17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

AMBIENT VIBRATION TEST AND REAL-TIME WEB-BASED PERMANENT MONITORING SYSTEM AS BACKBONES OF A SUCCESSFUL STRUCTURAL HEALTH MONITORING SYSTEM

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Abstract

Structural health monitoring systems have become increasingly popular during the last few of years. The main purpose of the existing monitoring systems is limited to recording vibrations during earthquakes. Unfortunately, the amount of useful information provided by these systems to engineers and asset owners have been minimal. Therefore, there is a need to enhance these systems to be able to perform in-depth data analysis and extract more information about the structure under test.

This paper presents a state-of-the-art approach to provide an advanced structural health monitoring solution. The first step is to perform a quick non-destructive ambient vibration test on a building to extract its modal properties. Such a system consists of wireless highly-sensitive low-noise sensors to deploy several sensors per floor to derive high quality modal characteristics. The building dynamic characteristics will act as a baseline and the test needs to be repeated every few months/years and after natural hazards to identify building changes and integrity issues. Moreover, this baseline is used to generate the global seismic engineering demands without a need for engineering drawings or finite element models. The seismic demands are compared with the FEMA damage thresholds to predict the building seismic performance.

The baseline response, extracted from the ambient vibration test, is used to design a permanent monitoring system layout with optimal performance and cost. A real-time web-based dashboard is used to monitor the structure and provide alarms to the asset owners and engineers in case of an emergency. The dashboard is capable of comparing the inter-storey drift-ratios with the damage thresholds in HAZUS and FEMA P-58 to estimate damages during an earthquake. Combination of both temporary and permanent vibration monitoring systems and data will greatly improve the performance of the SHM system and will help to quickly and more reliably evaluate buildings following earthquakes.

Keywords: Ambient vibration test, structural health monitoring, vibration sensors, seismic evaluation, earthquake

1. Introduction

Traditional approaches to monitor civil structures, such as visual inspections, are time consuming and leave the possibility for hidden undetected damage. These drawbacks have promoted the development of structural health monitoring (SHM) over the past decades. Many buildings worldwide have been instrumented with strong-motion sensors. However, the main purpose of these systems is to measure the vibration data during a strong shaking. As the amount of insights and information provided by such a system is limited, asset owners and engineers are still hesitant to deploy SHM systems on a large scale. There is a need for more advanced systems that can extract meaningful information from the gathered data and provide some key metrics during the building lifetime and after a natural hazard.

Vibration-based SHM uses measurements that contain information about the dynamic properties of a system, which can be subsequently mapped to structural damage and integrity measures. In essence, a global vibration-based structural health monitoring is used to detect the presence and approximate location of damage, followed by local non-destructive evaluations (NDE) for determining the extent of damage.

This paper introduces a state-of-the-art SHM solution consisting of both temporary ambient vibration tests and permanent monitoring systems. The ambient vibration test is a very detailed sensing test that results in high-quality 3D mode shapes, natural frequencies and damping ratios (modal characteristics are called baseline in this paper). The ambient vibration test acts as a non-destructive condition assessment test to identify building changes and integrity issues over time. The interval of the tests depends on the building importance, age, type and earthquake risks. The test should also be repeated after natural hazards. The baseline is used to design a permanent monitoring system that is optimized in terms of performance and cost. The number of permanent sensors is lower than the number of locations tested during the temporary ambient vibration test. A live web-based dashboard is used to provide alarms to the building management team in real time.

2. Periodic Monitoring

Currently, owing to advances in sensing techniques and analysing procedures, the most popular experimental modal test for large structures is ambient vibration testing (AVT/sensing test). The reliability of AVT to derive modal properties such as natural frequencies, mode shapes and estimates of internal equivalent modal damping ratios has been demonstrated in many studies over the past decades [1, 2]. High resolution sensors can measure very small ambient accelerations/velocities in buildings (Fig. 1). For instance, Sensequake Larzé wireless sensors can monitor horizontal and vertical vibrations in the building. In addition to high quality data collected by the sensors, one of main features of the Larzé Vibration Monitoring System is microsecond precision synchronization achieved through a wireless mesh network. The sensors need to be within the reach of the radios for a few seconds to achieve complete synchronization. Subsequently, they can be moved and placed in their designed locations (Fig. 1a) and they will keep precise synchronization for more than 12 hours. An Android application is used to configure the sensor network (Fig. 1b).

