

Living Laboratory Project at Curtin University for Building Structural Condition Monitoring

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Abstract

This paper introduces a living laboratory project at Curtin University for building structural condition monitoring and benchmark studies. An iconic building in Curtin University Bentley Campus has been installed with a long term structural health monitoring system in 2017 to continuously monitor the structural vibrations and environmental conditions. The sensory system includes more than 50 sensors, i.e. tri-axial and single-axis accelerometers, strain gauges and a tri-axial high sensitivity accelerometers for measuring ground motions. The initial finite element model of the building is built according to the design drawings, and the vibration characteristics are calculated. The monitoring data of the building measured under ambient vibrations are analysed to obtain its vibration characteristics, i.e. natural frequencies and mode shapes, which are used for model updating analysis. Dynamic responses of the building under simulated earthquake ground motions based on the design response spectra specified in the Australian Seismic Design Code are calculated with the finite element model before and after model updating. This instrumented building structure is an exclusive benchmark platform in Western Australia to conduct the continuous structural vibration measurements and condition monitoring, and is also ready for monitoring the structural performance under dynamic events including earthquakes should they occur.

Keywords: living laboratory; structural health monitoring; building structure; benchmark; earthquake response

1. INTRODUCTION

Structural Health Monitoring (SHM) provides practical approaches to assess and predict the structural performance under operational conditions. SHM is usually referred to measuring the operating and loading environment and the critical responses of structures to track structural performance and identify the anomalies, damage in structures that may affect the safe operation and serviceability (Aktan *et al.* 2000). The main objectives of SHM are, but not limited to: (1) Validate design assumptions and identify the true vibration characteristics of structure for performance assessment; (2) Identify the possible damages at an early stage to ensure structural safety under operational conditions; (3) Evaluate the current structural condition, load-carrying capacity and predict the remaining service life of structures; (4) Provide real-time information for safety assessment immediately after disasters and extreme events; (5) Support the decision making for optimum inspection, rehabilitation and maintenance planning; and (6) Obtain massive amounts of in situ data for leading-edge research with the benefit of improving design specifications and guidelines (Ko and Ni 2005, Frangopol *et al.* 2008, Li and Hao 2016).

Many benchmark structures have been developed for SHM studies in the last two decades, with the developments of sensing technologies and efficient sensor network communication techniques. Ventura *et al.* (1997) proposed a three-dimensional steel frame structure in the Earthquake Engineering Research Laboratory at the University of British Columbia, which has been selected as the IASC-ASCE SHM benchmark structure. Catbas *et al.* (2006) proposed a steel grid bridge model in the laboratory as a SHM benchmark. The above-mentioned benchmark studies are based on structures in the laboratory. The real civil engineering structures can also be installed with sensory systems and served as benchmarks. Zhou *et al.* (2005) proposed a benchmark problem for SHM based on a real highway bridge. Xia *et al.* (2009) established a benchmark study on SHM of high-rise slender structures by using the Guangzhou New TV tower and its comprehensive SHM system. In Australia, Nguyen *et al.* (2015) presented a long term continuous SHM system for the condition monitoring of a building structure in Queensland University of Technology, which can be used as a benchmark structure.

The Living Laboratory Project provides an exclusive benchmark platform on a building structure in Curtin University, Western Australia, to perform, but not limited to, the following research tasks:

- 1) Conduct the operational modal identification based on the vibration monitoring data to obtain the natural frequencies, mode shapes and damping ratios of the building, and analyse the effect of environmental and loading conditions on the vibration characteristics of the building;
- 2) Develop the initial finite element model of this building according to the design drawings, and obtain the analytical vibration characteristics, i.e. natural frequencies and mode shapes;
- 3) Perform the model updating to fine-tune the initial finite element model to represent the real structure, and investigate the uncertainty effect on the model updating process;
- 4) Validate the effectiveness and accuracy of developed approaches on modal identification, model updating, condition monitoring and long term progressive deterioration detection. One example could be by using the artificial intelligence and machine learning techniques, i.e. deep learning based neural networks and the big data analytics to perform the structural condition monitoring and damage identification.

Besides vibration monitoring sensors, i.e., accelerometers and strain gauges, the SHM system in Curtin also includes pressure sensors to monitor wind pressure, temperature and humidity sensors to monitor environmental conditions. Compared to the other SHM systems, the system in Curtin also consists of a sensor to monitor ground vibrations, which enables recordings of ground motions and building structural responses should an earthquake occur in the region.

