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Next Generation "Living" Laboratory for Engineering Education and Engagement

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ABSTRACT

CONTEXT

In a recent report of the AECD's Engineering Futures 2035 project, it is recommended that universities review and revise professional engineering education programs to embed a stronger focus on student engagement with contemporary engineering practice through greater use of practice-based pedagogies, project-based learning, and multi-disciplinary projects. The last decade has seen an encouraging trend in the development of "living" laboratories in Australian universities providing much-needed opportunities for engineering students across various disciplines to practice with instrumentation, data acquisition and data analytics in a real-world context. Most successful living labs in Australian and international universities have, however, been limited to high-rise and mid-rise building applications in urban areas. Many universities have engineering facilities outside of cities which highlights a need for living lab solutions for the low-rise building setting.

PURPOSE

This paper discusses the design and development of a novel living lab as an innovative tool for modern engineering education and engagement at the University of Southern Queensland (UniSQ). The focus of this work is to enable effective living labs in low-rise buildings through suitable structural monitoring strategies.

APPROACH

The centre of the developed living lab is an embedded Structural Health Monitoring (SHM) system designed to record structural responses of the lab building in a real-time and continuous basis. The lab testbed was intentionally designed such that drop ceilings are omitted to help students visualise and understand the arrangement of structural components and how sensors are placed strategically. To the best of the authors' knowledge, this is the first-ever living lab system where all the monitored structures and SHM system components are in the line of sight of the lab users. The system can function on a 24/7 basis using ambient excitation as the main excitation source in conjunction with a simple artificial excitation when needed. Geometrically truncated models of the monitored structures are developed to provide students and visitors an opportunity to correlate between experimental and theoretical/numerical analysis results.

OUTCOMES

Since completion in 2021, the living lab system provides students and visitors a unique opportunity to practice various exercises from instrumentation set-up to data acquisition, data processing, and structural performance evaluation. A live web interface is being developed to allow the users to interact with the equipment systems in capturing the structural responses. A cloud-based data storage system has been developed and deployed to store measured data and allow students, especially those who choose to study online, to perform post-processing of data and structural condition assessment. The subsequent modal analysis proved that the system can correctly identify important vibration characteristics of the building under ambient and artificial excitations, providing them with a deeper understanding in the dynamics of the structures.

CONCLUSIONS/RECOMMENDATIONS/SUMMARY

The paper concludes that the living lab system developed at UniSQ Springfield has been tested and proven to provide an effective tool for catering modern engineering education needs and advanced engineering skills.

KEYWORDS

Living laboratory, real-time structural health monitoring, project-based learning, low-rise buildings

Introduction

Rapid advances in engineering technologies, changes in the engineering marketplace, and changing societal expectations are some of the key challenges for engineering educators around the world to make changes in the nature of professional engineering education programs. Recently, the Australian Council of Engineering Deans (ACED) recommended in their Engineering Future 2035 reports (Burnett et al., 2019; Crosthwaite, 2021) that universities review and revise professional engineering education programs to embed a stronger focus on student engagement with contemporary engineering practice through greater use of practice-based pedagogies, project-based learning, and multi-disciplinary projects. Previous international research and reports also highlight a critical need for university courses to provide more experience in applying theoretical understanding to real-world problems (Atman et al., 2010; Goggins et al., 2012; Jamieson & Lohmann, 2009).

