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REAL WORLD CONDITIONS
REAL WORLD SOLUTIONS

Title Building sub-structure: Composite structural floor system

Location Leeds, UK

Structure

The structure is on the 1st floor (one storey height above ground) of a purpose-built office building. It has steel primary beams spanning 12m at 6m centres, secondary beams at 3m centres and steel columns approximately on a 6x12m grid. Composite steel-concrete slabs span between the secondary beams. The floor is based on sets of bays totalling 72x24m with additional voids for staircases. In general the primary cellular beams are constructed from an upper Tee 457x191x89UB and a lower Tee 610x229x113UB, with voids of diameter 550mm at 750mm centres. Secondary beams are 254x146x31UB and the columns are 254x254x73UC. Photographs taken on-site have provided an estimate for the concrete slab as being 130 mm deep, with 60 mm trapezoidal decking.

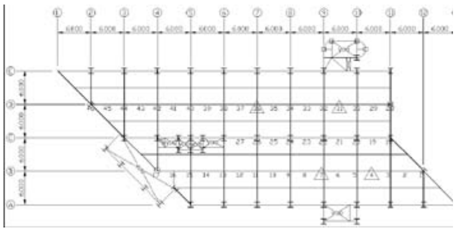

Figure 1: Floor layout (mm)

Figure 2: The office environment and the columns

Objectives of Structural Identification Application

The floor is considered by its occupants to be quite lively. The floor was chosen as the test bed for a new active vibration control system[1] requiring creation of a modal model for simulations, evaluation of structural contributions to dynamic performance through finite element modelling and correlation and measurements of vibration response to walking with and without active control in operation.

Figure 3: Primary and secondary beams supporting trapezoidal steel decking for RC slab

Model Development

ANSYS commercial FE software was used to model the floor. Composite slabs were modelled using orthotropic SHELL63 elements, where the slab thickness and density were constant throughout but the orthotropic behaviour of the slab in directions of the primary and secondary beams (due to the trapezoidal steel decking) were modelled by reduced Young's modulus (nominally 38MPa) in the secondary beam direction. The primary and secondary beams were modelled using BEAM44 elements which allow for taper and centroidal offsets (Figure 1). Composite connections between the beams and slabs were modelled using offset centroids of the beams and slab (Figures 2 & 3). Columns were modelled (without offsets) using the relatively simple BEAM4 elements. Both BEAM44 and BEAM4 elements incorporate tension, compression, bending and torsion capabilities.

The columns were assumed to be fixed one storey above and below the floor under consideration. All other internal connections were assumed to be fixed, an assumption generally taken as valid because the very small deflections resulting from walking-induced vibrations are not sufficient to cause significant rotation at joints, even if those joints are designed to be pinned with regards to ultimate limit state

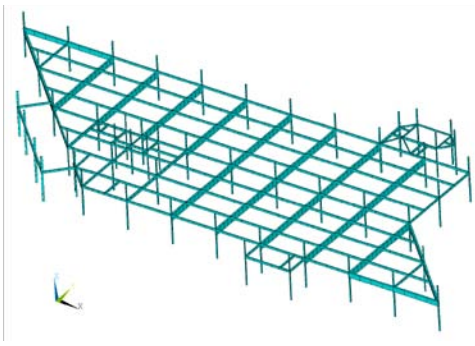

Figure 4: Beams and columns of initial FE model

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analysis. Imposed loads and non-structural dead loads were modelled as additional mass on the slab elements. Figure 4 shows the initial FE model.

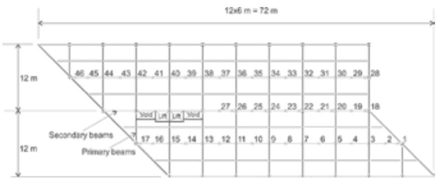

Figure 5: Test grid

Experimental Studies

Test Point (measurement) locations for the modal test are shown Figure 5, with vertical accelerometers located at column and mid-bay locations wherever possible. Attention was paid to TP04 and its surroundings because it was perceived to be a particularly lively location on the floor. Because the vibration perception was particularly acute at this point, this was a good initial candidate for the installation of the shaker for the subsequent active vibration control studies.