2. INITIAL FINITE ELEMENT MODEL

Designed and built in 2012, Building 215 in Curtin Bentley Campus, is developed as a 'Living Laboratory' for Curtin engineering students and researchers with an engaging and innovative platform. Building 215 is a three-storey steel-concrete composite building structure. This building consists of two parts. One part of the building is a three storey reinforced concrete structure with several shear walls, and the other part of the building is a steel structure with a large open space and two footbridges in levels 2 and 3. Fig. 1 shows the elevation view of this building and the footbridges inside the building. An initial finite element model has been developed in SAP2000 according to the design drawings. Figure 2 shows the model. The finite element model consists of 1186 nodes, 1321 frame and truss elements, and 50 shell elements. The material properties of the steel frame is defined according to AS 3679 Grade 300, with an elastic modulus of 200GPa and a mass density of 7849kg/m³. For the reinforced concrete structure, the elastic modulus and mass density of the concrete are defined as 30GPa and 2403 kg/m³, respectively. The concrete slabs of the reinforced concrete structure are modelled by using shell elements with a thickness of 25cm. The footbridge on the second floor is a double-girder concrete bridge, and the thickness of the slab is 25cm. In addition, two steel footbridges used to connect two structural parts are simulated by using I-type beams with concrete slabs. The vibration characteristics, i.e. natural frequencies and mode shapes, can be obtained from the initial model and are shown in Fig. 3.