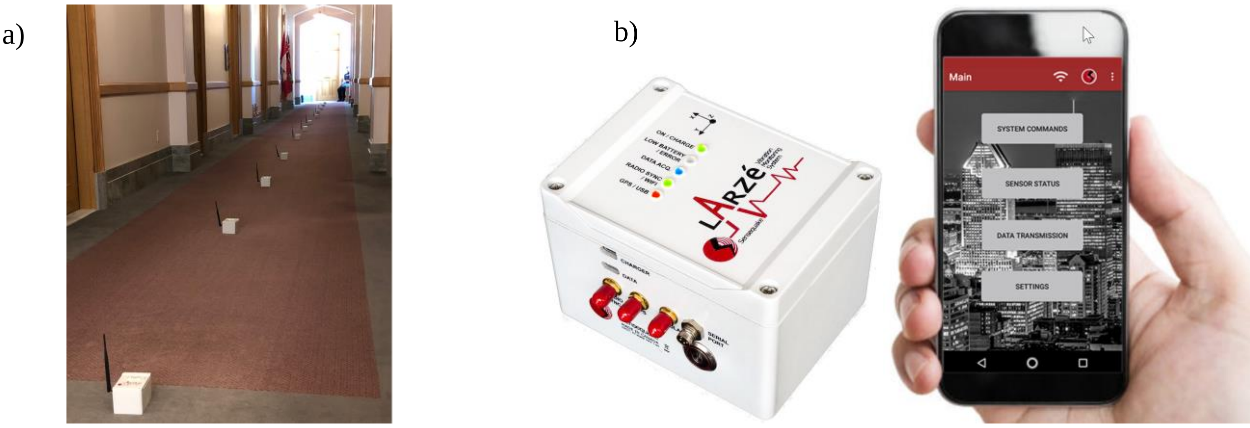

Fig 1. (a) Larzé sensors; (b) Larzé sensor and control application installed on a smartphone (https://www.sensequake.com/).

Larzé sensors can record both velocities and accelerations simultaneously in three orthogonal directions: two in the horizontal plane and one in the vertical direction. Geophones are used as velocimeters to achieve the very high sensitivity and low-noise performance required for ambient vibration tests. The accelerometer found in Larzé sensors is a combination of several MEMS sensors in order achieve a higher signal-to-noise ratio (SNR). The sampling frequency can be selected between 15 Hz and 976 Hz. The analog-to-digital convertors operate at a much higher sampling rate and filter and decimate the data to achieve higher signal-to-noise ratios.

In summary, the main features of Larzé sensors are as follows:

- Six channels of velocity and acceleration data (cover both very small to large vibrations)
- Very low-noise sensor
- Microsecond precision synchronization
- Accurate synchronization without sensor communication for several hours - ideal for large civil engineering structures
- Easy configuration through a phone app
- Compact size
- Wireless data transfer through Wi-Fi
- Battery powered and rechargeable

On a large structure, it is convenient to synchronize Larzé sensors locally before carrying them to their designated spots. In a local synchronization scheme, a waiting period can be added using the Android application during which the sensors are synchronized but do not yet record data. The recording only starts after the sensors are distributed to the desired locations. It should be mentioned that the duration of a sensing test depends on the rigidity, height and type of the structure.

After the test, the collected data is transferred to a PC via a USB connection or through Wi-Fi. The data is available in text format and is readable in Sensequake's 3D-SAM™ software [3]. The first set of features derived from the data is called baseline. A baseline includes natural frequencies, mode shapes and estimates of internal equivalent modal damping ratios. This information is analogous to a human's DNA, heart beat or temperature. It is essential to track future conditions of a structure and this will act as a reference of a structure life span in the case of degradations, retrofit or damage.

A typical building and sensor locations are shown in Fig. 2. After analyzing the vibration data (a few hours of vibration data at about 40 locations were measured by using 6 wireless Larzé sensors in the operational condition of the building) several modes were identified by the 3D-SAM software and are shown in Figure 3.

