# STRUCTURAL DYNAMIC PARAMETER IDENTIFICATION AND THE EFFECT OF TEST TECHNIQUES

Devin, A.[1], Fanning, P.J.[1], Middleton, C.J.[2] and Pavic, A.[2]

[1]University College Dublin,School of Civil, Structural and Environmental Engineering,Dublin 4, Ireland.

[2]University of Sheffield, Department of Civil & Structural Engineering, Sheffield S3 7QB.

**ABSTRACT**

Ambient and forced excitation test techniques are both widely used to dynamically identify civil engineering structures. Two floor levels of a newly constructed building, the Charles Institute at University College Dublin, were tested using both techniques. Both floor designs were identical although the layout of partitions above and below each were different. The objective of the tests was to determine the most appropriate test procedure and also to identify whether the layout of partitions contributes in a significant manner to dynamic response. It was found that at low levels of excitation, ambient test levels, the dynamic response of both floors was identical. In contrast, at higher vibration excitation levels, during forced vibration testing, the floor responses were substantially different. The differing modal parameters identified are attributed to an amplitude dependent response resulting from engagement, or not, of the partitions in the dynamic response of the system. The practical significance of this finding is that it is imperative to consider, and test at, the in-service vibration amplitude expected for a floor system.

**Keywords:** Amplitude dependency, Forced Vibration Analysis, Frequency Domain Decomposition, Covariance-based Stochastic System Realization.

## 1. INTRODUCTION

Dynamic testing is increasingly used for the identification of a structure's modal characteristics. Traditional experimental modal analysis and output-only methods are the most popular methods for determining these dynamic parameters from in-situ tests on real in-service civil engineering structures. The advantages and limitations of these methods have been widely documented [1] and research has also been conducted comparing the modal parameters resulting from forced vibration and output-only methods. Lamarche et al. [2] concluded that forced and output-only methods return similar frequencies and mode shapes with high MAC correlation between modes but that output-only analyses, which generally have low levels of vibration amplitudes, are more prone to contamination by noise. On the other hand Beyen and Kutanis [3] found that there could be variations in peak values between forced and ambient vibration responses which may indicate an amplitude dependency of modal parameters depending on test method used. Amplitude dependency was also observed by Ulusoy et al. [4] when examining the behaviour of a multi-storey building during earthquakes of different magnitudes. The reported amplitude dependency was attributed to joint and structural interfaces being more significantly mobilised as earthquake magnitude increased. Reynolds and Pavic [5] also investigated the differences between model parameters extracted from forced and ambient vibration measurements on a road bridge and concluded that longer sampling periods and a higher sampling rate is needed for similar reliability of output-only analysis compared to forced vibration analysis. Schwarz and Richardson [6], using the same data sets as [5], highlight that data extracted using two shakers and post-processed into Frequency Response Functions (FRFs) under controlled and measured excitation will usually result in the most accurate results, while impulse and ambient response data could still be utilised to derive meaningful modal parameters.

In this paper the modal parameters of two floors of a four story building, identified using both Operational Modal Analysis and Forced Vibration Analysis techniques, are discussed. The purpose of the tests was to examine the effect, if any, of different non-structural partition layouts on the response of otherwise identical floors slabs. Modal characteristics are determined for both floors using both test procedures. The modal characteristics extracted from ambient response data identified both floors as being identical. However modal characteristics identified from force vibration testing showed that this was not the case. The different findings are attributed to an amplitude dependent response and more active engagement of non-structural partitions at higher vibration amplitudes.

## 2. TEST STRUCTURE - CHARLES INSTITUTE

The Charles Institute on the University College Dublin (UCD) campus in Ireland is a four storey reinforced concrete frame office building (Fig. 1). Structurally it consists of two-way spanning flat slabs, 0.3m thick, supported on 0.4m square columns with a maximum bay size of 7.5m × 6.6m. The lateral load resisting system is made up of a number of reinforced concrete stairwells, lift cores and service ducts with wall thicknesses of 0.2m.

**Fig. 1** Completed Charles Institute Building

Each floor level is divided into state-of-the-art laboratories and office accommodation using light-weight non-structural partitions consisting of plasterboard with a thickness of 12.5mm and an approximate mass of 47kg/m, supported on lightweight metal studs.