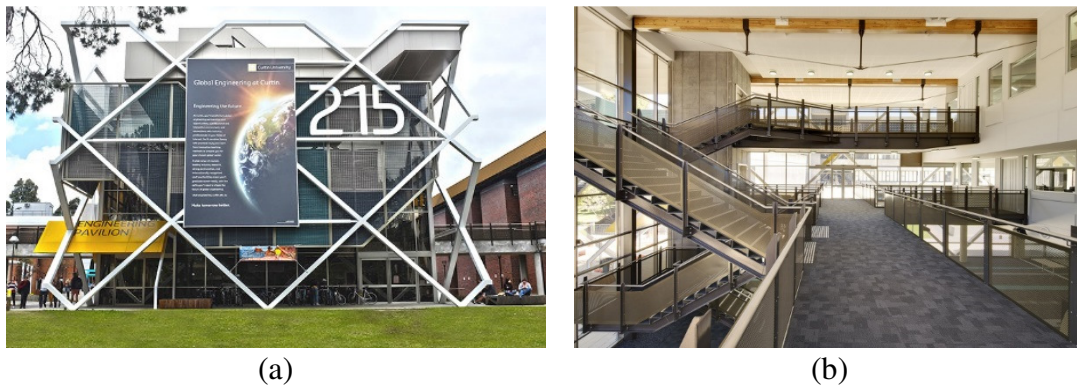


Fig. 1. (a) Elevation view of Building 215; (b) Footbridges in Building 215

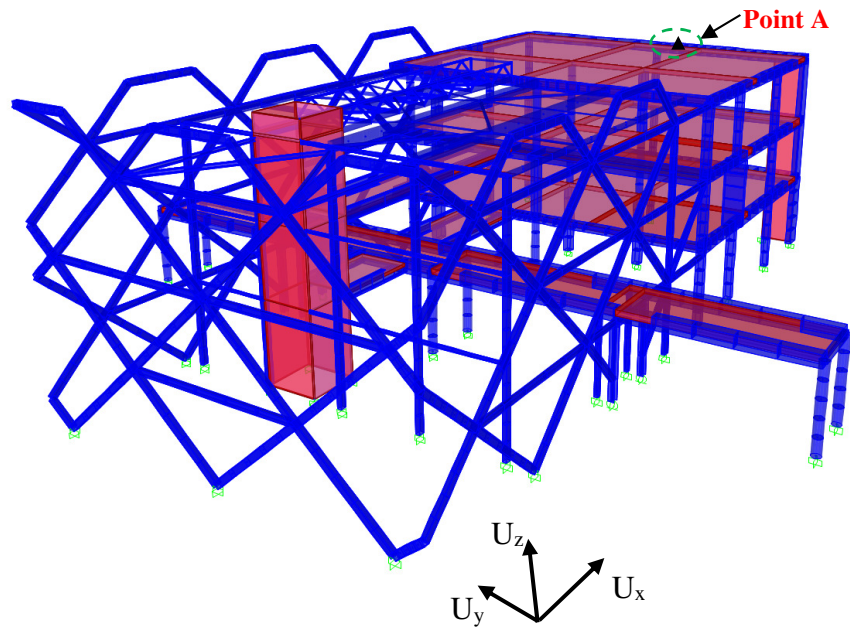


Fig. 2. The initial finite element model of Building 215

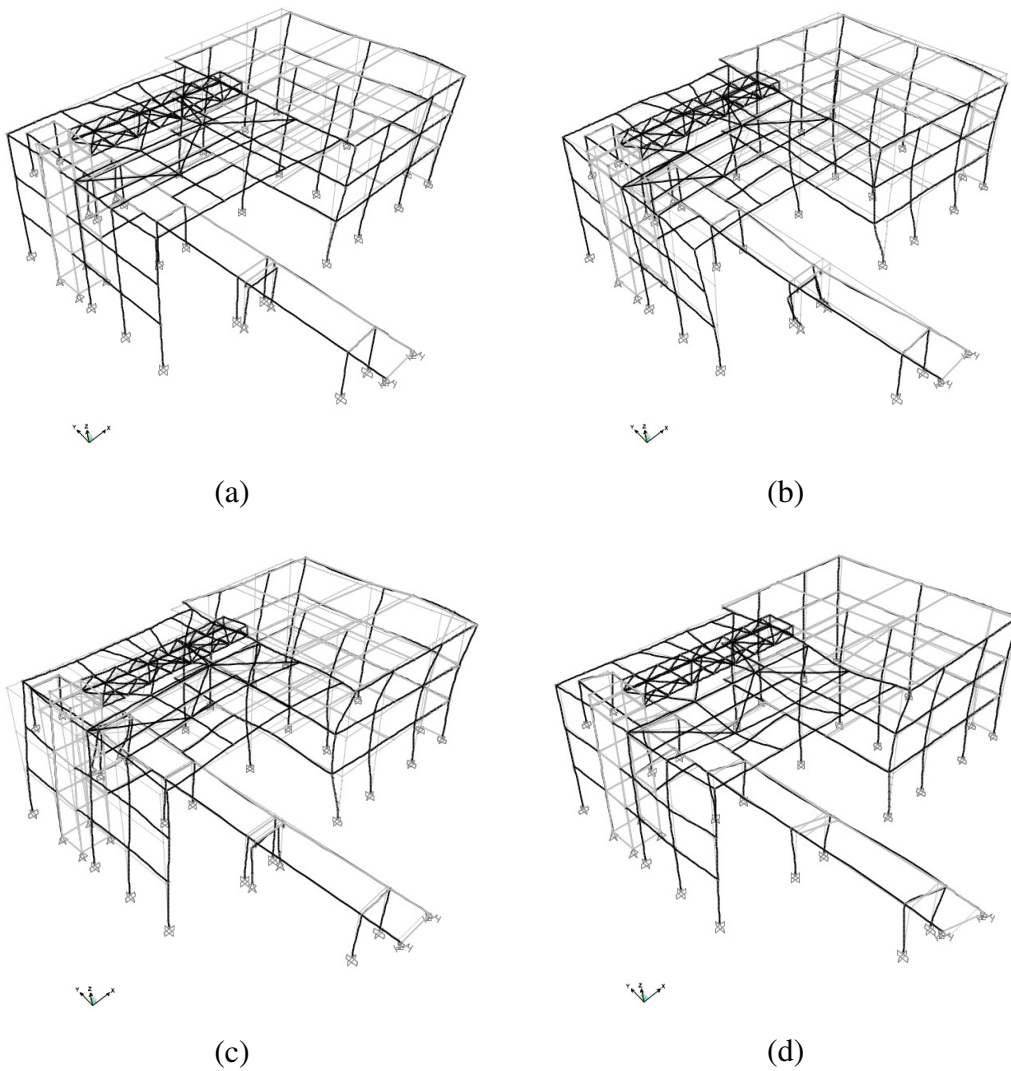


Fig. 3. Analytical modal information of Building 215: (a) Mode 1: 1.16Hz; (b) Mode 2: 1.85Hz; (c) Mode 3: 2.42Hz; (d) Mode 4: 3.52Hz

3. DESIGN AND IMPLEMENTATION OF THE MONITORING SYSTEM

Building 215 has been instrumented with a long-term structural health monitoring system to continuously acquire structural vibration responses and record the environmental conditions. Optimal sensor locations are identified based on a preliminary modal analysis with the initial finite element model of the building and experiences from senior researchers and engineers. Four components are included in the SHM system of this building, that is, the main building structure, the roof truss, the footbridges and the stairs. A tri-axial seismic accelerometer is installed underground outside the building to record the ground motions. 18 high sensitivity tri-axial accelerometers are mounted on all the levels of the three-storey building to monitor the global vibrations of the whole building structure. Another 18 single axis accelerometers and 6 strain gauges are installed on the footbridges at the second and third levels of the building. 5 single axis accelerometers are installed on the steel stairs. A weather station is also installed on the roof of the building to measure the external environmental conditions, i.e. temperature and humidity, wind speed and direction. Fig. 4 shows some photos of the installed single-axis and tri-axial accelerometers and strain gauges, and the data acquisition system.

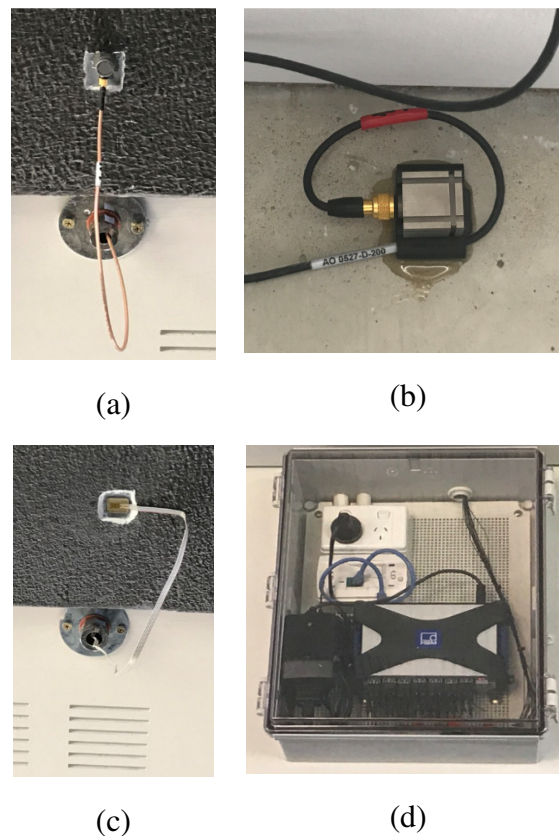


Fig. 4. Installed sensors and data acquisition system: (a) single-axis accelerometer; (b) tri-axial accelerometer; (c) strain gauge; (d) HBM data acquisition system