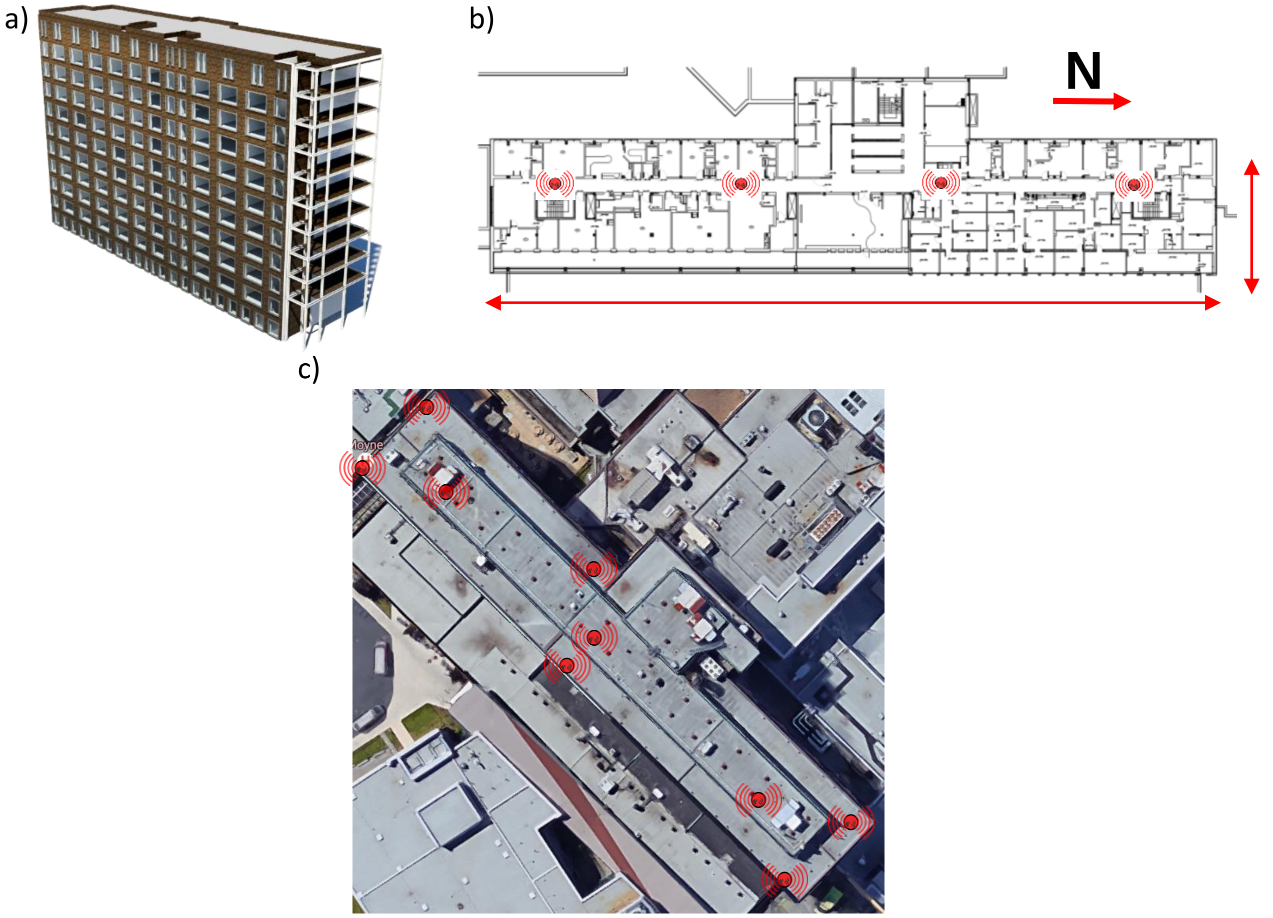

Fig 2. (a) 3D-view of the building; (b) Typical floor and sensor positions with red circles; (c) Sensor locations on bottom and upper roof.