Exterior wall cladding consists of large polished Chinese black basalt panels 40mm thick supported on galvanised steel rectangular sections fixed to the concrete slab above and below at 400mm centres. The polished Basalt has an estimated mass of 430kg/m. The structure of each floor is identical with only the layout of internal partitions varying from floor to floor. The layout of partitions for the two floors tests is shown in Fig. 2a and 2b. In both cases the solid black lines indicate the partition layout on the floors below.

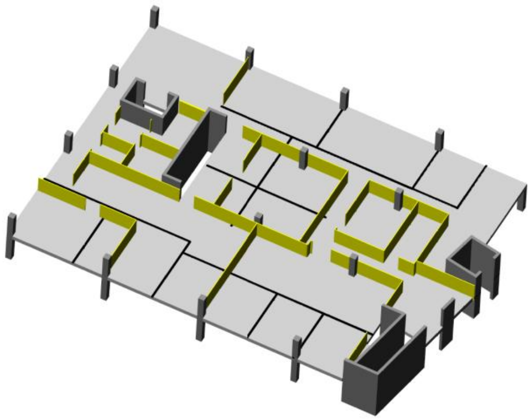

**Fig. 2a** First floor internal partition layout.

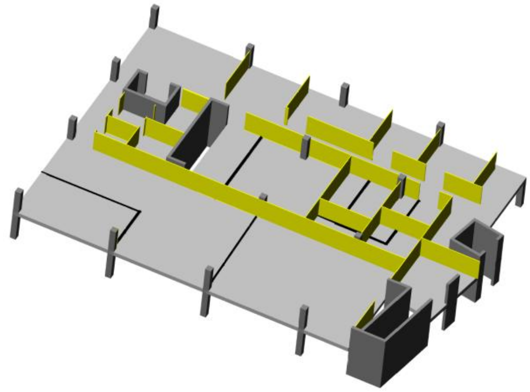

**Fig. 2b** Second floor internal partition layout

## 3. EXPERIMENTAL PROCEDURES

The objectives of the experimental tests were i) to compare the modal characteristics identified by forced and ambient vibration analysis, and ii) to investigate the effects of differing non-structural partition layouts on identical floors. For both test types accelerometers, located at the intersection of grid lines shown in Fig. 3, were used to measure the vertical acceleration on a grid of 195 measurement points.

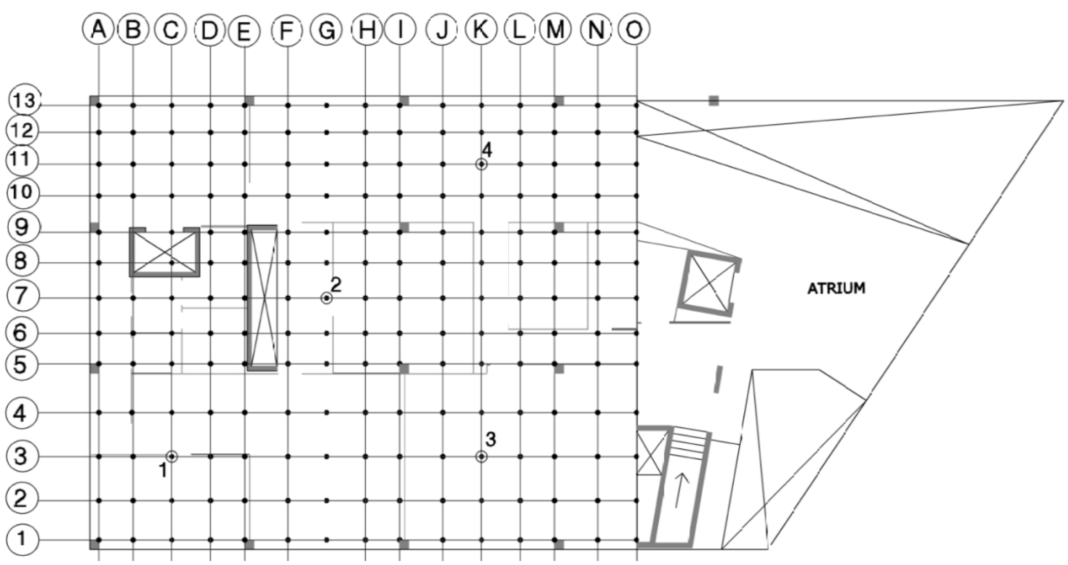


**Fig. 3** Detailed test grid for forced and ambient vibration analysis

### 3.1 Operational Modal Analysis (OMA)

The ambient acceleration response, due to prevailing environmental conditions, was measured on the first and second floors on two consecutive days. The peak acceleration recorded was approximately 0.0004g. Given that the expected frequency range was 5 - 30 Hz the record length used was 10 minutes with a sampling rate of 12 kHz; these datasets are considered more than adequate for structures with natural frequencies in the range of 5 to 30 Hz [8].

