher than 2D model mode 1. This is due to increases in stiffness of the 3D model with the inclusion of terrace and concourse slabs, as well as lateral beams in the 3D model.

The mode shapes in Figure4, indicate that the best locations for transducers are along the back of the stand. These locations ensure that the highest responses for all the mode of interest will be measured. Observing the mode shapes from this 3D model, optimize numbers of test points were selected for modal testing.

Table 2: Summary of the natural frequencies calculated using pre-test 2D and 3D FE models

	NATURAL FREQUENCIES [Hz]						
	Horizontal	**Vertical**					
Modes	**Sway**	**Mode 1**	**Mode 2**	**Mode 3**	**Mode 4**	**Mode 5**	**Mode 6**
2D FE Model		3.281 (5)	3.983 (7)				
3D FE Model	0.982 (1)	3.334 (9)	3.388 (11)	3.503 (12)	3.689 (13)	3.950 (15)	4.195 (16)

* Numbers in ( ) show the mode order

FE Model Refinement and Manual Updating

In the process to refine and update the FE model, to reach the closest match to the experimental results, several investigations were carried out. The following variations on the initial model were investigated:

1. The addition of concrete slabs on the seating deck and concourse area. The slabs are considered as shell elements in the model.
2. Consideration of eccentricities of beams and slabs to ensure the appropriate composite action of beam-slab members by increasing the second moment of area of the beams.
3. The inclusion of vertical and plan bracing members.
4. The inclusion of roof cladding.
5. The inclusion of non-structural walls.

Table 3 shows the summary of the modelling configurations for refinement and manual updating of the 3D FE model. Note that the basic 3D FE model was created by removing the shell elements from the pre-test 3D FE model previously described.

In addition, two variations for composite action of beam-slab members were investigated. Firstly, the increase of beam stiffness (increase in second moment of area, I_{steel}) as a recommended constant of 1.35 [9] and the second by calculating the actual increase in beam stiffness (I_{steel}) of the composite section when the neutral-axis lies somewhere near the interface of beam-slab members.

Table 3: Summary of the modelling configurations for the manual updating of the 3D FE model

Configurations	**Description**
1	Basic frame
2	Basic + seating deck slab + concourse floor slab
3	Basic + seating deck slab + concourse floor slab + vertical bracing
4	Basic + seating deck slab + concourse floor slab + vertical bracing + plan bracing
5	Basic + seating deck slab + concourse floor slab + vertical bracing + plan bracing + roof cladding
6	Basic + seating deck slab + concourse floor slab + vertical bracing + plan bracing + partition block wall
7	Basic + seating deck slab + concourse floor slab + vertical bracing + plan bracing + partition block wall + Pyrok wall
8	Basic + seating deck slab + concourse floor slab + vertical bracing + plan bracing + partition block wall + Pyrok wall + beam-slab[1]
9	Basic + seating deck slab + concourse floor slab + vertical bracing + plan bracing + partition block wall + Pyrok wall + beam-slab[2]

10	Basic + seating deck slab + concourse floor slab + vertical bracing + plan bracing + partition block wall + Pyrok wall + beam-slab^2 + roof tip restraint in vertical direction

RESULTS AND DISCUSSION

Manual Updating of 3D FE Model

The refinement and manual updating of the 3D FE model were carried out progressively from configuration 1 to 10 as tabulated in Table. Each configuration is described and the corresponding changes in natural frequencies (Table 4) of the model are discussed in this section. Note that the order (number in brackets) of the estimated modes in Table varies from 1 to 20, where the ‘missing‘ modes are the roof modes.

The basic 3D model consisted of beam elements (ANSYS BEAM44) to represent beams and columns with spring elements (ANSYS COMBIN14) for foundations. The properties of the beam elements were estimated from their cross-sections. Masses for concourse floor and seating deck concrete slabs and non-structural elements were incorporated by introducing concentrated masses (ANSYS MASS21) at appropriate nodal points on the model. The basic model identified all the first 6 modes and a sway mode of the stand. The natural frequency of the sway mode is very low as expected because there are no bracing and stiffness incorporated in sway direction. The same reason could be given to the small separation between the first 6 modes which varies from 3.540 to 3.798Hz.

In configuration 2, explicit modelling of terrace (assumed uniform thickness of 165mm) and concourse floor (200mm thick) slabs using ANSYS SHELL63 elements resulted in the frequency of sway mode increasing from 0.723 to 0.982Hz. Also, the separation between the 6 vertical modes also increased. This is because the inclusion of slabs increases the lateral stiffness of the stand.