Toward this end, universities around the world have been developing a new generation of engineering laboratories featuring teaching and research spaces equipped with world-class instrumentation to provide a more interactive teaching tool for engineering students in the 21st century (Goia et al., 2015; Kershaw et al., 2017). In Australia, the last decade has seen an upward trend in the development of “living” laboratories by equipping institutional buildings with a structural health monitoring (SHM) system. In the early 2010s, an SHM system was developed at the ten-storey P-Block building in the city campus of the Queensland University of Technology (Nguyen et al., 2015). This system has been proven to have significantly advanced research on the SHM of full-scaled civil engineering structures as reported by Nguyen et al. (2015) and Nguyen et al. (2019). However, the sensors and their ancillary components were on different levels and corners of the building, which limit the ability of undergraduate students to have access to and understand how such a system is operated. Another “living” laboratory equipped with an SHM system was developed at the Nathan campus of Griffith University, which aimed to equip students with knowledge and skills for 21st Century engineering (Aghdamya et al., 2019). As reported, this SHM system was designed with electronic sensors to capture the structural responses of a six-storey building due to environmental effects during its service life. The monitoring data is expected to be used in various engineering curricula across several disciplines of the university. In a third case, a sophisticated SHM system with hundreds of advanced sensors was installed on the five-storey Woodside Building at Monash University’s Clayton Campus in 2020 (Colin Caprani, 2019). However, further progress on these two recent SHM systems such as data analysis or use of monitoring results for research or educational purposes have not been reported. It should be noted that most of these SHM systems were developed for high-rise or mid-rise buildings in urban areas, while similar application to low-rise (one or two-storey) university buildings has been limited.

This paper presents the design and development of a novel living laboratory as an innovative teaching tool for improving the quality and performance of engineering education at the University of Southern Queensland (UniSQ) in Springfield. The paper aims to demonstrate how an SHM system can be implemented in low-rise building settings that are commonly seen in many Australian universities having campuses outside big cities. Ultimately, this paper will discuss the solutions to maximize the effectiveness of an SHM system in supporting undergraduate students with hands-on exercises as part of their study. The rest of this paper is organised as follows. First, the newly upgraded engineering laboratory for advancing future engineering education at the UniSQ is introduced. Next, the design and development of the SHM system as a “living” laboratory solution is presented. The success of the lab solution is then demonstrated through some key implementation activities. The paper concludes with summary and final remarks on the “living” lab solution.

The UniSQ Engineering Labs for future engineering education

In October 2021, UniSQ opened its newly upgraded F-Block Engineering building (Figure 1) at the Springfield campus (University of Southern Queensland, 2021). The two-storey building features specialised teaching and research spaces equipped with new world-class technology and equipment, designed to satisfy the need for both current and future engineering education. The labs include robotics and automation, future materials development, electrical power and electronics, civil and structural engineering, and a surveying preparation room. The building is expected to enhance research opportunities and the university's ability to provide a collaborative on-campus and online composite delivery of practical learning for solving real-world problems to engineering students.

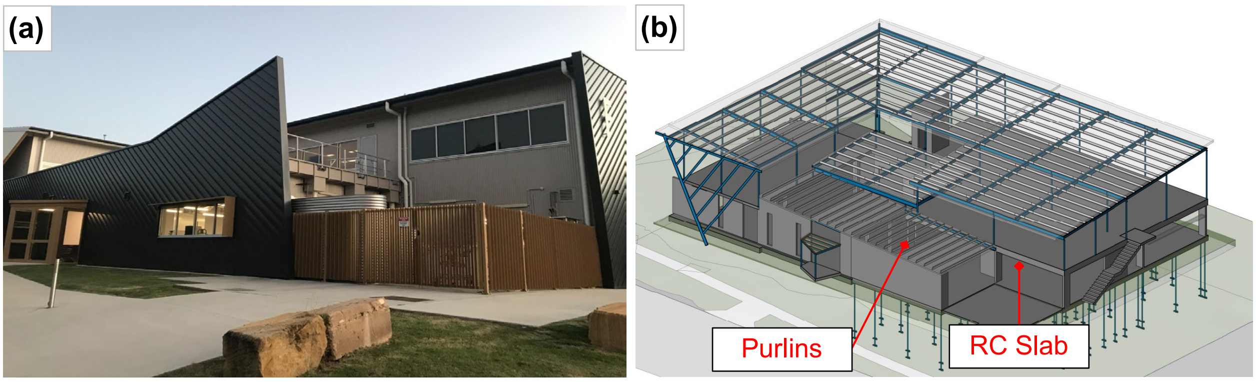


Figure 1: (a) The new F-Block building, and (b) Instrumented structures

One unique feature of the building is its SHM system including multiple sensors embedded on structural components allowing students to practice monitoring the structural behaviours on a real-time basis as part of their studies. This is the first time what would normally be seen in large bridges or tall buildings has been implemented in a laboratory setting, where all system components are in direct observation of the lab users. It means students can instantly start their hands-on activities at any time on a 24/7 basis. In the next section, this paper will summarize the design and development of this SHM system.