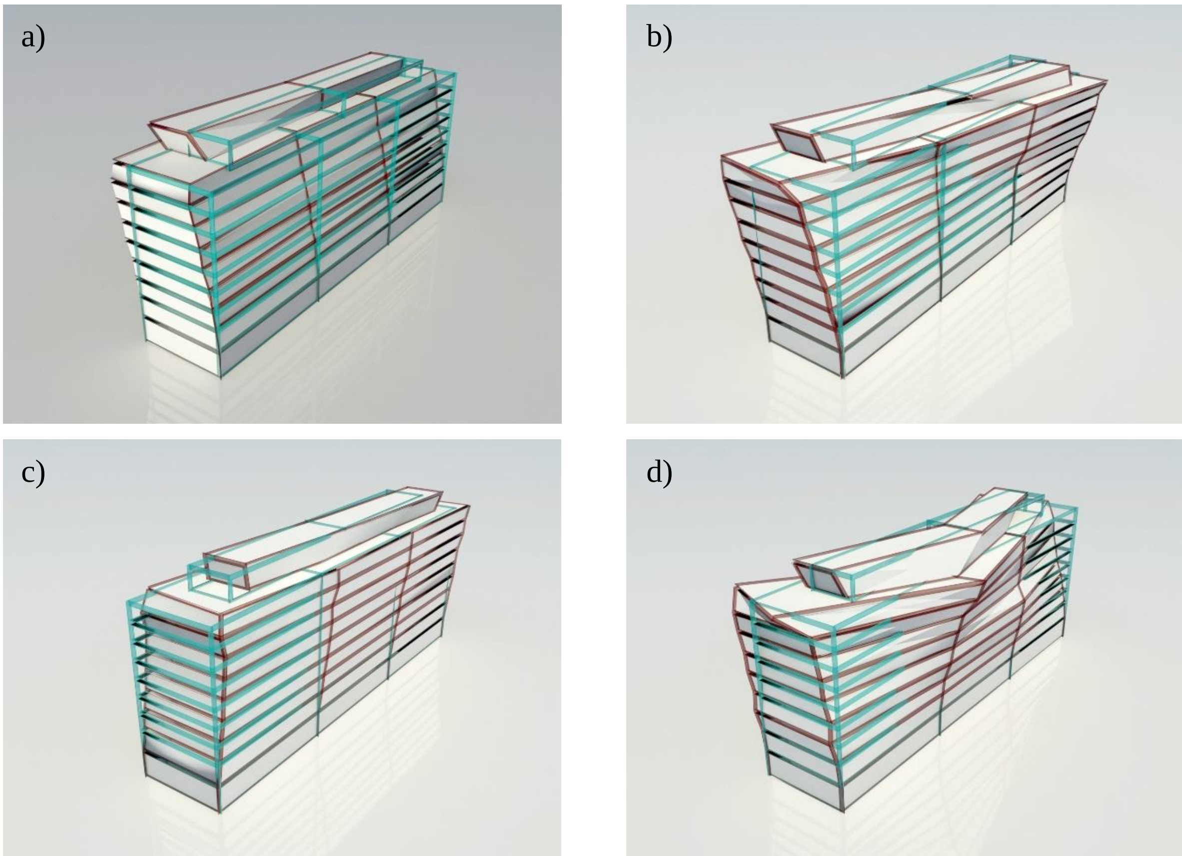

Fig 3. Mode shapes of the first four modes found by 3D-SAM software

3D-SAM is a direct top to bottom approach that makes use of in-situ derived modal properties and therefore bypasses the need for detailed engineering plans and finite elements (FE) analysis models. By extracting the dynamic properties of buildings from AVT, it is possible to calculate the building seismic response by convolution integral in the linear range according to classical structural dynamics theory. The patented 3D-SAM method [4] predicts global seismic demands and response histories of buildings to a future earthquake [5]. The procedure, with its inputs and outputs, is illustrated in Fig 4.

It should be mentioned that depending on the seismic demand parameter and intensity of the considered earthquakes, appropriate modification factors should be applied to the modal properties derived from AVT; i.e. modifying the ambient vibration modal properties to take into account their change during higher shaking levels based on the available data from other similar buildings subjected to large earthquakes that were permanently monitored with vibration sensors [6]. The 3D-SAM software can run time history analysis on as many ground motions as needed and provides response histories and maximum global seismic demands solely based on the sensing results without making any finite element models. Typical seismic demands outputs are shown in Fig 5. The calculated seismic demands are subsequently compared with FEMA (HAZUS 2003) [7] thresholds to determine the global performance level of the building to the applied earthquakes (whether it is going to have none, slight, moderate, extensive or complete damage states). Calculated demands can be compared with the FEMA P-58 [8] to quantify the component-level damage severity, repair time and expected repair costs.