Fig. 5 shows the live structural health monitoring system of this instrumented building. This system is running 24 hours/7 days. A sustainable long term data storage strategy has been designed, and all the collected data will be available for review and analysis. The sampling rate of all the sensor is set as 50Hz, as the natural frequencies of building structures are usually low. The environmental condition data are recorded every minute. This living laboratory project develops a comprehensive and valuable vibration monitoring system to record a large amount of data under various environmental

conditions (temperature, humidity, and wind conditions etc) and loading events (even extreme events like earthquake) for structure condition monitoring and environmental effect analysis. This building provides an exclusive validation platform to study the impact of environmental conditions to the structural conditions and detect the possible progressive degradation based on the long term data.

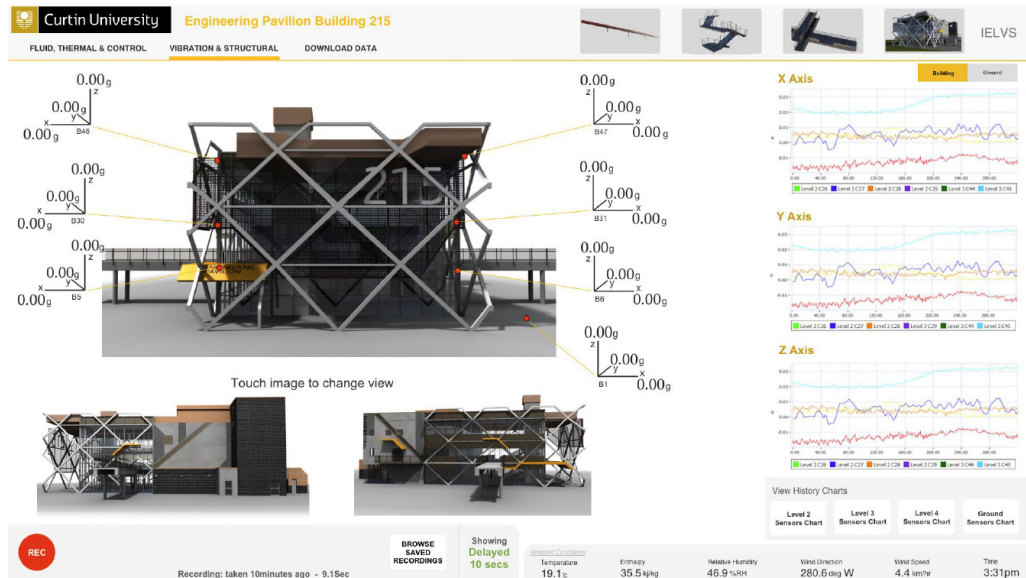


Fig. 5. Live structural health monitoring system interface of Building 215

4. TYPICAL RESPONSES AND MODAL IDENTIFICATION

Fig. 6 shows the measured responses from the steel frame under ambient vibrations. The measured vibration responses are pre-processed with a bandpass filter from 0.5-20Hz, and then used for frequency spectrum analysis and modal identification. Fig. 7 shows the Standardized Auto-Regressive (SAR) power spectrum in the frequency domain.

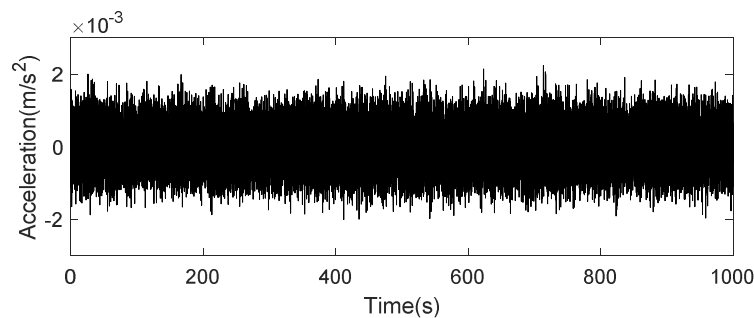


Fig. 6. The measured response from the steel frame under ambient excitations

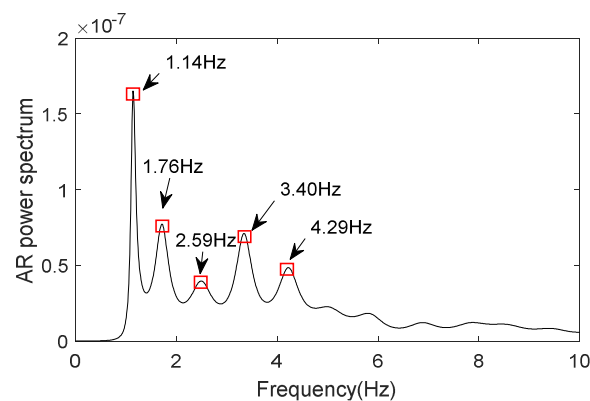


Fig. 7. SAR power spectrum of the response on the steel frame

5. MODEL UPDATING

The initial finite element model of this building as presented in Section 2 is updated based on the identified vibration characteristics, i.e. natural frequencies and mode shapes. In this model updating process, a limited number of physical parameters of the model is selected as parameters to be updated. The first order sensitivity-based model updating method is employed to update these selected parameters so that the analytical modal information, i.e. natural frequencies and mode shapes of the finite element model can match the measured results as closely as possible. Based on the sensitivity analysis of the modal information with respect to system parameters, five typical system parameters are selected for the model updating, which are described in Table 1.