Design and Development of the SHM system

Over the last few decades, SHM has emerged as a feasible technology for the structural assessment of critical infrastructures such as buildings, bridges, and dams (Le et al., 2020). The SHM process includes selection of the structures to be instrumented, sensors installation, data acquisition, and diagnostics through which the structural safety, integrity, and performance are assessed (Gharehbaghi et al., 2021). The timely identification of early damage can enable appropriate retrofitting measures to be taken before the damage escalates to an extent that can make the structures unserviceable (Chan & Thambiratnam, 2011). Within a laboratory condition, this paper will demonstrate that such an SHM system can also serve as an innovative teaching tool by providing engineering students opportunities to practice with contemporary engineering skills such as instrumentation, data acquisition, data analytics, and structural condition assessment in a real-world context. The following sections give details on how to provide effective "living" labs in low-rise buildings through suitable SHM strategies.

Structural Elements Instrumented

As mentioned earlier, most of the existing SHM "living" laboratory systems have been developed for high-rise or mid-rise buildings for capturing structural vibrational characteristics at an overall scale owing to their considerable flexibility in the horizontal direction. However, for low-rise buildings such as the UniSQ F Block, the stiffness of the building in the horizontal direction is relatively high, making it less effective to have such measurements under ambient excitations. The focus herein is, therefore, suitably directed to the development of an SHM system for recording vertical vibrations of structural elements such as beams and slabs, which are closely related to basic engineering problems in civil engineering education curriculum. This happens to be an advantage in this case since the concrete slab and steel purlins (beams) are structures that students can easily observe from the civil lab (Figure 1-b, Figure 2). In addition, these structural elements are chosen also because concrete and steel are the most popular materials in civil engineering structures.

The reinforced concrete slab

The monitored reinforced concrete (RC) slab is above the civil (engineering) lab and a portion of the

Level 1 renovated RC slab (Figure 2-b). The slab and its supporting beams are made of S40 strength-graded concrete, supported vertically by reinforced concrete columns and block walls. Drop ceilings of the slab are omitted intentionally to help students visualise and understand the arrangement of structural components and how sensors are placed (Figure 3, Figure 4). Above the Level 1 RC slab is a lightweight steel frame system that transmits the load directly to the foundation through the ground floor columns and walls without significant effects to vertical vibration of the RC slab (Figure 1-b).

The single-span steel purlin

Half of the civil lab is covered by an insulating corrugated iron roof carried by an array of steel purlins (Figure 1-b, and Figure 2-b). The purlins are 8 meters in length, made from Z25019 steel section, and are supported by two I steel beams at both ends. It is therefore reasonable to consider the purlins as simply supported beams, a simple structure that undergraduate structural engineering students are familiar with. In addition, the steel purlins are sensitive to thermal expansion, which are suitable for practicing with strain measurement as part of the student study.