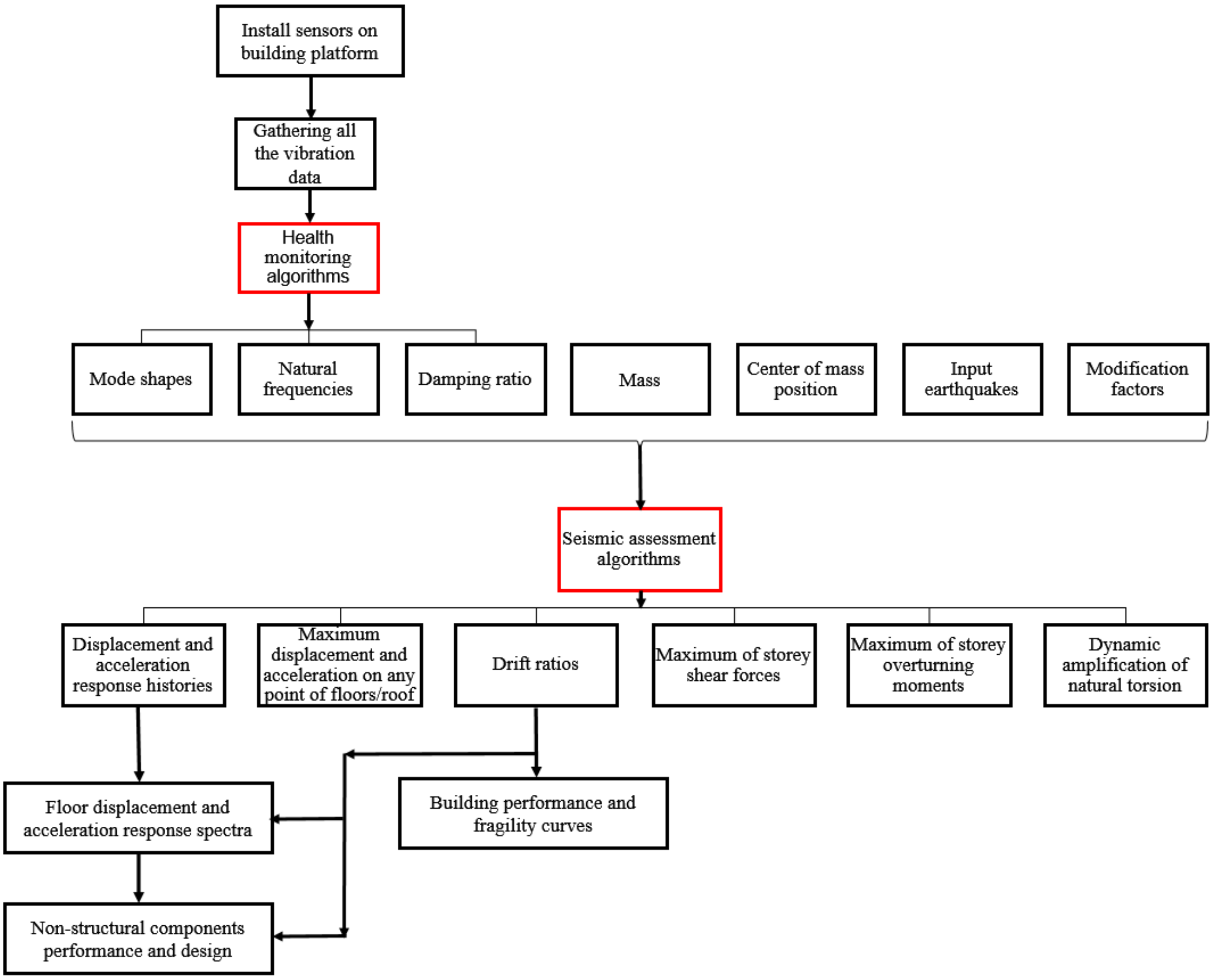

Fig 4. The patented 3D-SAM technology.

This approach is particularly useful and robust for large-scale building evaluation. In additional to deriving the building baselines, their seismic vulnerability would be predicted solely based on the vibration data without a need for detailed drawings or finite element models. For instance, Fig. 6 shows application of the 3D-SAM methodology on 16 buildings all across Canada. Such an information will help asset owners to triage the buildings and optimized their budget expenditures.

Results generated by this technology are experimental and directly based on the sensing test which can be used to calibrate finite element models to increase their reliability. It is also possible to design sectional condition assessment tests based on ambient vibrations to evaluate a building integrity, in-plane and out-of-plane floor flexibility, confirm behavior of expansion joins, as well as many other tests. The 3D-SAM methodology should be used as an initial seismic evaluation tool. For buildings that are predicted to have more severe damages or important one that are in need for nonlinear time history analysis the finite element model as shown in Fig 7 should be calibrated with the sensing results. It has been shown in the literature that a finite element without calibration can not accurately predict the seismic damages [9].

