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Verification of Crowd Dynamic Excitation Estimated from Image Processing Techniques

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ABSTRACT

Dynamic structural responses of a major UK stadium have been measured during a series of high-profile events. In order to verify and validate recent approaches to the determination of vibration responses, a series of models have been developed and comparisons between measured and predicted results made.

Using advanced image recognition and data processing techniques, video records of the events were used to determine approximations to the real forces induced by the crowds. The image processing is based on a digital correlation method and on post-processing aimed at decreasing image noise disturbance (due for example to camera flashes in the video). The output is the velocity field of the grabbed area. These data are further exploited to estimate the load on the structure.

The forces estimated from the image processing have then been used, in conjunction with a highly detailed and accurate FE model, to determine improved estimates of the responses. Comparisons are made between design, measured and back-analysis results using both codified and real crowd forces. The accuracy of the crowd dynamic forces determined from image processing is assessed.

1 PROBLEM OVERVIEW

Stadia are increasingly lightweight and flexible structures due to increased use of slender cantilevers and optimised design procedures. These structures are further subject to occupancy by high density crowds which can generate large loads, and may result in strongly perceptible vibrations. Much current research is aimed at improving methods for the prediction of such vibrations. In particular, the load models used in analysis are very simplistic and do not accurately represent the forces induced by real motions of actual crowds. This paper investigates levels of response predicted using more realistic dynamic loads estimated from image processing of real crowd motions.

In 2000, the City of Manchester Stadium (Figs. 1(a) & (b)) was designed for, amongst other criteria, the avoidance of uncomfortable or panic- inducing vibrations. The stadium itself is of concrete construction with a steel roof considered to act independently of the main bowl of the structure. With a capacity of 47,726 the stadium is the fourth largest in the English Premier league and has a reputation as a major international venue. Several high profile events, including the 2008 UEFA cup finals, the 2002 commonwealth games as well as multiple major concerts and international sports matches, have cemented this image.

Between 2004 and 2005 researchers at the University of Sheffield, UK, performed dynamic testing and long term vibration monitoring using a remote system [1] on the west stand. As well as identifying the characteristic dynamic

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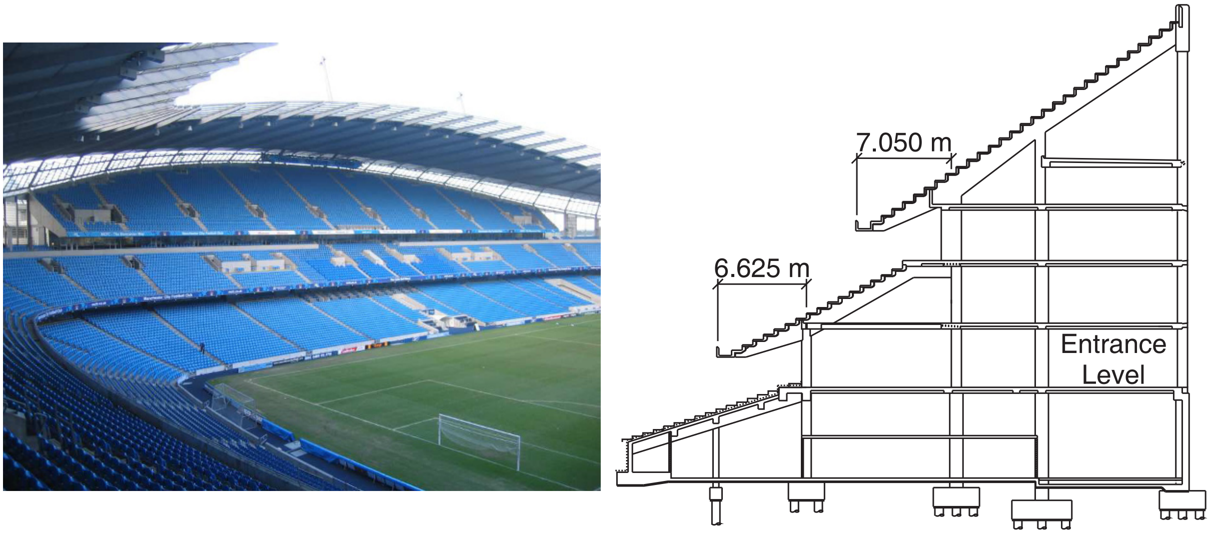

Figure 1: (a) City of Manchester Stadium and (b) a typical cross section of the west stand

properties of the structure, the actual performance of the stand was recorded in the form of structural accelerations and videos of crowd activity. This investigation focuses on recreating the responses of the structure to crowd actions observed during a concert headlined by U2 which took place on 14 June 2005.