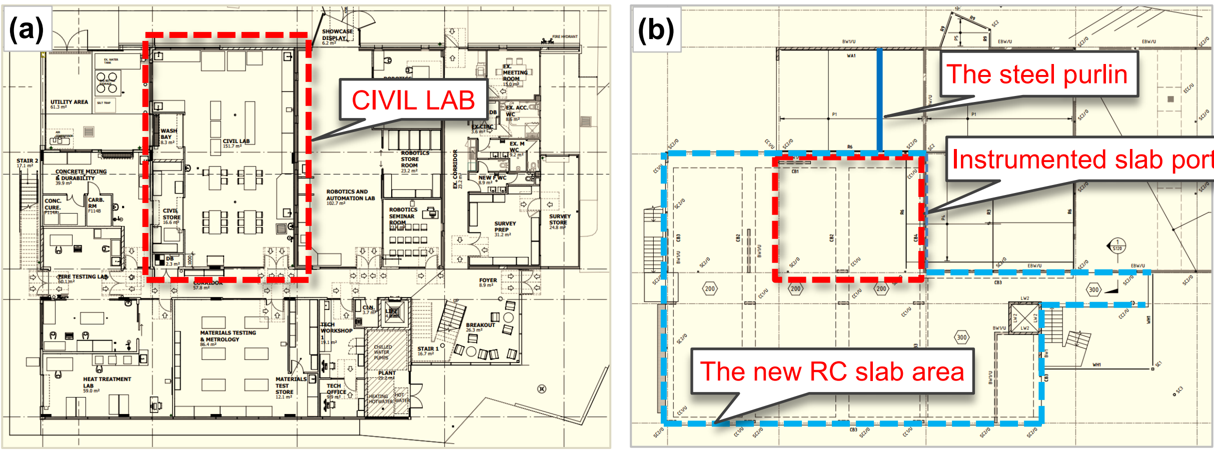


Figure 2: (a) Location of Civil lab, (b) Instrumented structures marked on the structural drawing

Instrumentation

Sensor installation

The selection and installation of the sensors need to be appropriate to ensure their effective operation for a specified duration. Each sensor can only measure a particular aspect of the structure such as strain, deflection, acceleration, temperature, etc. For measuring vertical vibration of the RC slab, nine PCB 393B12 accelerometers (ACC), numbered as 1 to 9 in Figure 3-b, were mounted on the concrete slab soffit through steel plates placed during concrete casting. With a high sensitivity of 10V/g and a frequency range from 0.15 to 1000 Hz, this type of sensor can accurately record the vibration history of the RC slab under ambient excitations at different magnitudes ranging from unnoticeable lab user activities to a strong seismic motion should it approach the building. The nine sensors are arranged in such a way that not only can they fully reflect the vibrational properties of the slab portion, but also facilitate student observation from the civil lab area (Figure 3).

For measuring the strain of the steel purlin, three high-resolution PCB 740B02 dynamic piezoelectric strain gauges with a sensitivity of 50 mV/με, named as ST1 to ST3 in Figure 3-b, were attached on the purlin's web at an equal distance of 2 meters. In normal operational conditions, the strain gauges can record strain deformation of the purlin due to temperature and/or operational load variations. In addition, a portable tapping rod was designed to trigger the beam vibration when needed. In addition, a weather station has been installed and will be integrated into the SHM data repository in due course. The temperature measurements are important for understanding strain-temperature correlation and how a change in temperature may cause a structural response similar to what a damage can cause to the structure so a call for damage presence can be correctly made.

Both acceleration and strain measurement data can be used for basic vibration, modal and stress analysis, which are important aspects in the dynamics of structures within the engineering curriculums.