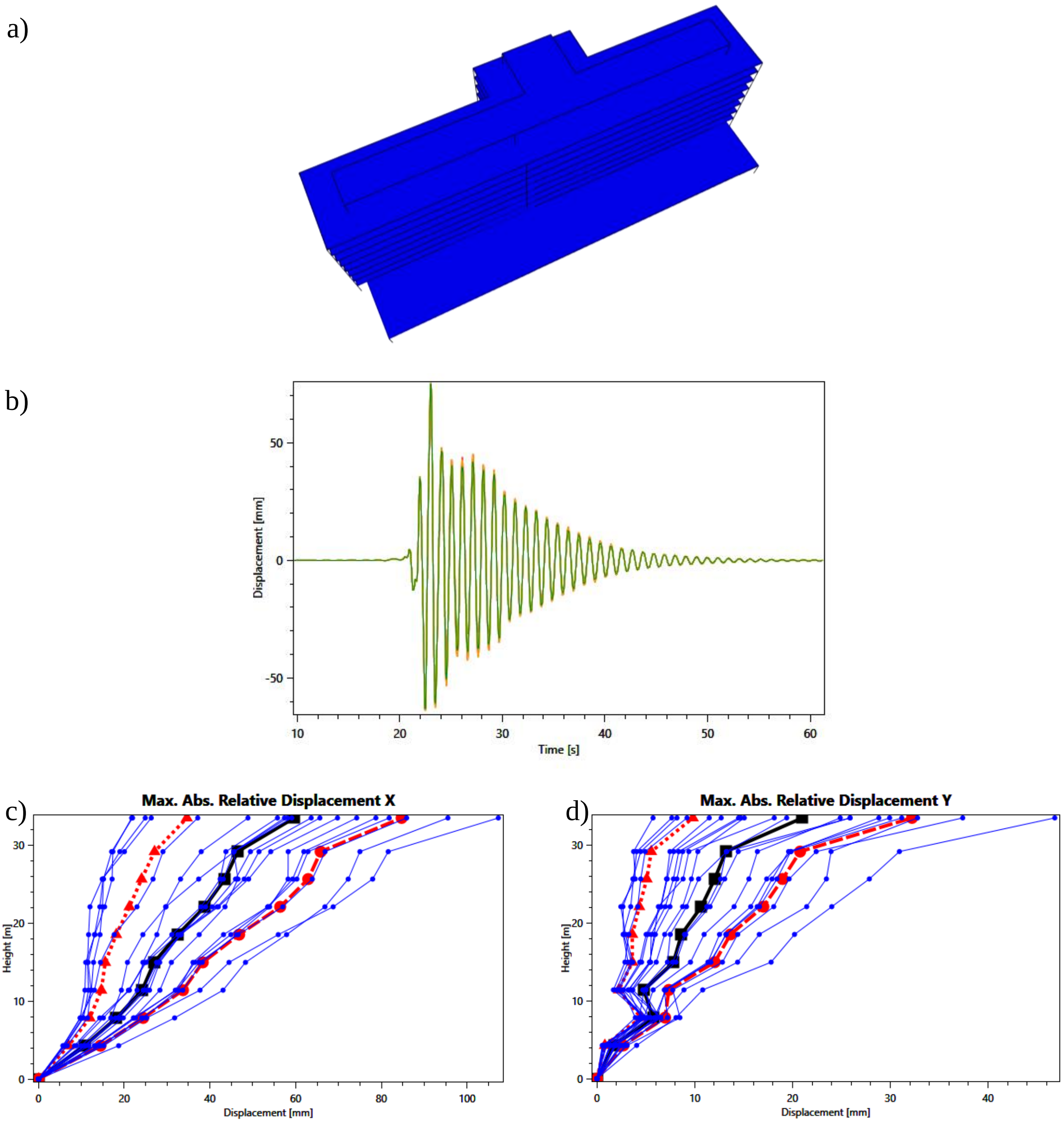

Fig 5. a) Building 3D-model in the 3D-SAM software for seismic assessment; b) Relative displacement time histories of all the corner joints on the bottom roof with respect to the ground when building is subjected to a particular earthquake; c & d) Maximum of absolute values (modulus) of different seismic demands for the 20 applied earthquakes.

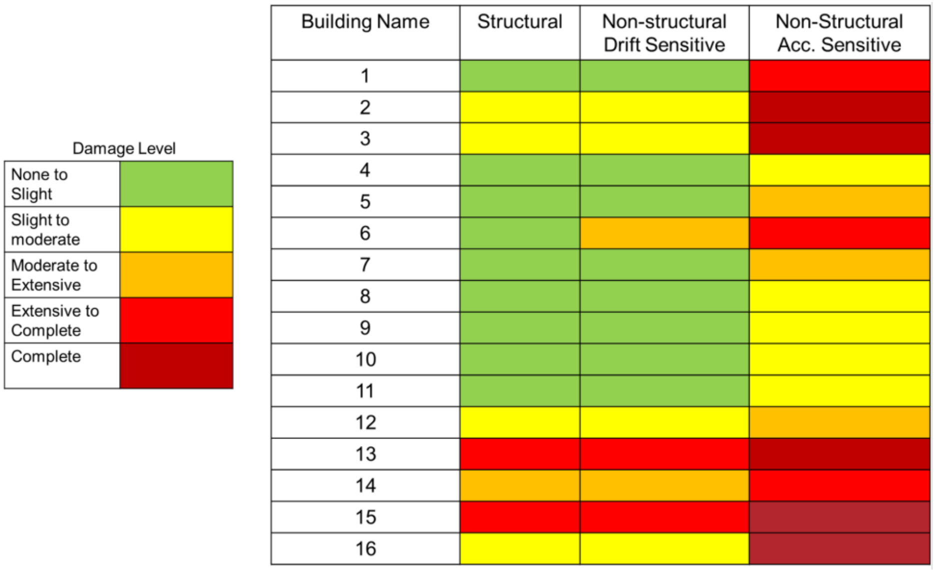

Fig 6. Large scale seismic evaluation using the vibration-based 3D-SAM technology.