A technique has been developed [2] which allows for the estimation of crowd accelerations from video records. With some processing, these data can be converted into time varying forces which can be applied as part of several different response analysis techniques. This paper describes the image/video processing techniques used, the derivation of the associated forces (put into context against other published values), the development of a system model for the structure and the estimation of responses of said system to the aforementioned loading. Subsequently, discussion of the predicted responses in comparison with measured values and the implications of using 'real' force histories leads into the conclusions of the investigation. The paper concentrates on the middle tier of the structure as that is where the initial video processing efforts were focused.

2 VIDEO PROCESSING

The aim of image acquisition and processing is to estimate the acceleration time histories of people in the crowd. This information will be used to estimate the exciting force produced by jumping people.

The authors have already developed a technique to estimate the crowd velocity, which is then used to derive acceleration [2–4]. The method is based on Digital Image Correlation (DIC) but it relies upon good resolution images (22 mm/px or better) to get reliable results. The images considered in this work are instead of relatively poor resolution, as can be seen in Fig. 2. This is due to the need to carry out imaging and monitoring a large area of the stadium. Because of the low resolution images available, the acceleration time histories estimated with the DIC technique are corrupted by a non-negligible level of noise. Therefore only the Root Mean Square (RMS) value of the crowd acceleration are estimated, as described later in this section. Moreover, as can be seen in Fig. 2 due to the perspective, the resolution of the images strongly changes as the region of the image changes, therefore image processing has not been carried out on the full image, but just on a single portion (highlighted in Fig. 2). The considered portion is that where the image resolution is the best possible.

Before discussing the whole adopted procedure to estimate the crowd motion, brief remarks are given about the DIC technique. The DIC technique consists of splitting a movie image into different rectangular Regions of Interest (ROI) with a fixed size. Then, for each ROI, the most similar region of the subsequent image of the movie is searched for (i.e. the region which minimizes a figure of merit; the definition of the figure of merit depends upon the adopted algorithm [5]). Once the displacement of each ROI has been estimated, it is possible to find the velocity field because the time lag Δt, elapsed between the acquisition of the two images, is known. The same procedure

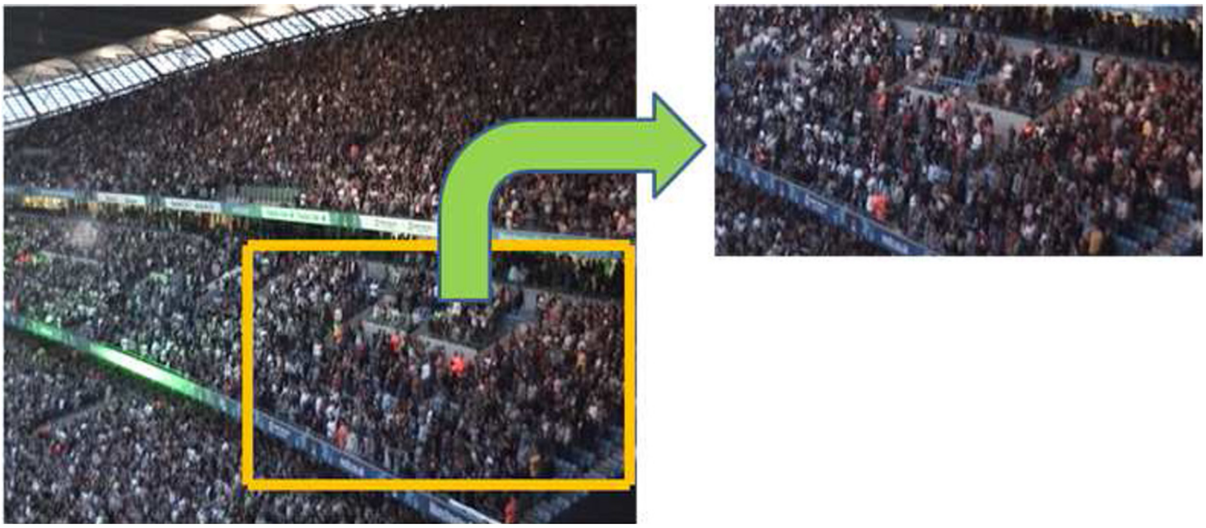

Figure 2: The analysed image area

can be applied to each pair of subsequent images (j and $j + 1$ with $j = 1, 2, 3 \ldots$) to estimate the velocity fields at time $t_j = j\Delta t$. More details can be found in [2]. In [4] the authors analysed the effect of the size of ROIs on the results uncertainty; it was demonstrated that ROIs size should be at least 8x8 pixels. In this paper the size of the ROIs was therefore fixed at 8x8 pixels.