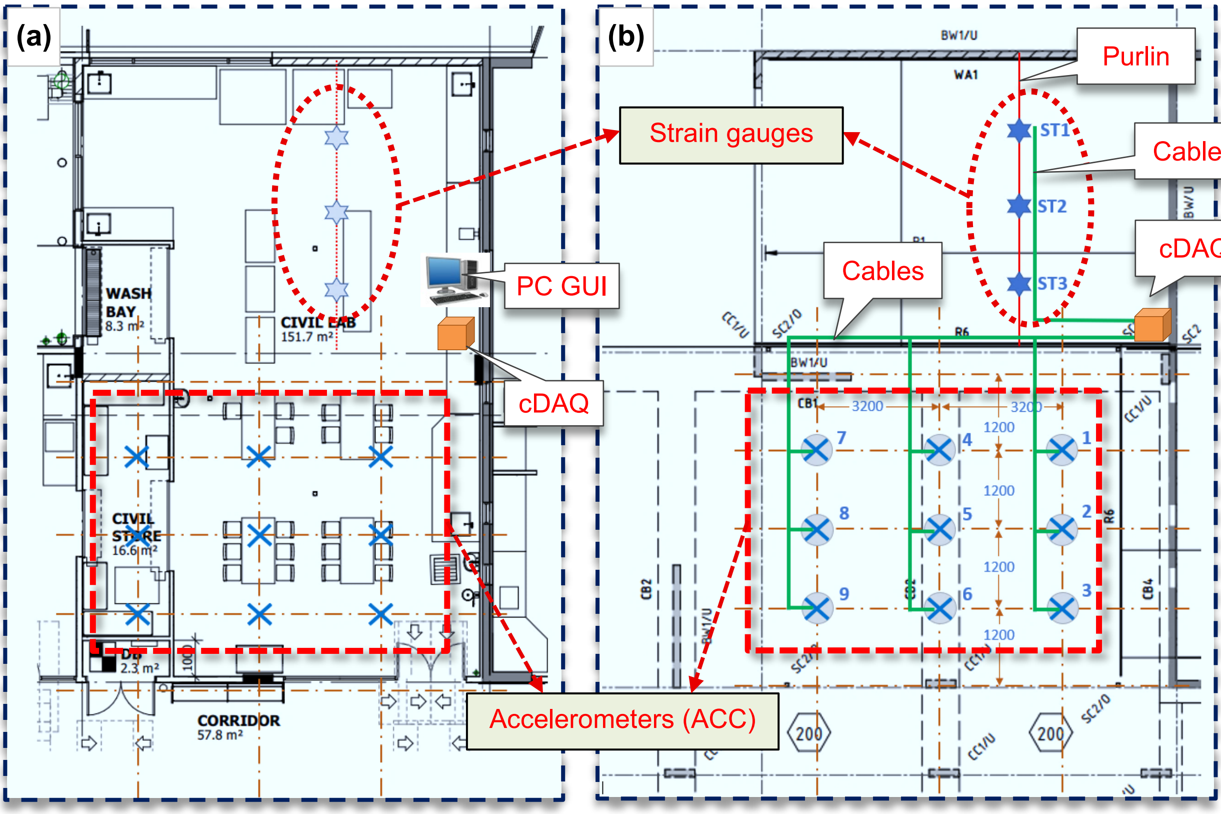


Figure 3: Sensor Arrangement Plan: (a) View of sensors from the lab, (b) Instrument arrangement

Data acquisition

A compact Data Acquisition (cDAQ) system has an important role in sampling signals from the instrumented structures via sensors and converting them into digital numeric values that can be manipulated by a computer. The system provides unique opportunity for UniSQ researchers and students to practice with signal processing using different programming languages. In this project, a cDAQ controller with embedded windows operating system (model cDAQ-9133) was suitably selected and mounted on the wall inside the civil lab (Figure 3, Figure 4). The cDAQ can host up to eight modules to collect measurement signals from different types of sensors. It controls the timing, synchronization, and data transfer from the modules to an integrated computer having a graphical user interface (GUI) that the students can practice with. Other components including cabling, enclosure, trunking, etc., all can be observed from the lab.

Data Storage System

Once measurement data is processed, it can be stored permanently either on local or network drives for future data retrieving and interpretation. This enhances the University's research opportunities and provides collaborative online and on-campus composite delivery of practical learning to engineering students.

User Interactive Environment

A LabVIEW-based software was developed in house to control the whole SHM system via a computer GUI. The software can read and log the data in a fully synchronized and automated acquisition manner. It is also possible for computer systems, instrumentation and mechatronics students to practice by exploring and re-programming the system as part of their studies.

Implementations

The living lab system has been used not only to educate university students but also to provide Continuous Professional Development (CPD) for engineering practitioners, as well as to stimulate the interest of high school students into engineering studies via exploring the system in an Experience Day (Figure 4). In the following section, the authors will illustrate some practical exercises and results obtained when applying the SHM system in monitoring and recognizing the dynamic characteristics of the structures. Due to the page limit and for illustration purposes, only the monitoring of the RC slab is presented.