The measured datasets were post-processed using the Frequency Domain Decomposition (FDD) method. The resulting singular value plots were then used to identify modal parameters associated with the ambient response datasets [7]. To aid accurate extraction of modal parameters, Covariance-based Stochastic System Realization (SSI), a combination of ERA and OKID was combined with FDD [8]. This method determines the 'real' physical modes of a system in the presence of measurement and computational noise using a combination of Stabilisation Diagrams and Modal Phase Co-linearity (MPCw). In a lightly damped system, physical modes behave as 'real' modes as MPCw approaches 100%, whilst a low percentage of MPCw indicates a complex mode shape indicating a computational or noisy mode [9].

### 3.2 Forced Vibration Analysis

Multi-shaker modal testing of both floors was also carried out separately over two consecutive days while the building was unoccupied. Endevco 7754-1000 piezoelectric accelerometers were used for vibration response measurements. The excitation of the floor structures was provided by four APS Dynamics electrodynamic shakers, with a capacity of 500 N each, located on the concrete slab at test points marked 1 to 4 in Fig. 3. These excitation points were distributed over the floor to ensure an even distribution of excitation energy to all parts of the floor. During testing the peak excitation was of the order of 0.008g (i.e. approximately 20 times higher than levels recorded during ambient testing).

A Data Physics DP730 24-channel 24-bit digital spectrum analyser was used to drive the four shakers simultaneously using uncorrelated random signals and to digitally acquire force and response data. Frequency response Functions (FRFs) were determined for all measurement points and curve-fitted using a multiple reference orthogonal polynomial algorithm to determine modal properties as implemented in the ME'scopeVES software [10].

## 4. EXPERIMENTAL RESULTS

### 4.1 Operational Modal Analysis

Singular value plots and a Stabilization Diagram for the first and second floors are shown in Fig. 4. Table 1 compares the first four natural frequencies and damping ratios of the 'real' physical modes extracted from the system. The natural frequencies for both floors range from 11 Hz to 25Hz and are consistent with each other. The shape and form of the singular value plots are also consistent although the vibration amplitudes in floor 2 are higher.

The first four clearly distinguishable modes extracted by Operational Modal Analysis results for Floor 1 occur at 12.02 Hz, 13.80 Hz, 14.22 Hz and 17.54 Hz. The maximum percentage difference between the FDD and SSI identified frequencies methods, for each mode, is 0.5 %. Each of these natural frequencies had an MPCw value greater than 85 % with the majority having values larger than 99.1 % and had numerous stable poles in the Stabilization diagram, indicating that they are all physical modes of the structure.

**Table 1** Identified modal frequencies f and damping ratios ζ extracted using FDD and SSI

| | Floor 1 | | | | Floor 2 | | | |
|---|---|---|---|---|---|---|---|---|
| | FDD | SSI | | | FDD | SSI | | |
| | f (Hz) | f (Hz) | ζ(%) | MPCw (%) | f (Hz) | f (Hz) | ζ (%) | MPCw (%) |
| **1** | 11.97 | 12.02 | 2.40% | 99.49% | 12.03 | 12.04 | 3.83% | 94.76% |
| **2** | 13.73 | 13.80 | 0.77% | 85.25% | 13.77 | 13.67 | 2.91% | 99.36% |
| **3** | 14.17 | 14.22 | 4.34% | 99.19% | 14.53 | 14.81 | 1.79% | 96.41% |
| **4** | 17.53 | 17.54 | 1.67% | 99.96% | 17.53 | 17.57 | 1.67% | 99.83% |