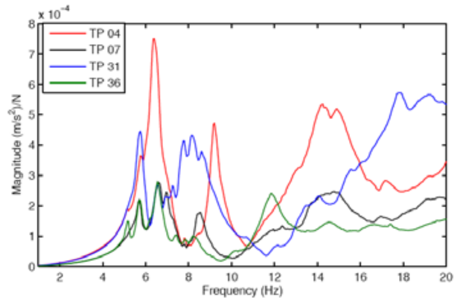

Figure 6: Driving point mobilities (accelerance or inertance values)

Modal testing was carried out using artificial excitation supplied by two APS Dynamics Model 400 electrodynamic shakers operated in inertial mode. Four excitation points were used (TPs 04, 07, 31 and 36) and responses were measured at all TPs, resulting in 4 columns of the frequency response function (FRF) matrix. The modal testing was carried out using continuous uncorrelated random excitation with two excitation points at a time (i.e. multi-input multi-output or MIMO modal testing). Time domain data blocks were of duration 20 s giving a frequency resolution of 0.05 Hz. The number of averages was 80 with 75% overlapping and a Hanning window was applied to all data blocks.

The magnitudes of the driving point mobility FRFs acquired are shown in Figure 6 where force and response are measured at the same point. From a visual inspection, there are approximately nine modes between 4 and 10 Hz. The lowest mode occurs at 4.86 Hz and the highest peak occurs at TP04 at approximately 6.4 Hz. TP04 is the point on the structure where the response was subjectively assessed to be highest.

On-site modal parameter estimation was carried out on the full set of acquired FRFs using the ME'scope suite of software. In particular, mode indicator functions were first calculated to give an indication of the locations of vibration modes and then the multiple reference orthogonal polynomial algorithm was used to estimate the modal properties, including modal mass for mode shape scaling. Between 4.86 and 9.19 Hz, 13 modes were estimated. Fig. 7 shows the estimated vibration modes which were dominant at TP04. The vibration mode at approximately 6.37 Hz is the most likely to be excited by pedestrian excitation; this mode has a damping ratio of 3% and a modal mass of approximately 20 tonnes.

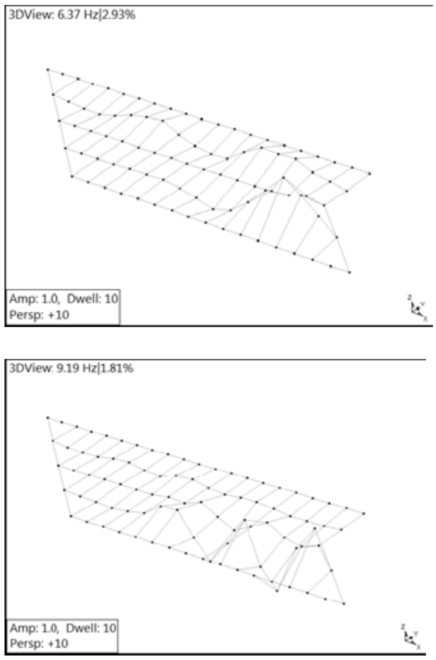

Figure 7: Dominant vibration modes at TP04 with frequency and damping estimates.

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Data Analysis, Model Calibration

The primary aim of the experimental modal analysis (EMA) was to generate an experimental modal model for designing and simulating the performance of the active vibration control system. Such a model represents reality in operational conditions and is chosen for performance simulations wherever possible and with access to the full-scale structure. For a-priori simulations only finite element analysis (FEA) is available and modelling technology for floors engages a different set of uncertainties. Both FEA and EMA can produce modal models that are suitable for performance simulations for assessment of vibration serviceability.

For this floor limited model calibration was undertaken in order to improve understanding of the performance of the structural system. Since this type of flooring system is common in the UK, such a correlation study has benefits for a-priori analysis of similar structures that may be problematic. Figure 8 shows matching of selected FEA and EMA modes, not necessarily the same as the critical modes for the AVC study, but intended for manual updating. An independent modal analysis was performed using a different mode estimation technique, explaining the slight difference in frequencies to the EMA results presented in Figure.

Figure 8 shows a reasonable correlation between the FE and EMA shapes for the first six modes, with the exception of the second FE mode which was not picked up by the EMA study. One area of uncertainty is the additional stiffness and additional mass from non-structural elements such as storage areas and office equipment. The natural frequencies from the preliminary FE study are noticeably higher than those from the EMA study, indicating a lack of mass or excessive stiffness in the model which could derive from differences in slab depth or effects of non-structural components. Other possibilities are incorrect assumption about concrete modulus and the degree of composite action.