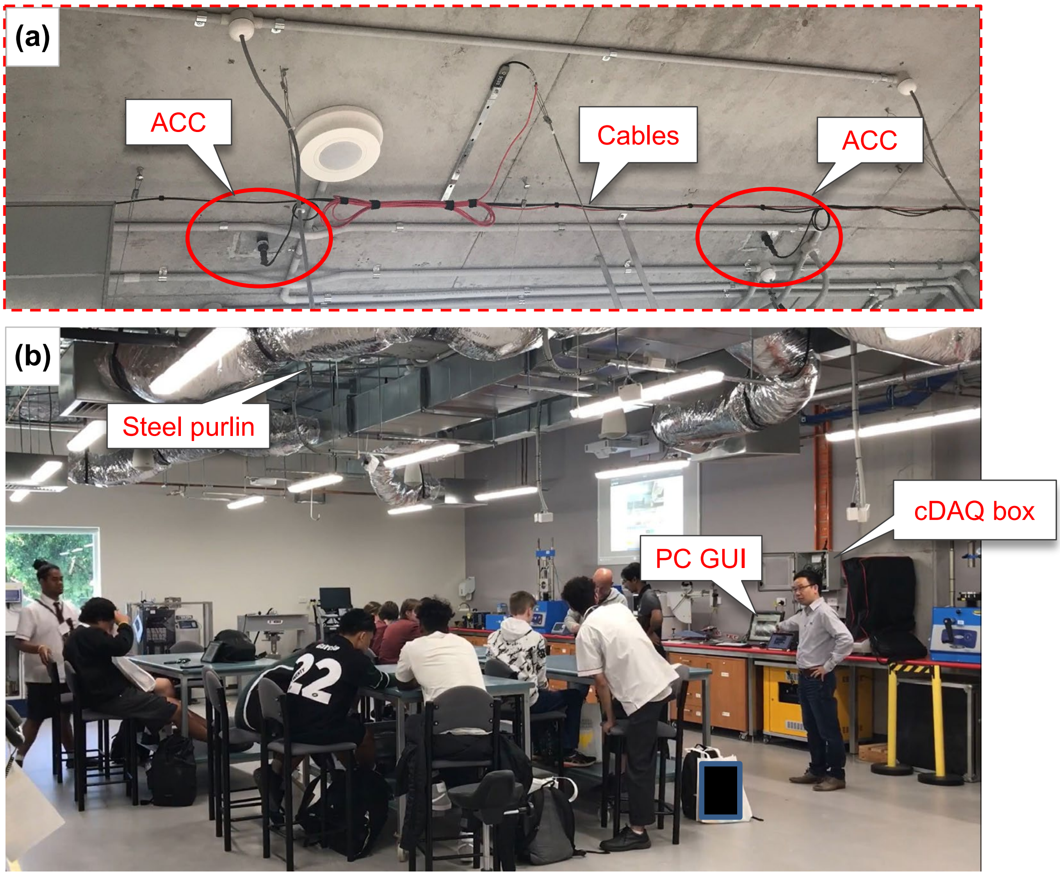


Figure 4: (a) View of the ACC on RC slab, (b) an Experience Day event for high school students

Obtaining measurement data

Recording the structural responses is the first step in extracting physical properties of the monitored structures to facilitate later structural assessment processing. The instrumentation installed can generate real-time vibration data and instantly indicate the results on the computer GUI (Figure 5). One advantage of this system is that the users can easily observe any changes in the vibration amplitude (such as impulsive signals marked in ellipses in Figure 6) corresponding to the excitations caused by lab activities on the second floor. For data storage optimization, the output signals are normally compressed and not readily readable. A Matlab code is, therefore, available for students to practice with data analytics to extract measurement data relevant to their experiments.

Structural modal analysis

After obtaining measurement data from the nine accelerometers, the students are instructed to use operational modal analysis (OMA) software like ARTeMIS Modal (https://www.svibs.com/artemis-modal/) to extract the structural vibration characteristics. Figure 7 illustrates a typical resultant singular values of spectral densities (SVSD) diagram that can be used to identify the natural vibration modes of the structure using a simple peak-picking technique (Gharehbaghi et al., 2021). For each of the identified modes, the software will extract the natural frequency (Table 1) and the corresponding mode shape of vibration (Table 2). In practice, measurement noises sometimes can cause false detection at some peaks of the SVSD diagram. However, with a solid understanding of the Dynamics of Structures, the students can eliminate these false detections. Alternatively, a correlation analysis between the OMA and numerical analysis results presented in the next section can solve the issue.