2.1 DIC SIGNALS POST PROCESSING

Once the velocity time history has been estimated for all the ROIs, some signal processing is required. In particular, one of the main difficulties in the post-processing of the obtained velocity time histories was the treatment of noise related to flashes of photo-cameras visible in the images. It has been estimated that each flash was present in one or in two successive images. These flashes often cause large (and meaningless) peaks in the estimated vertical velocity results. A method therefore was required to define an automatic method able to detect the spurious peaks of acceleration and to exclude them from the analysis.

The technique selected to exclude camera flashes was as follows. The numerical difference D was calculated for the velocity time-history of each ROI:

$$D(n \times \Delta t) = [\text{velocity}((n + 1) \times \Delta t) - \text{velocity}(n \times \Delta t)] \quad \text{for} \quad n = 1, 2, 3 \ldots$$

where $\Delta t = \frac{1}{f_s}$ and f_s is the sampling frequency. The ROIs were analysed individually and from each of them a D record was obtained. The Kurtosis coefficient was then calculated for each D record (one D record for each ROI). The Kurtosis coefficient of a time signal x is calculated as:

$$\text{Kurtosis} = \frac{1}{m} \times \frac{\sum_{i=1}^{m} (x_i - \bar{x})^4}{s^4} - 3$$

where m is the number of samples, $\bar{x} = \frac{\sum_{k=1}^{m} x_k}{m}$ and $s = \sqrt{\frac{\sum_{k=1}^{m} (x_k - \bar{x})^2}{m-1}}$. The Kurtosis coefficient increases in the presence of many spikes within the considered signal x. When this parameter was higher than a threshold T, the larger peak (in module) of the D signal was marked as a number not to be considered in the following calculations. The same operation was applied to the sample of the velocity time history causing the peak in the D record. At this point the Kurtosis parameter was recalculated and the comparison with the threshold T was performed once again, and so on until the Kurtosis parameter became lower than T. Different threshold values T were considered through trial and error. Finally T was fixed to 1 as this value guarantees to eliminate most flashes and outliers while preserving the dynamics of the signals.

A further processing was required to take into account the effect of perspective in the collected images. The DIC technique gives as output a velocity time history in px/s for each ROI. A conversion factor between millimetres and pixels was then computed as a function of the considered area of the image; in this way it was possible to calculate the velocity time histories in mm/s.

Once the above mentioned task was completed for all ROIs, a RMS of the processed velocity time histories was calculated for all of them. Each point of the running RMS was calculated on 25 velocity time samples and the adopted overlap was 50%. This means that the time resolution for the RMS history is 0.5 s (the image sampling frequency is 25 Hz). Finally a total RMS (named RMS_{tot}) was estimated on an interesting area containing different ROIs:

$$RMS_{tot}(t_k) = \sqrt{\frac{\sum_{i=1}^{N}(RMS_i(t_k))^2}{N}}$$

where N is the number of ROIs within the considered area and $RMS_i(t_k)$ is the RMS value at time t_k for the i^{th} ROI in the considered area.

2.2 REPRESENTATIVES OF THE ESTIMATED MOTION

Due to both the large number of people included in the imaged stand portion and the poor image resolution, it is not possible to estimate the jumping amplitude and frequency of each person; an average computation is therefore required. Since in the end the interesting data is the overall dynamic loading due to the crowd, the averaging procedure does not constitute a limit in the application of this measuring technique, providing that the averaging area respects two conditions: 1) it is large enough to produce an estimated acceleration with acceptably low uncertainty and 2) it is small enough to describe the distribution of loading on the structure.

Since the stadium stands are almost uniformly crowded, the second condition is actually not relevant. On the contrary the uncertainty linked to the estimated acceleration data has to be analysed. Because there is no practical way to estimate the motion of a large number of people with another measuring technique to be used as a reference, the only consideration that can be done is regarding DIC-estimated data repeatability. This can be done by comparing the results obtained in different areas of the stand on the condition of nominally uniform crowd motion, for example during the refrain of a very popular song, when most of the spectators jump following the beat frequency. Also, later in this paper, the acceleration estimated with the DIC will be used to predict the dynamic loading due to the spectators and, using a FE model of the hosting structure, the vibration response will be calculated. If the estimated vibration is comparable with that measured, another indirect validation of the predicted acceleration uncertainty will be given.