Increasing the slab depth causes lower modes to decrease in frequency (because these modes are global with concrete behaving more as added mass) while higher modes increase in frequency (because the stiffness of the slab dominates with more local bending in higher modes). Factors such as material modulus and member geometric properties could not be in error enough to explain the differences so possible reasons for a lack of composite action were explored. Adjusting shear lag in the slab and cracking in the concrete above hogging regions resulted in insignificant changes in natural frequencies. So, some mechanism exists in the real structure through which stiffness is lost.

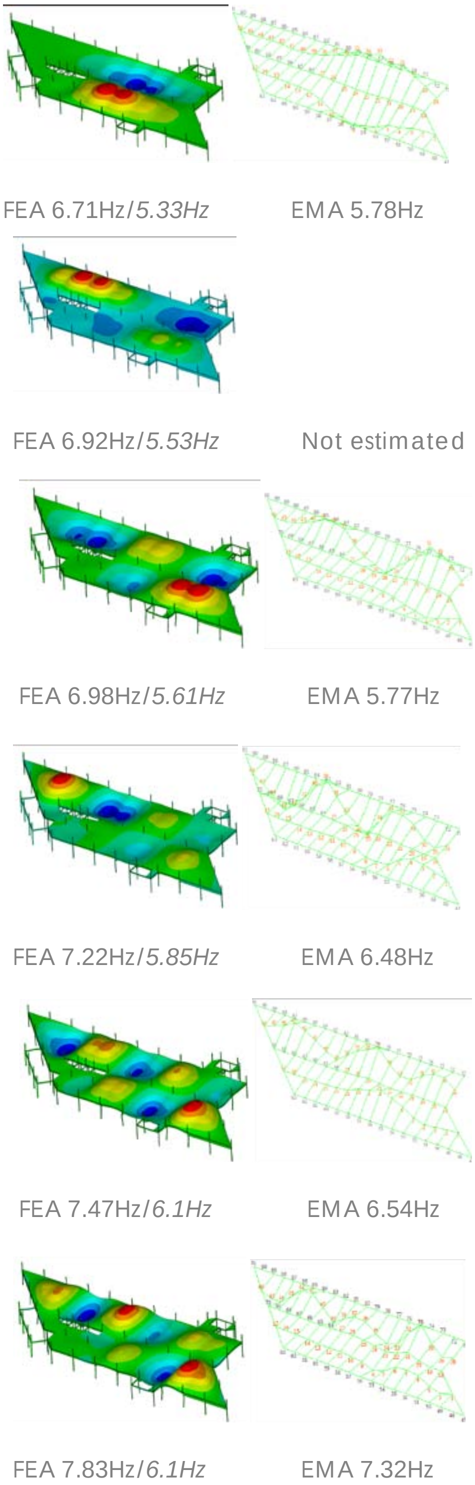

Figure 8: Matching of first six preliminary FEA modes and corresponding EMA modes, with updated FEA frequencies in italics

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The best improvement was obtained by a change in the offset for the beams and a small reduction in the Young's Modulus of the concrete. The updated FEA model frequencies are given in italics in Figure 8.

Figure 9 shows a comparison of the FRF obtained from EMA with that from updated FEA for TP04, the location of most lively response, assuming a damping value of 2.5% in the FEA in line with average of values from the modal test. The important features of the EMA in the frequency range of concern are re-created acceptably by the FEA.

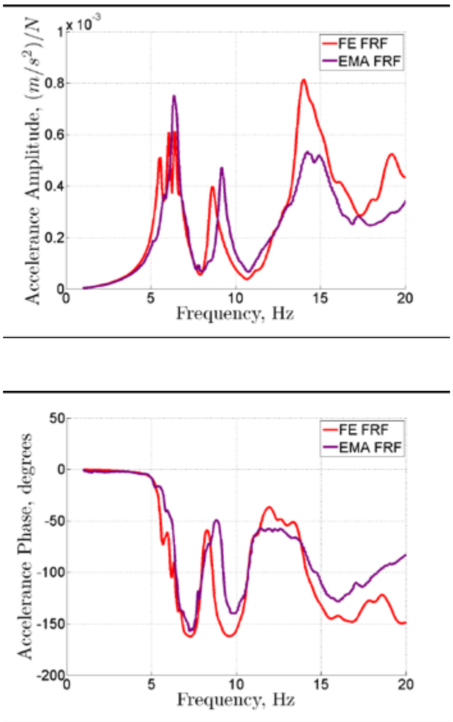

Figure 9: Matching of EMA and FEA frequency response functions for TP04, using updated FEA model.

