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# A LOW-COST MONITORING PLATFORM BASED ON WSN TO ESTIMATE SEISMIC VULNERABILITY LEVEL ON EXISTING STRUCTURES

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## *Abstract*

This paper presents the preliminary results of a proposal to develop and implement analytical and technology tools for estimating the level of vulnerability of existing buildings. The proposed system includes the design and implementation of comprehensive structural monitoring platform based on wireless sensor networks. This platform is a low cost instrument capable of providing necessary information, so that in turn improve and implement the methods of analysis of response and structural damage detection. With the development of the system, we will be able to obtain practical criteria and automated functions, in order to estimate seismic vulnerability of existing buildings.

*Keywords: Vulnerability level, structural health, Wireless Sensor Networks, monitoring platform.*

## 1. Introduction

The disastrous impacts of earthquakes to society (loss of life and property), stresses the important need for global seismic risk mitigating strategies.

One of the preventive strategies to reduce earthquake losses in existing buildings is the use of methods and tools to evaluate their seismic vulnerability. For this purpose, methods for damage detection and structural health monitoring systems based on sensors have been proposed and developed recently. These systems have been mainly focused on structural health monitoring of bridges, tall buildings, dams and critical infrastructure. Most of these systems use wired sensors instead of wireless sensors; and this can be difficult for deployment, especially in hospitals, school and ancient buildings. Another identified problem is related to the difficulty of end users to interpret and analyze information obtained from monitoring. In addition, the investment required to implement and operate these systems in most cases is very high, which limits their use for smaller, but also important buildings, such as hospitals, school buildings, and other public buildings. Indeed, in developing countries it is very difficult to implement these kinds of systems because of their high cost. For this reason, it is important to develop low-cost monitoring systems in order to estimate the structural vulnerability and deploy them on buildings such as schools, hospitals, among others [1]. So, in this paper is presented the SAVER Project, which aims at the development of a low-cost structural health-monitoring platform based on wireless sensor networks to estimate the seismic vulnerability level of buildings. This platform will be able to estimate the structural vulnerability level of existing buildings. This platform has been called as SAVER (Structural Analysis of VulnerabilitiEs of buildings through wiReless sensor networks). The expected results in the SAVER project intend to give the basis for the analysis of buildings and to gather instrumental data that can be useful for decision-making of institutions and users that are responsible for infrastructure and buildings [2]. Furthermore, in this project, we are developing and implementing a new wireless sensor node. It is important to note that this sensor node will be small size and low cost, capable of providing the necessary information to implement methods of vulnerability analysis and therefore, to estimate the seismic vulnerability of buildings, such as hospitals or schools. For the vulnerability analysis, we are proposing the use of instrumental data in order develop a simplified reference system, which will be capable to represent the general structural behavior of the current system. For estimating the seismic response of the simplified reference system we will carry out non-linear structural analysis.

Besides, the SAVER platform will offer several services that will notify users about potential risks of the structure through alarms, email and SMS. Besides, it will have a Web based monitoring platform and a mobile app for Android and I-Phone. Also, this platform will generate graphs, reports and statistics.

This paper is organized as follows. In Chapter 2, we briefly describe the related work. Chapter 3 presents the SAVER web-based monitoring platform. Chapter 4 presents a detailed description of the structural vulnerability module as well as the description for its implementation. Chapter 5 presents briefly the SAVER sensor Node. The modeling and deployment of an application example of the SAVER project is presented in Chapter 6. Finally, Chapter 7 provides some conclusions and future work perspectives.