To perform the repeatability analysis the area of the image highlighted in Fig. 2 was divided into 16 sub-regions (see Fig. 3) and the mean acceleration time history was computed for each sub-region. Finally for each of them the RMS_{tot} was calculated. It was verified that these 16 areas have similar and stable values of the mentioned RMS_{tot} parameter. Moreover other tests were done defining a small number of larger sub-regions and the RMS_{tot} parameter does not change significantly even if the size of the region is increased.

It is worth pointing out that the RMS_{tot} parameter is calculated in mm/s. The inertial force exciting the structure due to the crowd motion is instead linked to acceleration. Therefore the RMS_{tot} of the 16 areas have been transformed to acceleration by multiplying by a coefficient $2\pi f$ where $f = 2.1$ Hz. In fact it has been estimated, by auto-correlation operations of the estimated crowd motion, that in the considered condition the people movement is at about 2.1 Hz when the motion is significant. Of course the frequency of motion is linked to the rhythm of the music and it changes as the song changes, however it is quite straightforward to estimate it as soon as the crowd velocity is estimated with the DIC. Once the motion frequency is known the acceleration time history of each of the 16 areas can be

Figure 3: The 16 considered areas

calculated by multiplying the 16 RMS_{tot} by the coefficient $\sqrt{2}\cos(2\pi f t)$. Thus it was possible to estimate a mean crowd acceleration for the 16 areas of Fig. 3.

3 FORCE ESTIMATION

As the crowd accelerations were derived primarily from the middle tier, the rest of the analysis focuses on that tier, with less emphasis being placed upon other regions of the structure.

Force estimates were obtained by multiplying the accelerations obtained in section 2 by the apparent mass of the crowd in each considered area, assuming that force is equal to mass times acceleration. To obtain forces per unit area, these values were then divided by the estimated plan area beneath the crowd for each area. Tables 1(a) & (b) reproduce the estimated values for mass and area, whilst Table 1(c) lists the absolute maximum amplitude of the estimated forces per unit area.

Table 1: Estimated properties of video capture regions (a) plan area of area [m^2], (b) mass of crowd in area [kg], (c) Inferred maximum pressures for each area [N/m^2]

35.00	38.25	24.00	16.50
32.00	31.50	25.00	22.75
30.00	26.25	24.50	21.00
40.50	18.75	20.00	17.50

(a)

1680	1440	1440	1120
2480	1120	1200	1760
1120	1760	1920	960
1840	880	1200	560

(b)

492	350	424	466
705	246	354	522
290	446	540	349
420	272	394	209

(c)

Areas 7 and 9 were found to best reflect the mean of all areas and were thus considered for use as representative data sets. Area 7 was selected for further analysis over area 9 as it was entirely enclosed within a single tier. During the considered sub-event it was typical for 40% of the crowd to be obviously active, or about 0.9 people per square meter over the entirety of the structure. The result forces thus compare well with those generated by models for crowd bouncing activities. Fig. 4(a) shows a comparison between the pressures obtained from utilising 0.9 people per square meter with a model proposed by Parkhouse & Ewins [6] for crowds of 50 people bouncing at 2 Hz. It can be seen that the overall magnitude of the force histories is of a similar magnitude.

Although Fig. 4 illustrates that the derived and design loads are of a similar magnitude, the actual time histories, and their frequency domain representations, are quite different. Fig. 4(c) in particular indicates that the fundamental frequency of crowd motion is around 2.1 Hz as there is a strong peak in the data. Fig. 5(a) shows the overall time histories as derived from the available crowd acceleration data, whilst Fig. 5(b) presents the 240 second period of excitation investigated in detail from area 7, after normalisation to a unit weight of active crowd members.