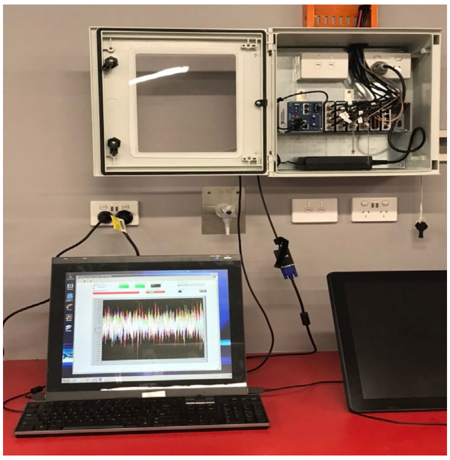


Figure 5: The system control screen

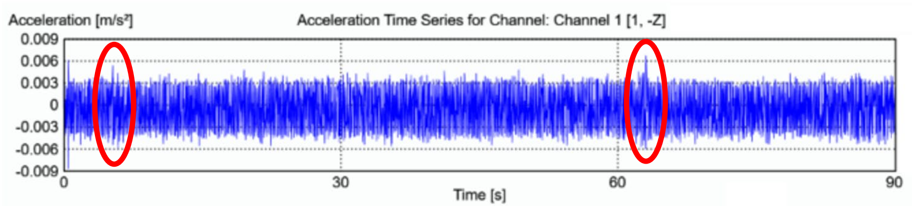


Figure 6: A typical recorded acceleration history of the RC slab

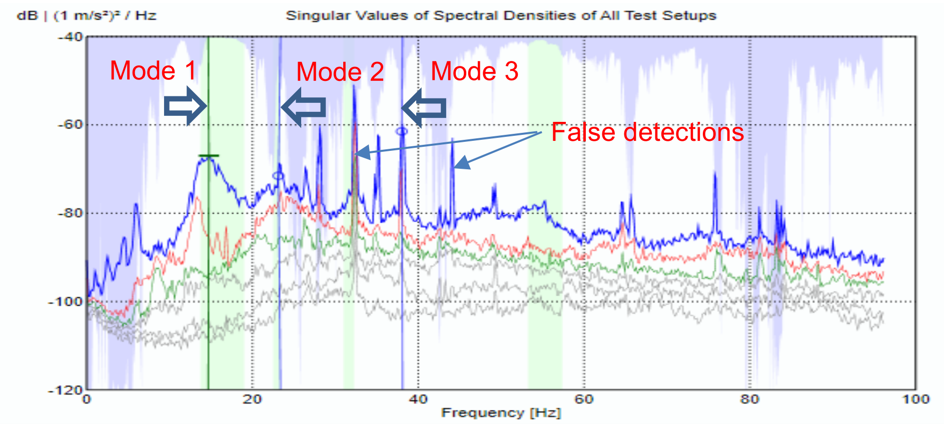


Figure 7: Modal identification using peak picking technique

Table 1: Natural Frequency comparison FEM vs OMA (Hz)

Mode	OMA	FEM	% Difference
1	14.66	14.13	-3.7%
2	23.30	24.79	6.3%
3	38.46	38.19	-0.7%

Finite Element Model Validation

A preliminary truncated finite element model (FEM) was developed based on the as-built information of the building (Figure 8). Based on identified modal parameters from OMA, the FEM was suitably updated by adjusting its structural and material properties so that the FEM results are best correlated with OMA results (Table 1, Table 2). After this stage, the updated FEM can represent the actual structure, and be used to validate experimental results conducted by students. As illustrated in Table 1, a comparison between the tested and the FEM results can help students quickly identify actual natural frequencies among the resultant SVSD peaks. A comparison between OMA mode shapes (from a limited number of sensors) and the more completed FEM ones (Table 2) can help students in visualising the whole structure vibration patterns.