Table 1. The selected model parameters

Parameters	Description
E_s	Elastic modulus of structural steel
E_c	Elastic modulus of concrete
ρ_1	Density of concrete slab on 1 st floor
ρ_2	Density of concrete slab on 2 nd floor
ρ_3	Density of concrete slab on 3 rd floor

The objective function defined in this study is

$$G(\boldsymbol{\theta}) = \sum_{i=1}^{N_m} \beta_i \mathbf{r}_i(\boldsymbol{\theta})^T \mathbf{r}_i(\boldsymbol{\theta}) \quad (1)$$

In Eq. (1), N_m is the number of modes; $\boldsymbol{\theta}$ denotes the vector of the selected system parameters, which are listed in Table 1; $\mathbf{r}_i(\boldsymbol{\theta})$ is the i^{th} difference vector between the measured and analytical modal parameters; β_i represents the weighting coefficient for the mode i . The residual vector $\mathbf{r}_i(\boldsymbol{\theta})$ in Eq. (1) is defined as

$$\mathbf{r}_i(\boldsymbol{\theta}) = \begin{bmatrix} \mathbf{r}_i^f(\boldsymbol{\theta}) \\ \mathbf{r}_i^m(\boldsymbol{\theta}) \end{bmatrix} \quad (2)$$

$$\mathbf{r}_i^f(\boldsymbol{\theta}) = \frac{f_i(\boldsymbol{\theta}) - \tilde{f}_i}{\tilde{f}_i} \quad (3)$$

$$\mathbf{r}_i^m(\boldsymbol{\theta}) = \frac{\boldsymbol{\Phi}_i(\boldsymbol{\theta})}{\|\boldsymbol{\Phi}_i(\boldsymbol{\theta})\|} - \frac{\tilde{\boldsymbol{\Phi}}_i}{\|\tilde{\boldsymbol{\Phi}}_i\|} \quad (4)$$

in which $\mathbf{r}_i^f(\boldsymbol{\theta})$ and $\mathbf{r}_i^m(\boldsymbol{\theta})$ denote the frequency and mode shape difference vectors of the i^{th} mode, respectively; $f_i(\boldsymbol{\theta})$ and \tilde{f}_i represent the i^{th} analytical and measured natural frequencies, respectively; $\boldsymbol{\Phi}_i(\boldsymbol{\theta})$ and $\tilde{\boldsymbol{\Phi}}_i$ denote the i^{th} analytical and measured mode shapes, respectively.

The effects of environmental factors including temperature, humidity, and wind speed are not included in this study. Only the mode shapes on the steel columns are included in this preliminary mode updating, considering the current available processed mode shape data. The optimization is performed by using a simulated annealing algorithm, which is available in MATLAB optimization toolbox. The initial system parameters $\boldsymbol{\theta}_0$ are determined according to the original design data. The constrained boundaries for the selected parameters are defined as $0.7\boldsymbol{\theta}_0$ and $1.3\boldsymbol{\theta}_0$, respectively.

The initial and updated model parameters are listed in Table 2, and the comparison of the measured, analytical frequencies before and after model updating are shown in Table 3. It can be observed that the updated model can accurately predict the natural frequencies of the building structure. Fig. 8 shows the first two mode shapes on the steel columns after model updating. Generally a good match in these two mode shapes is observed.

Table 2. The model parameters before and after updating

	E_s (10^9Pa)	E_c (10^9Pa)	ρ_1 (kg/m^3)	ρ_2 (kg/m^3)	ρ_3 (kg/m^3)
Initial values	200	30	2403	2403	2403
After updating	192.0	24.8	2621.5	2638.1	2514.3

Table 3. The measured and analytical frequencies before and after updating (Hz)

Mode	Measured	Before updating	After updating
1	1.14	1.16	1.14
2	1.76	1.85	1.81
3	2.59	2.42	2.64
4	3.40	3.52	3.47
5	4.29	3.87	4.38