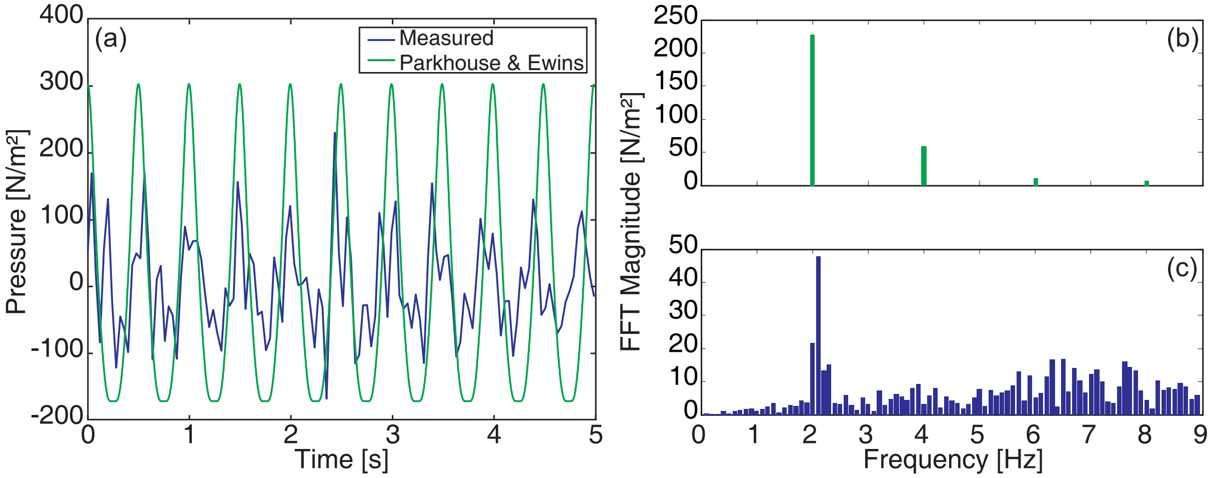

Figure 4: Comparison of measured and design load histories in (a) the time domain (b)&(c) the frequency domain

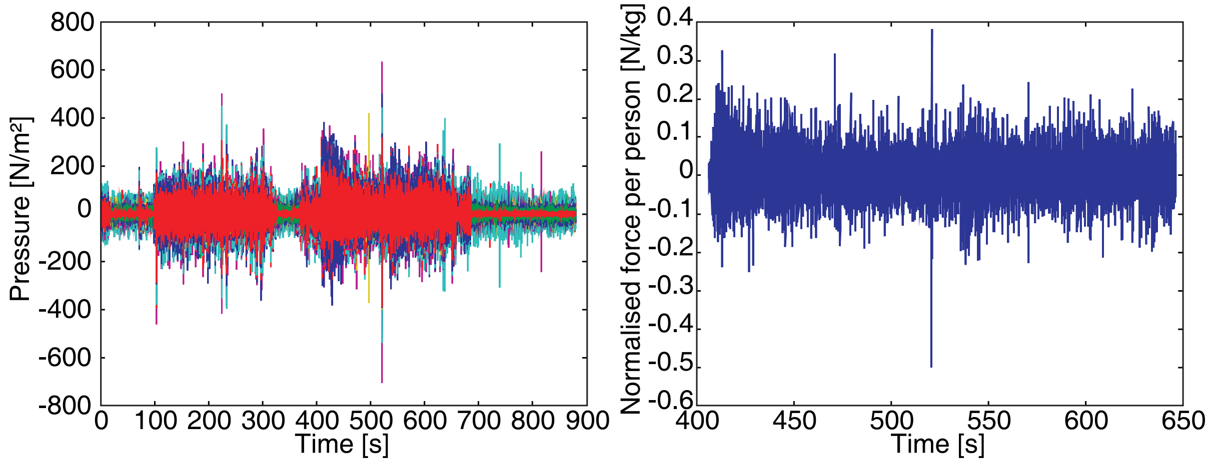

Figure 5: (a) Full excitation time histories derived from video data (b) 240 second of greatest excitation from area 7 used for further analysis, normalised to a unit weight of active crowd members

4 SYSTEM IDENTIFICATION

The dynamic properties of the empty structure were determined through a series of experimental measurements. The obtained properties were further expanded upon through the development of supplementary FE models which offered more detailed spatial information than could be obtained in the limited time available for measurements.

4.1 EXPERIMENTAL MODAL ANALYSIS

Experimental modal analysis of the structure was a two-phase process comprising of controlled excitation testing with shakers and a series of ambient vibration surveys. The shaker testing was used to identify the local cantilever modes under levels of excitation which are feasible in-service. The ambient vibration surveys acted both as a quality assurance check for the shaker testing and as a method for identifying global modes. In the case of the City of Manchester stadium, the vertical component of the global modes was small and hence can be safely ignored for vertical load analysis. On other structures, especially stadia with long cantilevers and short backspans, combined front-to-back and vertical 'nodding' modes can prove critical.

The test scheme identified the modes shapes and modal properties outlined in Fig. 6.