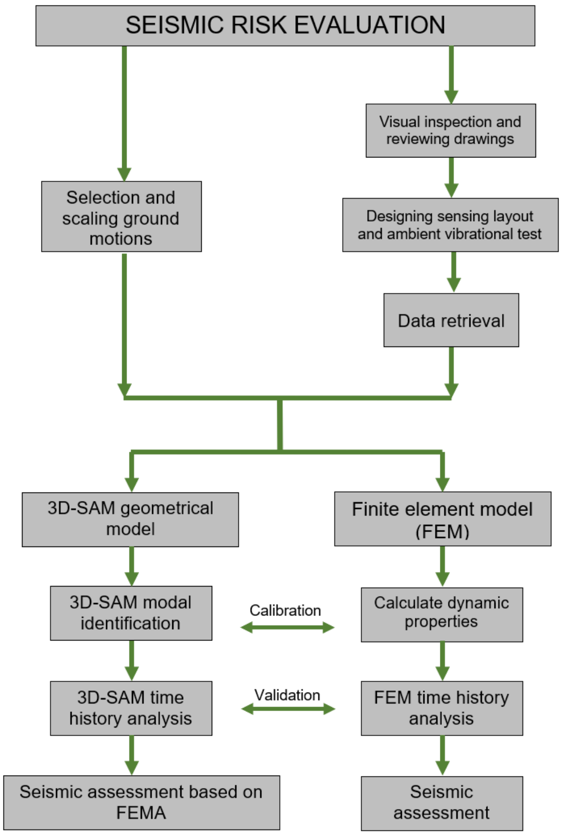

Fig 7. Large scale seismic evaluation using the vibration-based the 3D-SAM technology.

Finally, it is recommended to derive a detailed baseline with several sensors per floor for new buildings right after the construction is finished. The detailed baselining should be repeated every few months/years (more tests lead to a more accurate structural evaluation). In case of an existing retrofit project, an initial detailed baseline (having several sensors per floor) should be completed before starting the retrofit and a new baseline needs to be created after the construction. Baselines need to be compared using the Modal Assurance Criteria (MAC) and the mode shape curvatures and any changes should be reported to the building owner.

After a major event that raises concerns regarding the safety of the building and its occupants, a detailed baseline needs to be created and compared with the database of baselines to quickly evaluate building risk and its damage state.

Moreover, the baselining system can perform seismic evaluation directly based on the modal characteristics without the need for creating finite element models. Therefore, after an earthquake, the system is capable of performing seismic time history analysis to evaluate the building seismic risk to probable future events. This seismic evaluation report as well as the damage detection analysis will provide the building owner with information to decide whether building operations can continue as normal or if the building is in a need of a retrofit. If the results show that the building requires a retrofit, the results will be provided to engineers to perform a detailed seismic evaluation and to calibrate their theoretical models based on the baseline tests to design a reliable and cost-efficient retrofit scheme.

The 3D-SAM sensing technology has been used on many landmark structures in Canada such as Canada’s parliament buildings (Centre Block, East Block and Peace Tower), the historic Connaught building (Canada revenue agency office) and the Supreme Court of Canada.

3. Permanent monitoring

A state-of-the-art permanent monitoring solution installs vibration sensors at locations on the building determined based on the initial building baseline. The permanent monitoring system needs to be optimized in terms of both cost and performance and will be installed during the final phase or after the building construction. The main features of such a system are:

- Sensors
  - Low-noise channels to measure very small ambient vibrations and accelerometers to measure large ground motions
  - synchronization with a precision better than 1 ms, required to achieve quality mode shapes
  - Back-up battery in case of power failure
  - Data transfer to a secure cloud

- Software:
  - Detecting events and issuing alerts through text messages or emails
  - Saving important events. Methods like STA/LTA could be employed to detect an event and reduce possibility of false alarms [10].
  - Periodic recording of ambient vibration data
  - Tracking the first 3 natural frequencies over time
  - Inter-storey drift ratios are computed and compared to Hazus and/or FEMA damage thresholds

- An online dashboard to visualize the vibration records in the time domain and in the frequency domain