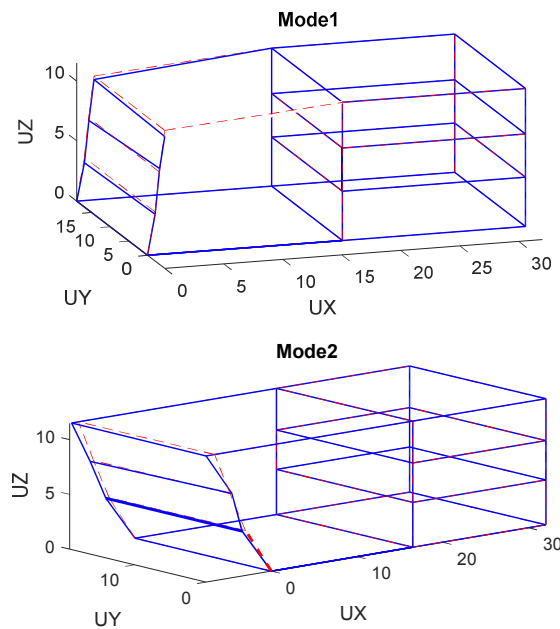


Fig. 8. The first two mode shapes on the steel columns after model updating (blue line: measured; red line: analytical).

6. RESPONSE PREDICTIONS UNDER EARTHQUAKES

This section investigates the performances of the building when it is subjected to the seismic excitations. The earthquake loadings in the two horizontal directions are simulated (Bi and Hao 2012) to be compatible with the design spectrum specified in

the Australian Seismic Design Code (AS1170.4; 2007), and used as inputs in the analyses. Two site conditions, i.e. the rock site (Class Be) and very soft site (Class Ee) are considered, and for each site condition three sets of ground motion time histories are simulated. In the numerical simulations, the sampling and upper cut-off frequencies are set as 100 and 25 Hz respectively. The duration of 20.47s is assumed in order to have a convenient total number of points (2048) for a fast Fourier transform, and the peak ground acceleration is scaled to 0.09g for Perth. Fig. 9 shows one typical acceleration and displacement time histories for classes Be and Ee, respectively, and Fig. 10 compares the response spectra of the simulated ground motions and the target design spectra. Good matches are achieved as shown.

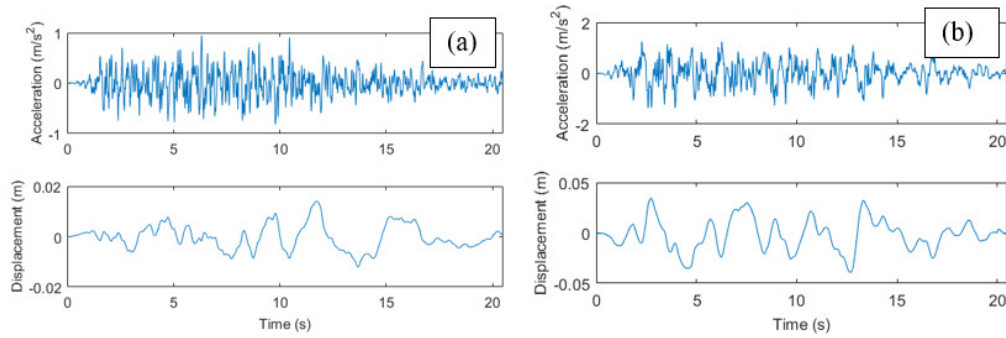


Fig. 9. Simulated acceleration and displacement time histories. (a) Class Be and (b) Class Ee.

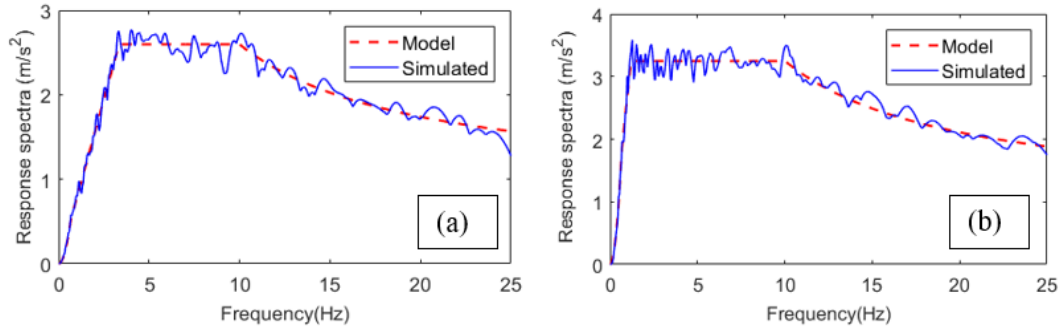


Fig. 10. Comparison of the response spectra of the simulated ground motions with the target spectra. (a) Class Be and (b) Class Ee.

To investigate the influence of model updating on the seismic responses of the building, both the original model and the model after updating are considered in the seismic response calculations. Fig. 11 shows the horizontal acceleration and displacement time histories at the top of the concrete part (Point A in Fig. 2) when the two building models are subjected to the first set of the earthquake loadings simulated for site Class Be. The corresponding results for site Class Ee are shown in Fig. 12. It can be seen that Class Ee results in larger structural responses compared to Class Be. This is because Class Ee corresponds to the very soft soil site, which results in much larger displacement at the foundation of the building as compared to Class Be. The larger inputs obviously lead to larger structural responses. Moreover, the displacement in the Y direction is larger than that in the X direction. This is because the building is more flexible in the Y direction as demonstrated in the modal analysis. For the rest two sets of earthquake loadings, the same trend can be observed. For conciseness, these results are not shown in the paper.