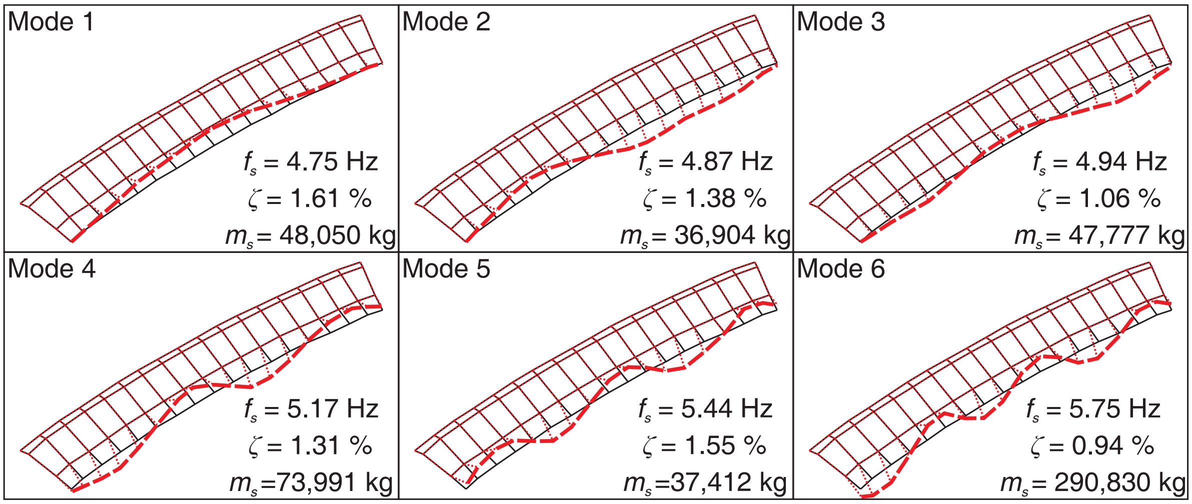

Figure 6: Middle tier modes

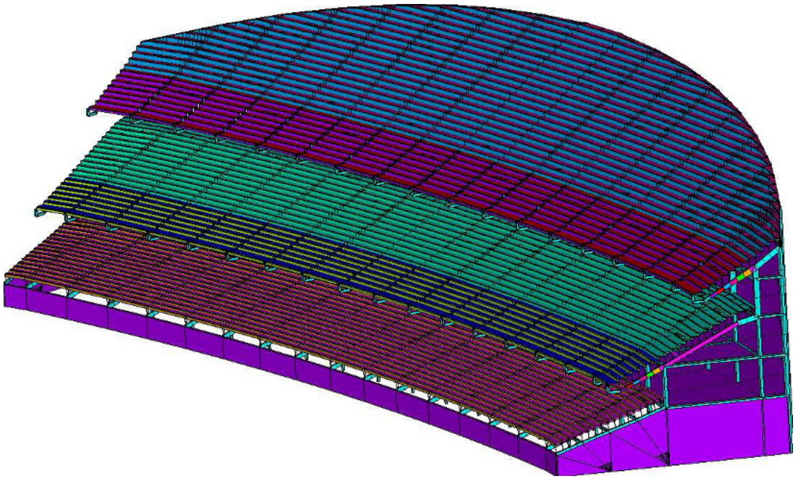

Figure 7: Final FE model

4.2 FE MODELLING

In order to supplement the experimental modal analysis a series of FE models were developed in ANSYS [7]. The final 3D model (Fig. 7) encompassed the entire west stand to a high level of detail and gave some consideration to non-structural elements. A finite element updating scheme, utilising a mixture of manual and automated processes on both the macro (geometry tweaking) and micro (property tuning) scales, helped to identify sources of error and improve the representativeness of the model.

Post-updating MAC values reached above 65% average, which for such a large and complex structure is reasonable, whilst frequency errors were smaller than 5% (Table 2). The largest single source of error was the stiffness of the concrete, especially in the rakers, which had been reduced significantly by cracking.

The final FE model served to supplement the experimental modal analyses, primarily through a greatly increased resolution of mode shapes, which would prove useful for determining responses of different locations to a dispersed crowd.

Table 2: Middle tier EMA-FE Correlation

Natural Frequencies			Mode Shapes
EMA [Hz]	FE [Hz]	Error [%]	MAC [%]
4.75	4.73	-0.43	86
4.86	4.86	-0.01	77
4.94	5.03	1.81	69
5.19	5.14	-0.97	87
5.44	5.35	-1.67	93
5.72	5.60	-2.11	86

5 CALCULATION OF RESPONSES

Simulated responses were calculated using a methodology similar to the one presented by Pavic & Reynolds [8]. That is, a modal space approximation to the problem was made whereby occupying humans are considered as additional modal-space degrees of freedom. Structural DOF properties were taken from Fig. 6, supplemented by mode shapes calculated in section 4.2. The crowd was, based on observations of the whole structure, assumed to be uniformly distributed with approximate density 2.25 people per square meter, of whom 40% were considered to be active.