## 2. Related Works

Structural health monitoring (SHM) systems are emerging tools to help engineers improve the safety and maintainability of critical and conventional structures. SHM combines a variety of sensing technologies with an embedded measurement controller to capture, log, and analyze real-time data. SHM systems are designed to reliably monitor and test the health and performance of structures. Most of the existing solutions of SHM systems around the world employ movement sensing devices, like accelerometers, but the majority of them use wired networks. In addition, most of them are used for detecting only one parameter correlated with the damage level and this is typically the inter-story drift. This parameter is enough to evaluate the performance given the occurrence of an earthquake; it means that is useful for evaluating the post-earthquake condition. But the problem rises when we need to evaluate the performance or vulnerability condition before an earthquake, in this case we need more information and the drift is not enough, because we also need to generate a model and obtaining the non linear response for the structural system.

On the other hand, in the literature we can find some studies that apply WSNs (Wireless Sensor Networks) for structural health monitoring. Among these, we find the work of [3]. In this project Mica2 motes [4] are used to determine the structural health of the Golden Gate Bridge located in San Francisco CA. Other works are focused on the structural health monitoring of offshore wind turbines [5]. However, most studies are oriented to the monitoring of large structures, i.e. bridges [6], [7], dams, etc. This allows us to claim that even today there are few efforts to monitor and determining the structural vulnerability of buildings. Furthermore, many of the existing systems are focused on determining the health status of the buildings during an earthquake event with considerable intensity. So, these systems are very useful for a post-seismic evaluation conditions, security and stability. Given the great advantages of having a structural monitoring system to determine some dynamic properties that have strong correlation with the structural responses, it is necessary to make efforts for the development of such systems.

The use of WSNs have brought several advantages in structural monitoring and the establishment of structural health compared to conventional methods where computers connected to accelerometers are used. In conventional methods, it is necessary to install cables through the structure, disturbing its normal operation and generating maintenance cost. Other disadvantages are low efficiency, high cost, inflexibility and disturbance. Another problem is the high equipment and wiring installation and maintenance cost. Compared with conventional methods, WSNs provide the same functionality at a much lower price and a more flexible monitoring. Other advantages are high efficiency, flexibility, reliability and scalability. WSNs are not easy to be disturbed by operation equipment and can facilitate efficient distributed data processing and real time damage detection [7].

The cost of a conventional system with a computer and a force balanced accelerometer is about USD 20000 per sampling point. The estimated cost of the proposed system, in this work is less than USD 200 per point. In WSNs no wiring is required, making installation and maintenance much easier and inexpensive. Moreover, the use of WSNs allows SAVER platform to be deployed and operate even if the building is in operation. It does not cause further visual impact due to its small size, low power consumption and installation flexibility. The advantage of structural health monitoring based on WSNs can be extended if the MEMS acceleration sensor type is used. The MEMS accelerometer is a silicon chip, which is very compact in size, low power consumption and cheap. Without MEMS, a small WSN, even low-power and low-cost accelerometer, would be degraded.

Thus, the SAVER platform will aim at gathering information to establish the structural vulnerability level of buildings. Such information will be used in decision making for two schemes, for prevention programs and for post-seismic evaluation. As mentioned before, knowing the structural vulnerability or seismic risk level of a specific building could be useful for the owner, because he or she can implement retrofit strategies on the building in order to recover its structural health condition and avoiding possible collapse, structural damage or injuries from users in case of a future earthquake.

The SAVER platform will be able to monitor and display information in real-time. It will determine, from the implementation of several methods, seismic response and damage detection as well as the level of structural vulnerability of buildings. A complete description of SAVER project's architecture can be found in [8].

## 3. Web based WSN Monitoring Platform

The SAVER Web-based platform will aim at gathering information to establish the vulnerability level of buildings. Such information will be used in decision making for both schemes and prevention programs, and for post-seismic evaluation. The SAVER Web-based platform will be able to monitor and display information in real-time. It will determine from the implementation of several methods for estimating seismic response and damage detection, the level of structural vulnerability of buildings. In addition, our platform will offer several services that will notify users about potential risks of the structure through alarms, email and SMS. Besides, it will have a Web based monitoring platform and a mobile app for Android and IOS. Also, this platform will generate graphs, reports and statistics. Some preliminary results of the SAVER project was publish in [8]. The SAVER web-based platform provides a building's structural vulnerability analysis, generating statistics, reports and graphics of the records of the different sensors inside each building, the reports provide information like the power supply and the time capture of each parameter. This platform is available on http://saver-buildings.com/

The preliminary results of the project SAVER are presented in this section. These results principally involve the assembly, setup and configuration of a wireless sensor network including the sensor node. The details of the results obtained so far are described in the following sections.