Introducing the vertical bracing elements (configuration 3) at the back of the stand increased the natural frequencies of the higher modes (modes 2 to 6). The natural frequencies were increased because the higher modes are engaging the vertical bracing elements more compared to lower modes (mode 1 and sway mode).
Inclusion of the plan bracing elements (configuration 4) on the roof, terrace deck and concourse slabs increased the sway mode tremendously from 0.983 to 2.402Hz. The increase confirms that, by proper placing of bracing elements, the corresponding natural frequencies of the stand could be increased significantly [7]. Except for mode 1, other vertical modes increased slightly due to the plan bracing elements.

In configuration 5, the roof cladding (2.6mm thickness) was modelled using shell elements (ANSYS SHELL63). Note that in order to suppress local roof modes, the stiffness of the roof was artificially inflated by increasing the value of $E_{steel\text{-}roof}$ from 205 GPa to 205x10^4 GPa. Although the increment successfully removed all the local roof modes, it resulted in a significant increase of the natural frequency of the sway mode from 2.402 to 4.386Hz. The separation between other vertical modes, particularly modes 2 and 3, was also increased significantly. The experimental natural frequencies for modes 2 and 3 were 3.55 and 4.09Hz respectively (separation of 0.54Hz), but the separation calculated using this model was too high (1.449Hz).

In addition, even though there is a contribution of stiffness due to cladding on the roof beams, the roof cladding was modelled as loads on roofing nodes by Letchford et al. (2002) and Salyards and Hanagan (2005) and/or a slight increase in the stiffness (second moment of area) of the roof beams [7]. Therefore, the modelling of roof cladding using shell elements was not carried further. The roof cladding was therefore incorporated by adding mass at appropriate roof nodes and a slight increase in second moment of area of roof beams. The progressing modelling was continued by removing the roof cladding and used the subsequent configuration.

In configuration 6, intermittent partition block walls (thickness = 125mm, $\rho_{block\text{-}wall}$ = 1200 kg/m^3) (Gere, 2001) for kiosks, toilets and shops located underneath the seating deck (on the concourse floor) were included using ANSYS SHELL63 elements. The inclusion of the block walls resulted in a uniform increased in the frequencies of all the modes.

However, in configuration 7, the addition of Pyrok (cement bonded particle board) wall cladding along the back of the stand at the concourse and terrace levels resulted in reasonable separation of the estimated frequencies. The wall cladding was modelled using ANSYS SHELL63 elements with thickness of 35mm, ρ_{Pyrok} = 1250 kg/m^3 and E_{Pyrok} = 18.5GPa. The proper modelling of the Pyrok wall along the back of the stand is important as it helps to govern the separation of the frequencies of the modes.

To consider the stiffness contributed by the composite beam-slab sections (for both terrace and concourse area), two investigations were carried out as explained earlier. Firstly, the increase in the beam stiffness is calculated by multiplying the second moment of area with a factor of 1.35 [7,8] (configuration 8). It can be seen that, the frequencies increased for all the modes of interest. However, the fundamental frequency, mode 1 is 3.352Hz, which is high compared to 3.28Hz from EMA, which suggests that the stand is slightly over stiff. Then, by calculating the exact position of the neutral axis of the composite section, the second moment of area of the section was calculated and the increase stiffness of the beam is introduced (configuration 9). The fundamental frequency is reduced compared to configuration 8.

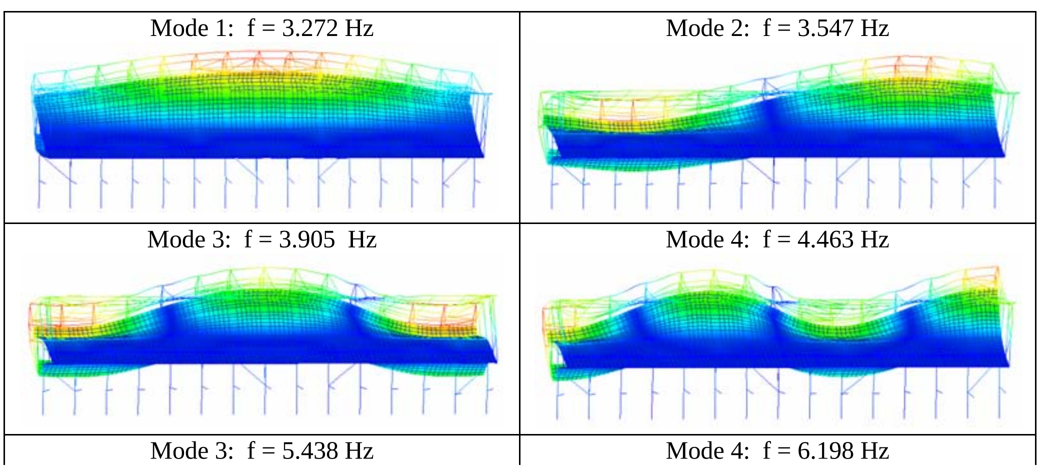
For simplification and further analysis, restraints in vertical direction were applied on the tip of the roof on each frame in the model (configuration 10). Note that the changes in frequencies are very small (compared with those from configuration 9) and negligible and the order of the modes (numbers in brackets) are continuous from 1 to 7. This model with its corresponding modes is chosen as the final model and its modal parameters are shown in Figure 6. The correlation analysis between FE model and EMA were carried in the next section.