The modified modal space model approach (Fig. 8) has been investigated by multiple authors and shown to capable of improving estimates of structural responses [9–11].

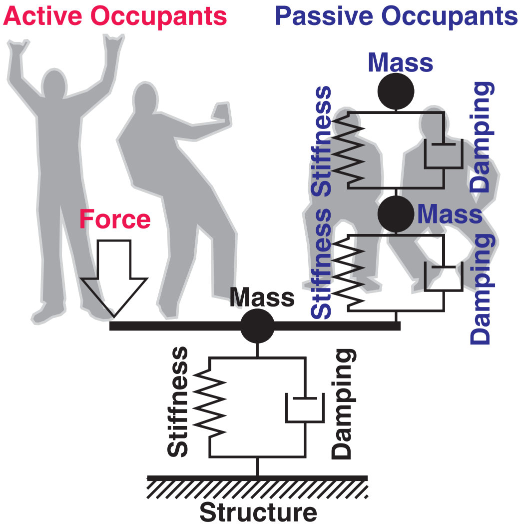

Figure 8: Example occupied modal space model utilising human body model 2a from [12]

A total of 16 different simulations were run, considering 6 different load models and 7 slightly different methods of considering the effects of human occupancy upon the final system. Table 3 summarises the maximum transient vibration values (MTVV), as obtained from the maximum of running one-second RMS average acceleration responses at mid-span on the tip of the middle tier cantilever. Table 4 describes the load and crowd models utilised in more detail.

The loads proposed by Parkhouse & Ewins [6] result in responses with magnitudes close to measurements, especially once the effects of human occupancy are considered. In comparison the loads proposed in ISO 10137:2007 [14], which are admittedly intended as extreme design limits, result in several times the measured response magnitude even when accounting for human-structure interaction. The loads estimated using the video processing techniques outline herein lie somewhere in the middle ground - prior to consideration of human-structure interaction the responses are higher than obtained utilising the design loads from Parkhouse & Ewins and hence the UK design guidelines. Inclusion of human-dofs greatly reduces the responses and brings them more into line with measure-

Table 3: Measured and Simulated responses from mid-span, middle tier

Scenario	Load Model	Energy Absorption	MTVV1 [m/s^2]	Error [%]
Measured	-	-	0.38	-
1	L1	A1	0.23	-39
2	L1	A2	0.22	-42
3	L1	A3	0.42	11
4	L1	A4	0.37	-3
5	L1	A5	0.30	-21
6	L1	A6	0.21	-45
7	L2	A7	0.53	39
8	L3	A7	0.35	-8
9	L4	A3	1.84	384
10	L5	A3	0.80	111
11	L6	A1	1.26	232
12	L6	A2	0.35	-8
13	L6	A3	0.33	-13
14	L6	A4	0.21	-45
15	L6	A5	0.18	-53
16	L6	A6	0.56	47

ments. Despite this, the variability is between each scenario is high, requiring that parametric and sensitivity studies be performed in the future.

Fig. 9 illustrates the measured responses as well as the time histories obtained when investigating scenarios 1 and 11, which do not consider the occupant dynamic properties. Fig. 10 focuses more closely on the average response levels, considering the measured responses and the values obtained from simulation scenario 12, which best matched the measured MTVV levels.

Table 4: Identifers used in Table 3

Load Model	Description
L1	Parkhouse & Ewins [6], coefficients for 50 people bouncing at 2 Hz
L2	UK Guidance [13], Scenario 4 (highly active events where stand motion expected), based on L1
L3	UK Guidance [13], Back substitution of observed events, based on L1
L4	ISO 10137 [14], Jumping actions of crowds, poor coordination.
L5	ISO 10137 [14], Vertical actions of seated crowds.
L6	As inferred from video processing
Damping/HSI Model	**Description**
A1	Measured modal damping only
A2	Additional (seated) 2dof passive crowd, properties from Wei & Griffin's [12] model 2(a)
A3	Additional (standing) 2dof passive crowd, properties from Matsumoto & Griffin's [15] model 2(a)
A4	Additional passive crowd sdof, properties from UK guidance [13], based on A2/A3
A5	A4 plus additional active crowd sdof, properties from UK guidance [13], based upon curve fitting by Dougill et al. [16]
A6	Modal damping set to 6% for all modes
A7	A5, but the active crowd DOF is actuated (equal and opposite force on active crowd DOF and structure instead of just structure)