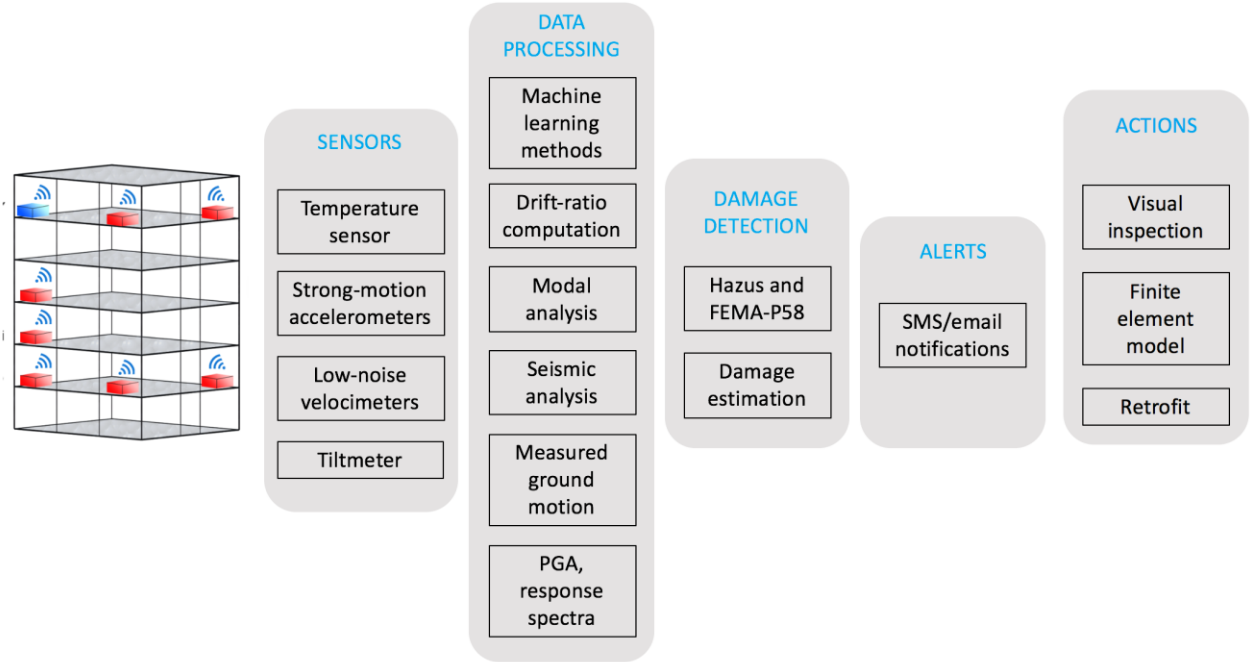

Fig 8. An advanced permanent monitoring system for civil structures.

Fig. 8 shows the different elements needed to build an advanced monitoring system. Ambient vibration data is gathered periodically over the lifetime of the structure. Strong-motion sensors are triggered by important events, such as earthquakes, and record ground motions. The sensors could be wired to a central gateway using serial communications such as RS-485, establish wireless connections to the gateway, or upload data directly to the cloud. Recent developments in radio networks, such as Zigbee, LORA, LTE CAT-M1 or Wi-Fi provide multiple solutions depending on the project requirements. Once data is received on the gateway or on a cloud server, it is time to extract useful information out of raw vibrations. Ambient vibration records are used to derive the modal properties, which are unique to the structure and do not change over its lifetime. Therefore, tracking the natural frequencies, mode shapes and modal curvatures provides insights into any major structural changes.

Calculating inter-storey drift ratios in real-time during an event and Hazus fragility guidelines provide global damage estimations, while using the more recent FEMA P-58 methods result in fragility assessment for both structural and nonstructural components. The identified damage levels are communicated to building managers via SMS notifications and email reports.

In case the dynamic properties of the structure have changed during the seismic event, a new high-resolution ambient vibration test combined with the 3D-SAM methodology will accurately predict the building behavior to future earthquakes. Results extracted from the monitoring system along with visual inspections are used for decision making. Finite element modeling calibrated by the sensing results and retrofit design are possible actions if the structure has undergone damages.

Measuring other parameters such as temperature or tilt could provide more information about the structure. Machine learning methods could take advantage of different data types to better model the building, find damage sensitive features, and detect anomalies [11].

4. Conclusion

Structural health monitoring systems are gaining popularity because of availability of low-cost sensors, wireless communication methods, cloud platforms, and improved data processing and machine learning algorithms. An advanced SHM system, combined periodic and permanent monitoring systems, such as the combination of Sensequake hardware and software presented in this paper, will help in predictive maintenance of the structures, resulting in more effective retrofits with lower cost. In case of an emergency, damage levels are estimated in real-time and notifications are sent to asset owners to help them in decision making. After the natural hazard vibration-based non-destructive condition assessment methods can be used to evaluate the structure and calibrate the finite element model to design a reliable cost efficient retrofit scheme.

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