Table 4: Summary of natural frequencies calculated using 3D FE model

	Natural Frequencies [Hz]						
		Vertical					
Configuration	**Sway**	**Mode 1**	**Mode 2**	**Mode 3**	**Mode 4**	**Mode 5**	**Mode 6**
1	0.723 (1)	3.540 (11)	3.566 (12)	3.581 (13)	3.621 (14)	3.692 (15)	3.798 (16)
2	0.982 (1)	3.334 (9)	3.388 (11)	3.503 (12)	3.689 (13)	3.950 (15)	4.195 (16)
3	0.983 (1)	3.333 (9)	3.477 (10)	3.602 (11)	3.708 (12)	4.145 (15)	4.209 (16)
4	2.402 (3)	3.299 (8)	3.498 (9)	3.662 (10)	3.847 (12)	4.195 (13)	4.387 (15)
5	4.386 (8)	3.020 (3)	3.219 (4)	4.668 (9)	5.848 (14)	6.406 (17)	6.721 (20)
6	2.420 (3)	3.373 (8)	3.545 (9)	3.728 (10)	3.953 (12)	4.319 (14)	4.479 (15)
7	2.808 (5)	3.043 (7)	3.263 (8)	3.557 (10)	4.039 (12)	4.967 (16)	5.704 (19)
8	3.060 (1)	3.352 (4)	3.596 (6)	3.942 (8)	4.527 (11)	5.488 (14)	6.224 (16)
9	3.059 (1)	3.307 (4)	3.552 (6)	3.901 (8)	4.507 (11)	5.459 (14)	6.204 (16)
10	3.072 (1)	3.275 (2)	3.549 (3)	3.908 (4)	4.465 (5)	5.441 (6)	6.200 (7)

* beam-slab[1] = Increase I_{Beam} by 1.35 factor
* beam-slab[2] = Increase I_{Beam} is calculated using N.A. of composite section

** Numbers in ( ) show the mode order from analysis



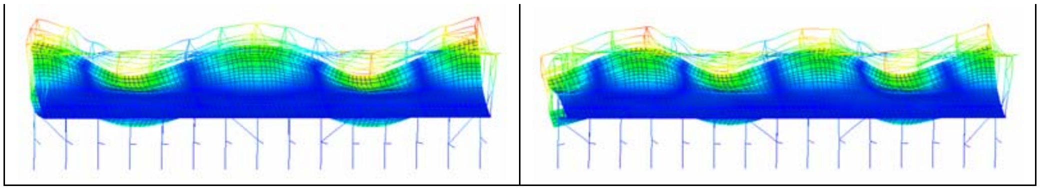


Figure 6: Updated mode shapes from the FE model of the Midland Road Stand

Correlation Analysis

The modal properties for the final FE model (configuration 10 in Table) were compared with those estimated from shaker modal testing to verify the analytical modal properties were suitable for use in the 2DOF crowd-structure simulations. The FEMtools software was used for this purpose 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 6.3Hz, 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 analysis 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 7(a)) and the reduced mode shapes pairing (Figure8) 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 5) which indicates good correlation of mode shapes (Figure 7(b)) between FE model and experimental results. The COMAC is illustrated in Figure 9*Figure* . 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 EMA as shown in Table 5. 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 5: Comparison of modal properties identified by EMA, initial and final FEA

Mode	EMA Natural Frequencies [Hz]	FEA Natural Frequencies [Hz]	Difference in Frequencies [Hz]	Errors in Frequencies [%]	MAC Values [%]
sway	3.06 (AVT)	3.072	-0.012	0.39	-
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