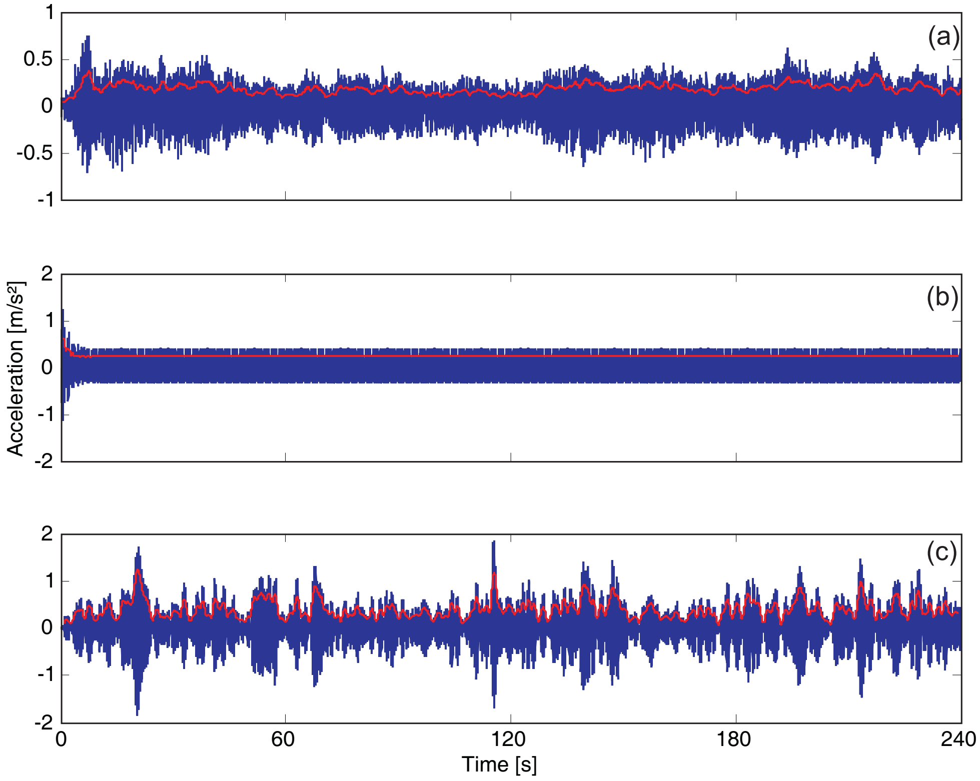

Figure 9: Mid-span, middle tier responses (a) measured and (b) simulated by scenario 1 (c) simulated by scenario 11

6 CONCLUSIONS

This paper has presented a series of forces derived from video records of crowd activities upon a major UK stadium. These forces have subsequently been used in simulations involving modal space approximations of a large scale complex FE model. The responses obtained are closer to measurements than traditionally predicted by design

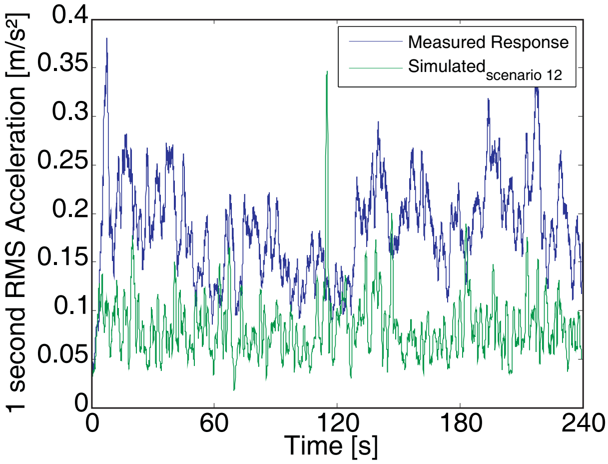

Figure 10: RMS responses at mid-span, middle tier, as measured and best simulated (scenario 12)

codes. Further tweaking of the simulation approach in line with current research into human-structure interaction yielded, although the actual time histories still differed, simulated responses which well match the measured ones.

Although there are obvious differences between data used in simulations attempting to recreate measurements and data for use in safely conservative design codes, better understanding of the overall phenomenon will eventually yield optimised design methodologies. The results obtained in this paper indicate that one potential avenue for further research is a more in-depth study of the load generated by real, large, crowds of people which otherwise remain largely unknown.

In particular, further work with the techniques described in this paper would allow for a better understanding of transient excitation and responses in the context of active crowds on stadia grandstands to be developed.

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