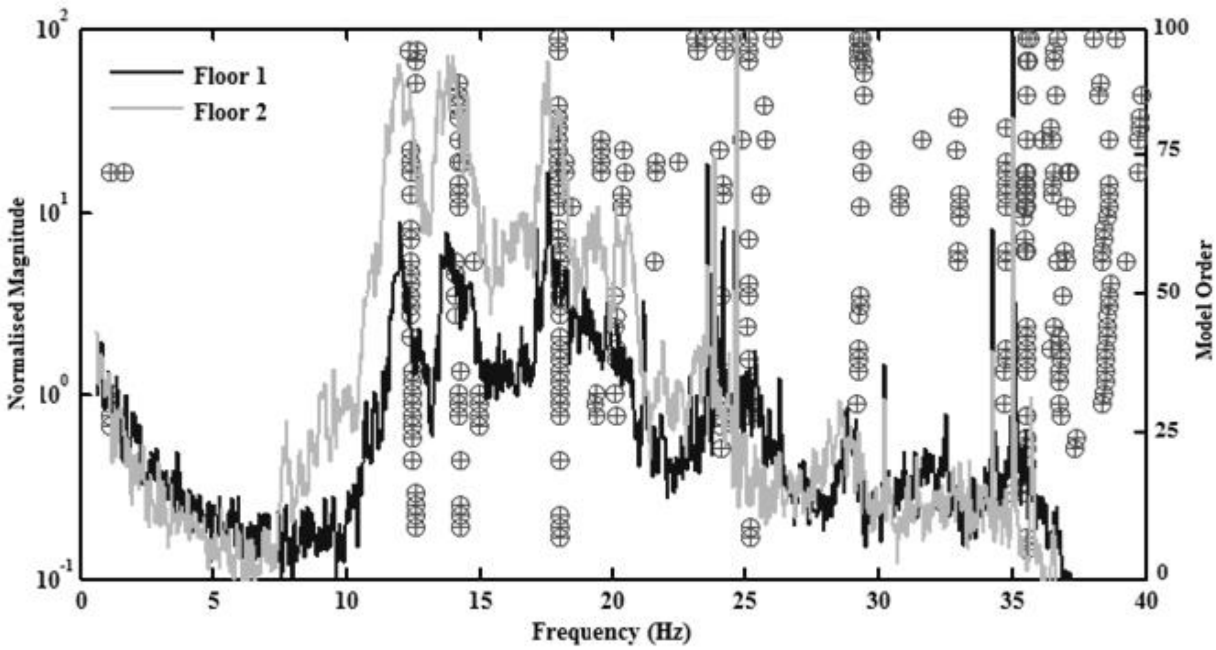


**Fig. 4** Singular value plots and Stabilization Diagram of floors 1 and 2;the symbol '⊕' indicates the location of a stable pole

The frequencies of the first four clearly distinguishable modes for Floor 2 are within 4% of those identified for Floor 1. The first mode shapes, for Floors 1 and 2, are shown in Fig. 5. Visually these modes are similar and comparing them using the Modal Assurance Criteria (MAC) yields a MAC value of 0.983. This indicates a very high correlation between the floors' modal shapes. Given the (essentially) identical frequencies and highly correlated mode shapes it is concluded that both floors are nominally identical. The only substantial difference between the floors is that the amplitude of the singular value plot for floor 2 is larger for the first three peaks compared to floor 1. This would indicate that these modes were preferentially excited during the tests; this is attributed to differing prevailing ambient conditions in the building on consecutive days.