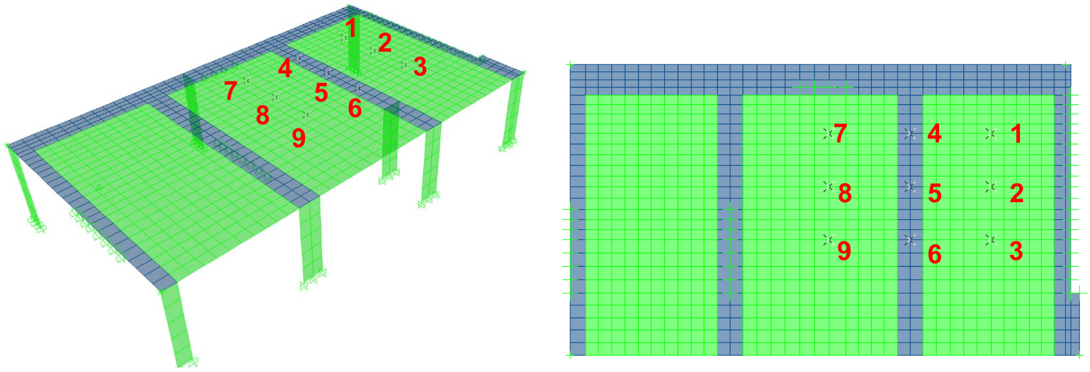
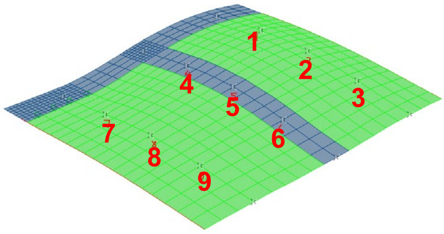
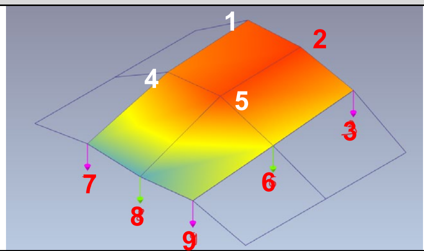
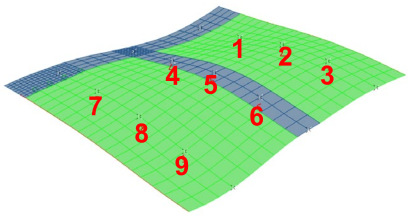
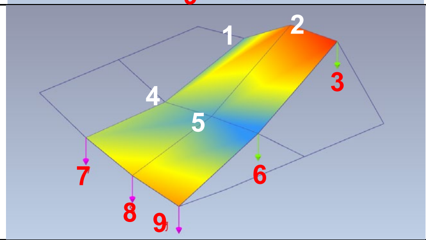
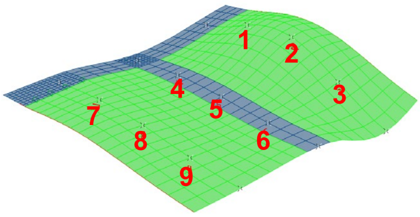
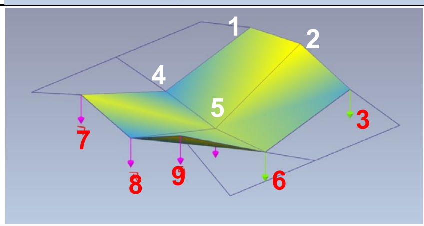


Figure 8. The truncated FEM model

Table 2: Mode shape comparison: FEM vs OMA

Mode	FEM	OMA
1		
2		
3		

Conclusions

This paper has presented the design and development of an SHM system as a novel "living" laboratory solution for low-rise buildings that can be applicable to many Australian traditional laboratories, especially those in regional universities. The "living" laboratory system presented in this paper provides an effective teaching tool for catering contemporary engineering education needs and advanced engineering skills in instrumentation, data acquisition, and structural assessment in a real-world context. The paper has focused on technical solutions for the selection and installation of the SHM components that are relevant to an engineering education context. The readiness of the "living" laboratory solution for improving the quality and performance of engineering education is demonstrated through experimental and numerical illustrations in extracting basic vibration characteristics of the monitored structures.

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