The results also show that for this building structure, the influence of model updating on the seismic responses is not evident and the two models result in very similar responses. For the maximum acceleration response, the maximum difference occurs in the Y direction of the building (a_y) with an average of 9.4% when the two models are

subjected to the earthquake loadings corresponding to the site Class Ee. This is because as shown in Table 3, the vibration characteristics of the building before and after updating are very similar, and moreover, the seismic excitations for the building are small, the building almost behaves linear elastically under these excitations. The influence of modal updating might be more evident when the structure shows obvious nonlinear responses (Li et al. 2014). These results indicate that the predict vibration characteristics of this building based on design drawings are accurate. This is because the structure of this building is relatively simple, and the building is very new.

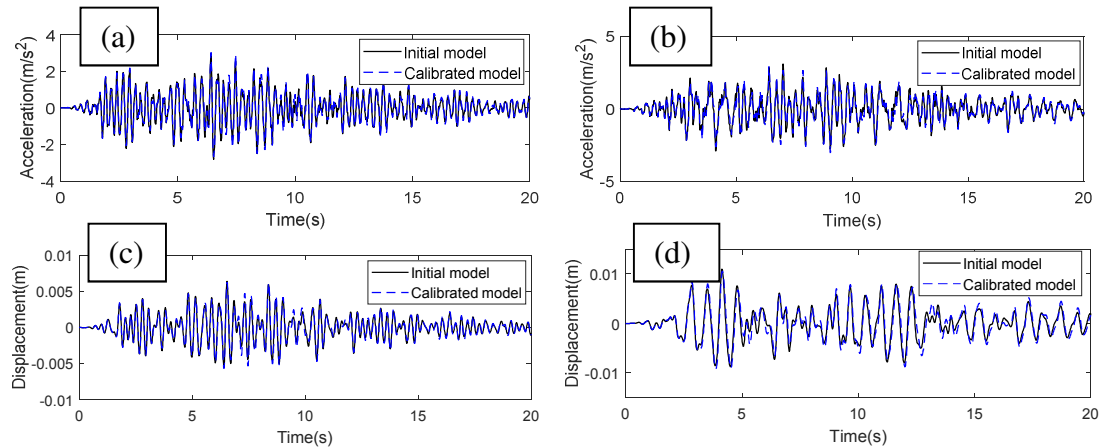


Fig. 11. Seismic responses of the building under the earthquake excitation simulated based on Class Be: (a) a_x , (b) a_y , (c) u_x and (d) u_y .

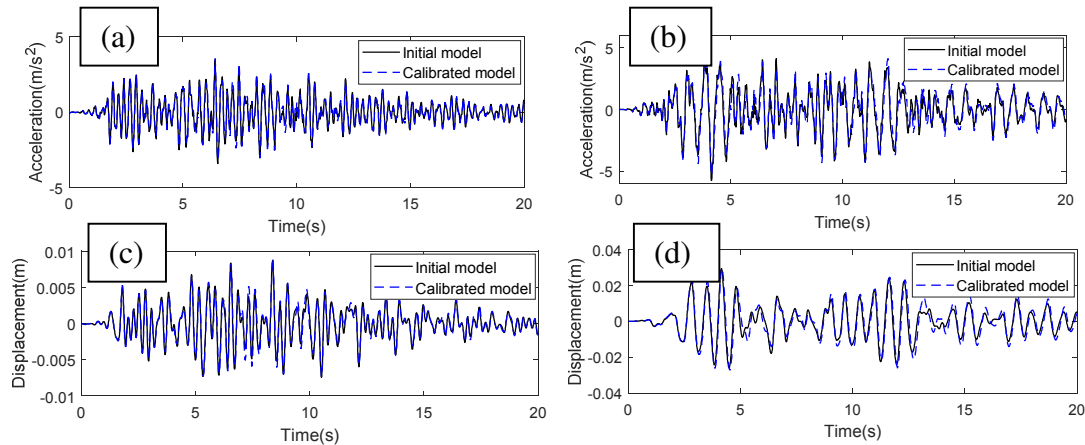


Fig. 12. Seismic responses of the building under the earthquake excitation simulated based on Class Ee: (a) a_x , (b) a_y , (c) u_x and (d) u_y .

Figs. 13 and 14 show the maximum interstory drift ratios of the building under different earthquake excitations. As shown the drifts of the building under Class Ee excitation are larger than those under Class Be excitation, and those in the Y direction are larger than in the X direction. The drift ratios are similar for the two models, and the maximum differences occur in the Y direction of the building when it is subjected to the Class Ee excitations. These results demonstrate again that the FE model created based on the design drawings for this new building structure is accurate. It is noted that the maximum drift ratio of the building is smaller than 0.4% as shown in Figure 14(b), which is much smaller than 1.5% as specified in AS1170.4, indicating the building is safe under the design seismic excitations.