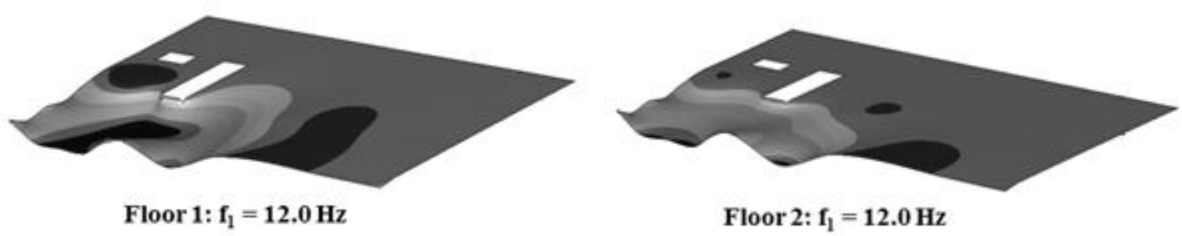


**Fig. 5** Comparison of mode shape at 12.0 Hz extracted using FDD for first and second floor, MAC = 0.983

### 4.2 Forced Vibration Analysis

The frequency response functions derived from the excitation point datasets are plotted in Fig. 6 for both floors. The natural frequencies ranged from 15.7 to 27.0 Hz and 15.0 to 23.7 Hz for floors 1 and 2 respectively. While the frequency ranges were similar the floor point mobility responses are noticeably different. The lowest frequency identified, at approximately 15.0Hz was also higher than that (12.0 Hz) determined from ambient testing. The mode shapes extracted from forced vibration analysis are plotted in Fig.7. There are a larger number of Floor 1 modes in the 15 - 30 Hz range and the modes shapes, at similar frequencies, are visually different from those associated with Floor 2. Where there is a degree of similarity between Floor 1 and Floor 2 modes the associated frequency is higher for the Floor 1 mode (for example mode 5 from floor 1 and mode 2 from floor 2 in Fig.7); this would suggest that Floor 1 is stiffer than Floor 2.