The SAVER web-based platform allows real-time monitoring with graphics of the Acceleration Sensor parameters and the Temperature and Humidity Sensor records in accordance to the different location of the sensors into the building; they also show their power supply and the time capture of each parameter. For proper operation, nine main tables are handled, which have the necessary information to control the sensors parameters: *Building, sensorAcceleration, sensorTempHum, Node, Cluster, Seism, accelerationAmplitude, User* and *Scenarios.*

For each building, we can store: i) geometry and dimensions; ii) number of floors; iii) occupants and basements; iv) foundation type; v) structural elements in "longitudinal" axis and "transversal" axis; vi) floor and ceiling system, vii) plan and elevation irregularities, viii) building use; ix) blueprints per floor, in which the location of each node is shown; and, x) Clusters, where a cluster is composed by a set of nodes. It is important to note that a building can be cover by one or more clusters. Each node contains four kinds of sensors: one of them is an Acceleration Sensor which records three-axial acceleration movement (longitudinal, transversal and vertical), Temperature, Humidity Sensors that record the ambient temperature and humidity, respectively, and a GPS sensor. All this data are used to establish when an earthquake occurs by overcoming the condition of an acceleration threshold and after this happen, we store the date, time, maximum amplitude, the acceleration and frequency amplitude for each axis, both of them used to calculate the Fourier spectrum in terms of frequency (Figure 1).

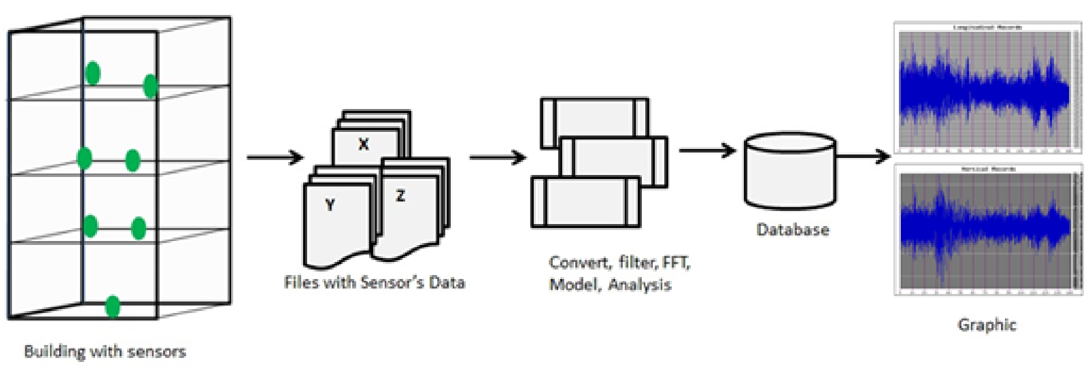



Fig. 1 – Flow of the process

The "Home" section (Figure 2) includes a brief description of the project, while the "Building" section is able to display the plans and basic information of each building (Figure 3). The "WSN" (Wireless Sensor Network) section shows the topology of the network, its description and real-time location of each sensor inside the building. The "SVS" (Structural Vulnerability System) section will provide the generation of vulnerability reports, in order to consult the building's structural health and establish its possible rehabilitation strategies. As an example, Figure 4 shows the graphs of the longitudinal, transverse and vertical records captured each 0.005 seconds at UPAEP High School.