Interpretation and Decision Making

For this type of structure the major concern is with vibration serviceability due to footfall-induced vibrations. Both FEA and EMA results can be used for performance simulations using either published design guidance[2], referred to as CSTR43, or by direct simulation using measured ground reaction force (GRF) time histories as moving dynamic loads[3].

For a prototype structure, whose design may have been adjusted on the basis of such simulations using a-priori FEA, walking response measurements can be made as the final proof test of actable performance.

Figure 10 shows simulations using the updated FE model showing the response hotspot around TP04 for walking at 1.6Hz, exciting response in modes around 6.5Hz by the fourth harmonic of the walking force fundamental frequency component. The simulations use first principles approaches of CSTR43 implemented using bespoke MATLAB software VSATs[4]. The numerical values are 'R factors' referenced to a RMS acceleration value of $0.005 m/sec^2$ calculated with a 1 second averaging time and with ISO-standard frequency weighting.

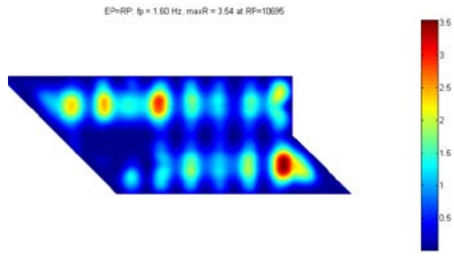

Figure 10: Vibration response simulations using first-principles approaches and published design guidance on footfall forces. R=1 denotes frequency weighted RMS response of $0.005/sec^2$.

The structure is classed as a 'low frequency floor' because its performance with respect to footfall forces generated is dominated by modes in which resonance can be generated by strong components of the walking force occurring at lower multiples of the pacing rate. High-performance (i.e. low response) floors typically found in hospitals and micro-chip plants are classed as 'high frequency floors' since their response is dominated by rapid transient decay of modes with frequencies above 10Hz due to the impulse-like force characteristic of individual footfalls.

Vibration tests as described in this study are often required to demonstrate compliance of an as-built structure with design specifications (i.e. a maximum R-factor, according to usage), while a-priori modelling, influenced by experience of model/test correlations of similar structures seeks to use best

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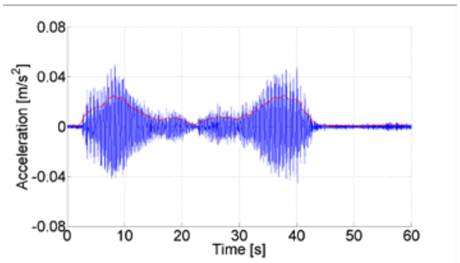
practice to predict performance capability before construction, giving an opportunity to adjust a poor design.

The maximum R-value for the floor (over all pacing rates and response points) is 7.3. This is just within acceptance limits for an office floor.

With the main objective for this particular study being the development of an active vibration control, the outcome of the experimental study has been generation of an appropriate modal model for design of the AVC. Figure 11 shows on-site evaluation of the AVC designed using the EMA results. AVC performance was assessed for controlled excitation, driving with one shaker and controlling with another, and for more usual (design) scenario of footfall loads due to a single pedestrian.

Figure 11 Active vibration control system in operation: (left) simulating excitation with one shaker while controlling with another.

Figure 12 shows the success of the AVC in controlling response at the most lively point, TP04. The figure also shows the in-situ measured response to walking. The red lines are the RMS envelope, and for the uncontrolled floor, the values are a good match the predictions of Figure 10. The exercise demonstrates the capability of AVC system for significant improvement in floor vibration performance.



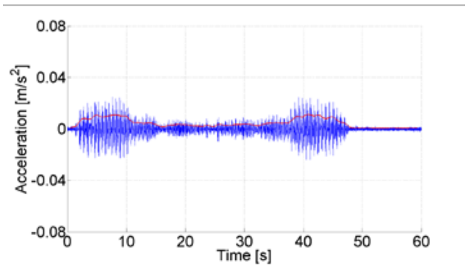


Figure 12: Floor response for walking at 1.58Hz (top) without AVC and (below) with AVC engaged.

Acknowledgements

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References

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4. Pavic, A., Brownjohn, J.M.W. and Zivanovic S. (2010). VSATs software for assessing and visualizing vibration serviceability based on first principles. ASCE Congress 2010, Orlando, Florida, USA, 12-15 May.