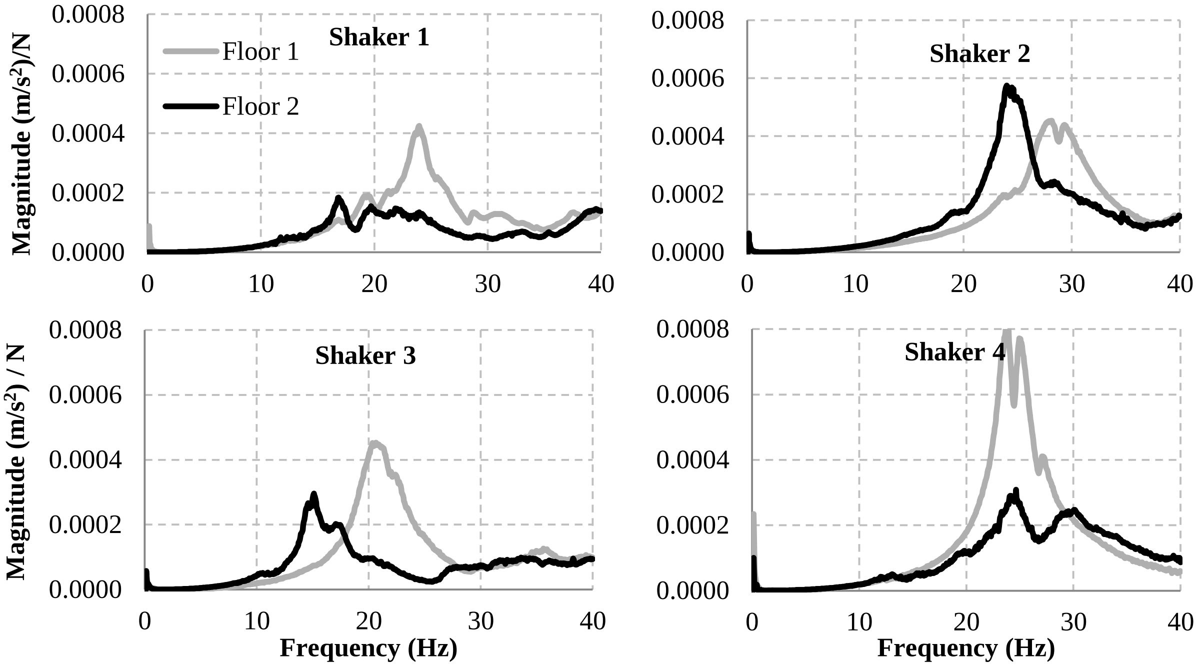


**Fig. 6** Comparison of forced vibration FRFs at shaker locations for floors 1 & 2

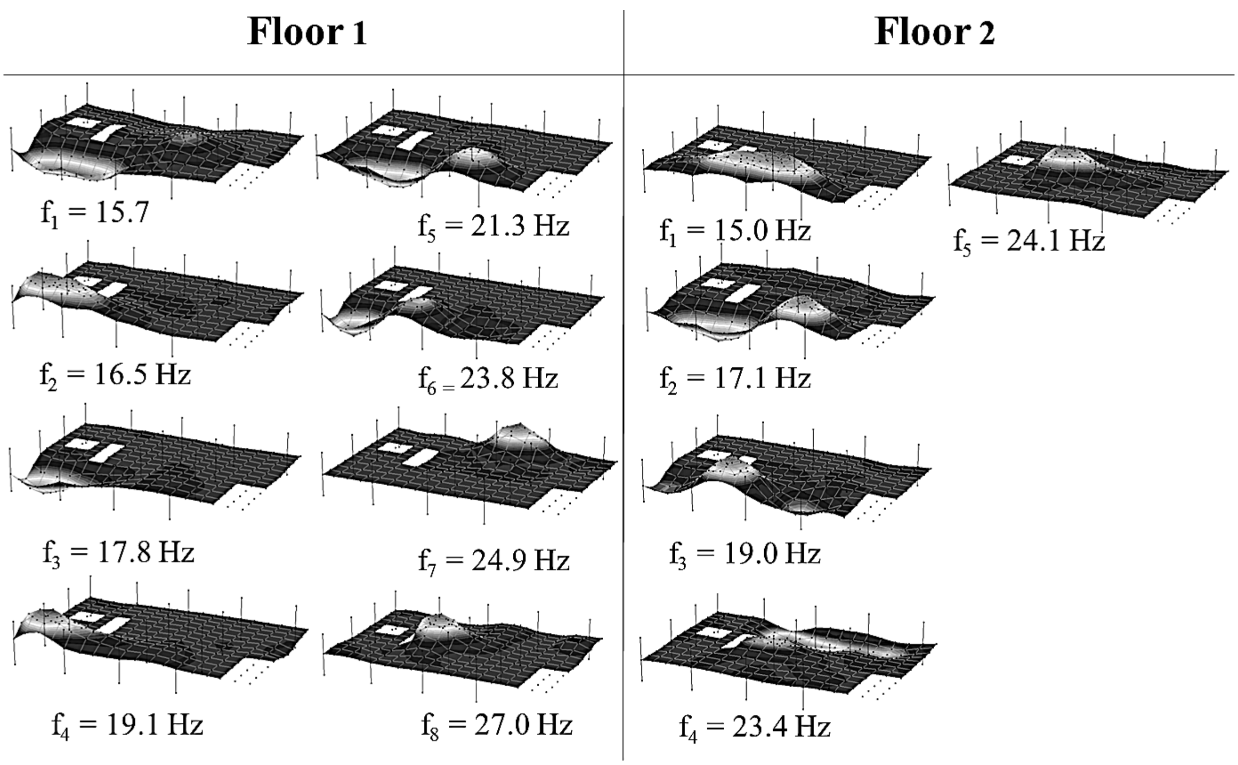


**Fig. 7** Mode shapes extracted from Forced Vibration Analysis for floors 1 and 2

## 5. DISCUSSION OF RESULTS

The two different test techniques are found to yield different and contrasting findings. Modal parameters extracted for both floors, from ambient response data, are essentially the same thereby characterising the dynamic response of both floors as being identical. However, in contrast, there are significant differences between the modal parameters for both floors using forced vibration analysis; the frequencies identified vary and the modes shapes are different. Furthermore the frequencies of response determined using forced excitation were higher than those determined from ambient responses.

To explain this apparent anomaly two explanations are considered. It is possible that the shaker layout chosen could have preferentially excited higher modes of the structure leaving those lower modes (identified by ambient response analysis) not easily discernible. However this can be discounted as in such a case it would still be expected that the responses of both floors would be identical as the same test set-up, including shaker locations and forced excitation level, was used for both floors, and the design of both floors (thickness and reinforcement details), as well as their restraints at columns and internal shear walls, are the same.

The second and more probable reason for the differing findings is that the response of both floors are amplitude dependent due to the presence of differing partition layouts on, and below, each floor level (see Fig. 2). The maximum acceleration level recorded under ambient conditions was 0.0004 g compared to 0.008 g during forced excitation testing. It is believed that during low level excitation there is little or no engagement of the partitions in the dynamic response of the system. As the excitation level is increased any small clearances between the partitions and the floors above them are closed and the partitions engage in the dynamic response. This has the effect of producing stiffer behaviour at increased vibration amplitude levels and hence explains the higher frequencies identified from forced vibration testing. The greater density of partitions beneath Floor 1 compared to Floor 2 would also explain why the frequencies for similar modes, on these floors, are higher for Floor 1.The floors thus behaviour similarly at low levels of excitation (ambient conditions) but are different due to differing partitions layouts at higher levels of excitation (forced excitation conditions).