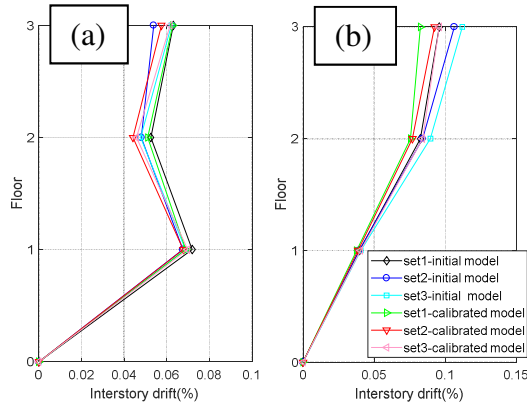


Fig. 13. The maximum interstory drift ratios of the building when it under Class Be excitation. (a) X and (b) Y directions

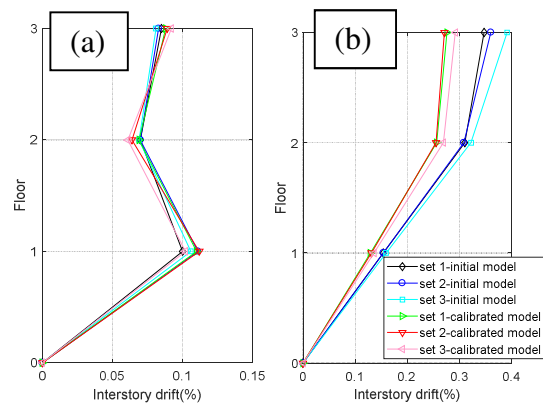


Fig. 14. The maximum interstory drift ratios of the building when it under Class Ee excitation. (a) X and (b) Y directions

7. CONCLUSIONS

This paper presents a benchmark building structure at Curtin University for long-term and continuously monitoring the structural vibration and environmental conditions. A structural health monitoring system was designed and installed on this iconic building at Curtin University. The sensory system includes more than 50 sensors, i.e. tri-axial and single-axis accelerometers and strain gauges installed on building columns and footbridges, and a tri-axial high sensitivity accelerometers installed underground outside the building for measuring the ground motions. The initial finite element model of the building is built according to the design drawings, and the vibration characteristics, i.e. natural frequencies and mode shapes, are obtained. The monitoring data measured under ambient conditions are analysed to obtain the vibration characteristics of the building, which are used for updating the FE model. Dynamic responses of the building under simulated ground motions for Perth are calculated with the model before and after model updating. The results are compared, the accuracy of the model created based on design drawings is discussed. This instrumented building structure is an exclusive benchmark platform in Western Australia to conduct the continuous structural vibration measurements and condition monitoring, and can be used for monitoring the structural performance and predicting structural responses under various dynamic events.

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REFERENCES

- Aktan A.E., Catbas F.N., Grimmelsman K.A. and Tsikos, C.J. (2000), Issues in infrastructure health monitoring for management. ASCE Journal of Engineering Mechanics Vol 126, No 7, pp 711-724.
- AS1170.4 (2007), Structural design actions, Part 4: earthquake actions in Australia. Standards Australia.

- Bi, K., and Hao, H. (2012), Modelling and simulation of spatially varying ground motions at sites with varying conditions. *Probabilistic Engineering Mechanics* Vol 29, pp 92-104.
- Catbas, F.N., Caicedo, J.M. and Dyke, S. J. (2006), Development of a Benchmark Problem for Bridge Health Monitoring, *Proceedings of the International Conference on Bridge Maintenance, Safety and Management, IABMAS, Porto, Portugal, July*, pp 16-19.
- Frangopol, D.M., Strauss, A. and Kim, S. (2008), Use of monitoring extreme data for the performance prediction of structures: general approach. *Engineering Structures* Vol 30, No 12, pp 3644-3653.
- Ko, J.M., Ni, Y.Q. (2005), Technology developments in structural health monitoring of large-scale bridges. *Engineering Structures* Vol 27, No 12, pp 1715-1725.
- Li, J. and Hao, H. (2016), A review of recent research advances on structural health monitoring in Western Australia. *Structural Monitoring and Maintenance* Vol 3, No. 1, pp. 33-49.
- Nguyen, T., Chan, T. H., Thambiratnam, D. P. and King, L. (2015). Development of a cost-effective and flexible vibration DAQ system for long-term continuous structural health monitoring. *Mechanical Systems and Signal Processing* Vol 64-65, pp 313-324.
- Ventura, C.E., Prion, H.G.L., Black, C., Rezai, M.K. and Latendresse, V. (1997), Modal properties of a steel frame used for seismic evaluation studies, *Proceedings of the 15th International Modal Analysis Conference, Orlando, Florida, USA, February*, pp 1885–1891.
- Xia, Y., Ni, Y.Q., Ko, J.M., Liao, W.Y. and Chen, W.H. (2009). “ANCRiSST benchmark problem on structural health monitoring of high-rise slender structures - Phase I: field vibration measurement”, *Proceedings of the 5th International Workshop on Advanced Smart Materials and Smart Structures Technology, Boston, MA, USA, July*.
- Zhou, W., Li, H. and Ou, J. (2005), A benchmark problem for structural health monitoring based on a real bridge structure, *The SPIE Symposium on Smart Structures and Materials, San Diego, CA, USA, March*.