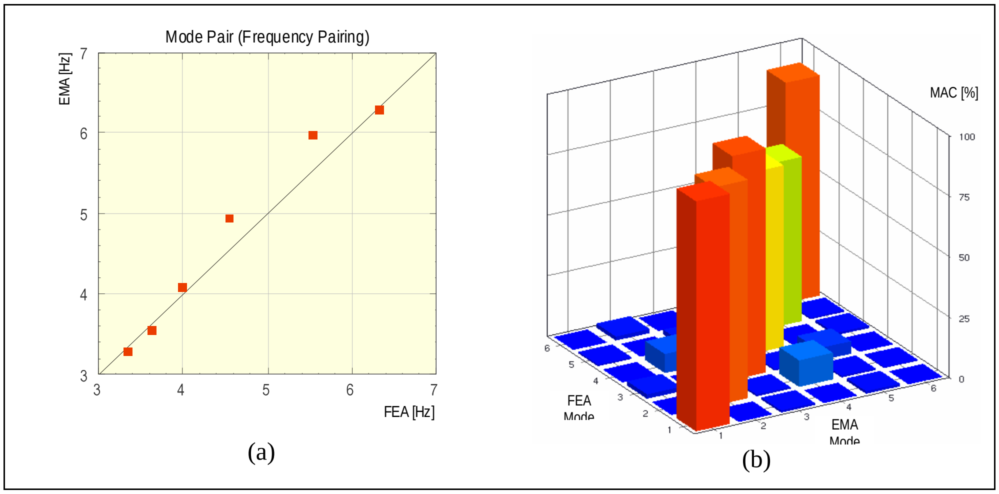


Figure 7: Plots of (a) Frequency Pairing and (b) Modal Assurance Criterion (MAC) between experimental modes and modes from the final FE model

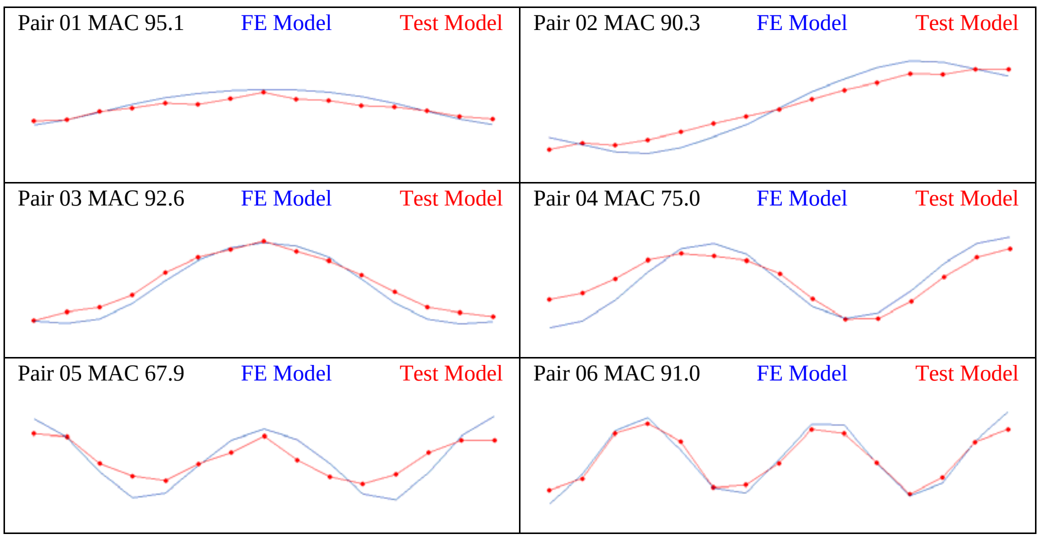


Figure 8: Reduce Mode Shapes Pairing (measurement points)

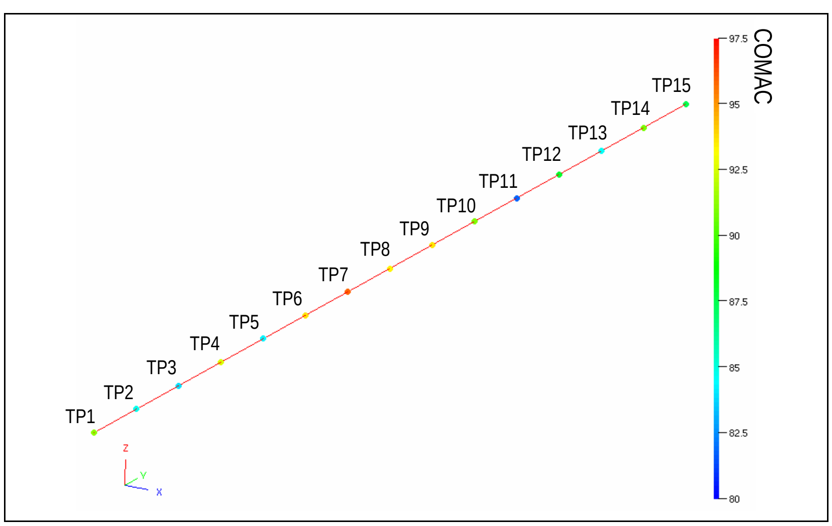


Figure 9: Plot of COMAC over all test points and corresponding nodes from FE analysis.

CONCLUSIONS

This paper has shown a good correlation of natural frequencies and mode shapes from experimental results and FE modelling. The good correlation indicates that the progressive process of modelling different configurations in the FE model are fairly accurate approach to be taken in the FE modelling of a grandstand structure. 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.

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