The concept of amplitude dependent response is not novel; Ulusoy et al. [4] found that the modal parameters identified for a multi-storey building varied depending on earthquake amplitude. It's interesting to note though that in their case the effect of increased vibration level was an apparent reduction in stiffness due to greater joint mobilisation. In this study mobilisation of the partitions in the dynamic response resulted in a stiffer response.

The floor slabs in this building are supported on a column grid that results in nominal bay widths of up to 7.5 m. Given a slab thickness of 0.3 m this does not constitute what would be considered a slender floor system. Notwithstanding this the effect of partitions was found to be important depending on vibration level; their effect on slender floor systems is likely to be more pronounced. It is thus important when testing for vibration serviceability assessment to ensure that test vibration levels are consistent with those expected during operational use of the structure so as to cause the partitions to engage, or not, as appropriate in the response of the system.

## 6. CONCLUSIONS

Ambient and forced vibrations were recorded at the Charles Institute on the University College Dublin campus to investigate the effect of experimental techniques and partition layouts on the dynamic response of two otherwise identical floors. The following conclusions are drawn:

- The floor responses were found to be amplitude dependent. At low vibration levels, with peak accelerations of 0.0004 g, the response of two identically designed floors were found to be the same. At higher vibration levels, peak accelerations of 0.008 g, the same two floors were found to behave differently.

- The amplitude dependent response is attributed to the different partition layout above and below each floor level, the rational being that these non-structural elements were not mobilised during ambient vibration analysis whilst they were during forced vibration tests.
- When testing for vibration serviceability, particularly in the case of slender floor systems, it is recommended that the test excitation amplitude is comparable to the expected in-service structure vibration levels so as to ensure that any amplitude dependent effects are represented in the test data. This is likely to result in forced vibration testing being more appropriate for vibration serviceability assessment of slender floor systems.

**ACKNOWLEDGEMENTS**

The authors wish to express their gratitude to i) the Irish Research Council for Science, Engineering & Technology for their financial support, ii) the Vibration Engineering Research Section of Sheffield University for use of their equipment, and iii) UCD for access to the Charles Institute at UCD.

**REFERENCES**

[1] Zhang, L., Brincker, R., Andersen, P. "An Overview of Operational Modal Analysis: Major Development and Issues", SVIBS, October 2005.

[2] Lamarche, C., Paultre, P., Proulx, J., Mousseau, S., "Assessment of the frequency domain decomposition technique by forced-vibration tests of a full-scale structure", Earthquake engineering and structural dynamics, 2008, **37**:487-494.

[3] Beyen, K., Kutanis, M., "Comparison of the Results Inferred from OMA and IEMA", 4th International Operational Modal Analysis Conference, 9-11 May 2011, Istanbul, Turkey.

[4] Ulusoy, H., Feng, M., Fanning, P.J., "System Identification of a building from multiple seismic records" Earthquake Engineering and Structural Dynamics **40**:661-674. 2011.

[5] Reynolds, P., Pavic, A., "Comparison of forced and ambient vibration measurements on a bridge", IMAC-XIX, Kissimmee, Florida, February 5-8 2001.

[6] Schwarz, B., Richardson, M., "Post-processing ambient and forced response bridge data to obtain modal parameters", IMAC-XIX, Kissimmee, Florida, February 5-8 2001.

[7] Brincker, R. Zhang, L. And Andersen, P. "Modal Identification of Output-Only Systems using Frequency Domain Decomposition". Smart Materials and Structures, 10.Pp 441-445. 2001.

[8] Peeters, B., De Roeck, G., "Stochastic System Identification for Operational Modal Analysis: A Review", Journal of Dynamic Systems, Measurement and Control, Vol. 123 pp. 659-667. December 2001.

[9] Verboven, P., "Frequency-domain system identification for modal analysis", PhD Thesis, May 2002, Vrije Universiteit brussel. Belgium.

[10] Vibrant Technology. "ME'scopeVES 5.0 – Reference Manual - Volume IIA – Basic Operations". August 2008.