Fig. 2 – SAVER web-based platform homepage

Fig. 3 – Section "Building"

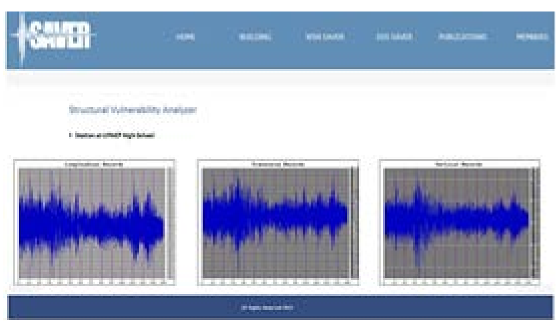


Fig. 4 – Section "SVS"

## 4. Structural Vulnerability Module

In the problem to establish the seismic risk for existing buildings we need to consider at least two components, the structural vulnerability and the seismic hazard level at the site where the building is built. In this context our approach considers the possibility to take into account both of them. But in the following paragraphs we only describe the general criteria to estimate the structural vulnerability module.

To evaluate the structural vulnerability we can use a diagram as the shown in Figure 5. This procedure was originally proposed by [8] and shows the process to establish the structural vulnerability level. The structural vulnerability level will be associated with a damage level. The damage level can be estimated using a damage function defined as:

$$d(u) = 1 - \exp(-au^m) \quad (1)$$

In this equation, *a* and *m* are parameters to be determined according with the structural system features (for example if the structural system includes frames, walls or a combination of this sub-systems); *u* is the local deformation of interest, normalized with respect to its peak value at failure (total loss). The damage function for the structural system is obtained as function of the corresponding interstory distortion (drift). In this way the parameter *u* is related to the lateral displacement. The damage function is continuous, for that reason the damage levels are given by an interval of values. The lateral displacement *u* can be determined considering two criteria: 1) using actual seismic records; and 2) using ambient vibration records.

The first approach is direct, because we use the record acceleration time history on different floors along the building. A double integration of the acceleration time-history can be used in order to obtain the response displacement. For this is necessary to apply a numerical procedure for integrating the corrected and filtered acceleration time-history, assuming that it has a linear variation between each time increment. For the velocity time-history this procedure is repeated in order to estimate the displacement time-history. The maximum interstory average distortion can be determined by the following expression [9]:

$$\varphi_{\max j} = \left| \frac{u_{j+1}(t) - u_j(t)}{h_{j+1} - h_j} \right| \quad (2)$$

Where $\varphi_{\text{maxj}}$ is the maximum interstory distortion, $u_{\text{j}}(t)$ is the lateral displacement at level "j" for a time *t*, and $h_{\text{j}}$ is the vertical distance between each level. Previous studies [10] have shown that values of this parameter in several structural systems and non-structural elements, subjected to different stress level, may represent an acceptable damage indicator of the structure.

The second approach, based on ambient vibration records, considers several steps that are described in the follow. First, it is necessary to synchronize the signals with a common time reference and carry out the polarization procedure according to the sensor´s orientation and the reference system. The baseline correction of the original records also is needed. In order to eliminate the undesirable components of frequency a signal filtering procedure is recommended for this we can use a Butterworth filter. For the ambient vibration records in three directions we can apply the Fast Fourier Transform (FFT), in order to obtain the Amplitude Fourier Spectra. With this information we can estimate the transfer functions, as well as the vibration periods and mode shapes. The vibration period and the mode shapes can be used for generating a Simplified Reference System (SRS) using the criteria proposed by [11]. The SRS has dynamic properties that represent the behavior of the building, however is necessary introduce the corresponding transform response factors. These factors are also defined in [11]. In order to obtain the non-linear response of the SRS, in terms of lateral displacement, an adequate hysteretic model will be adopted. The non-linear responses can be related with a specified seismic scenario. In Figure 5 we present the activities to estimate the vulnerability structural level using the second approach.

Details related to the scientific basis and methodologies to be used for estimating the structural vulnerability level, applied in school buildings, are presented in a complementary work presented by the second author [12].

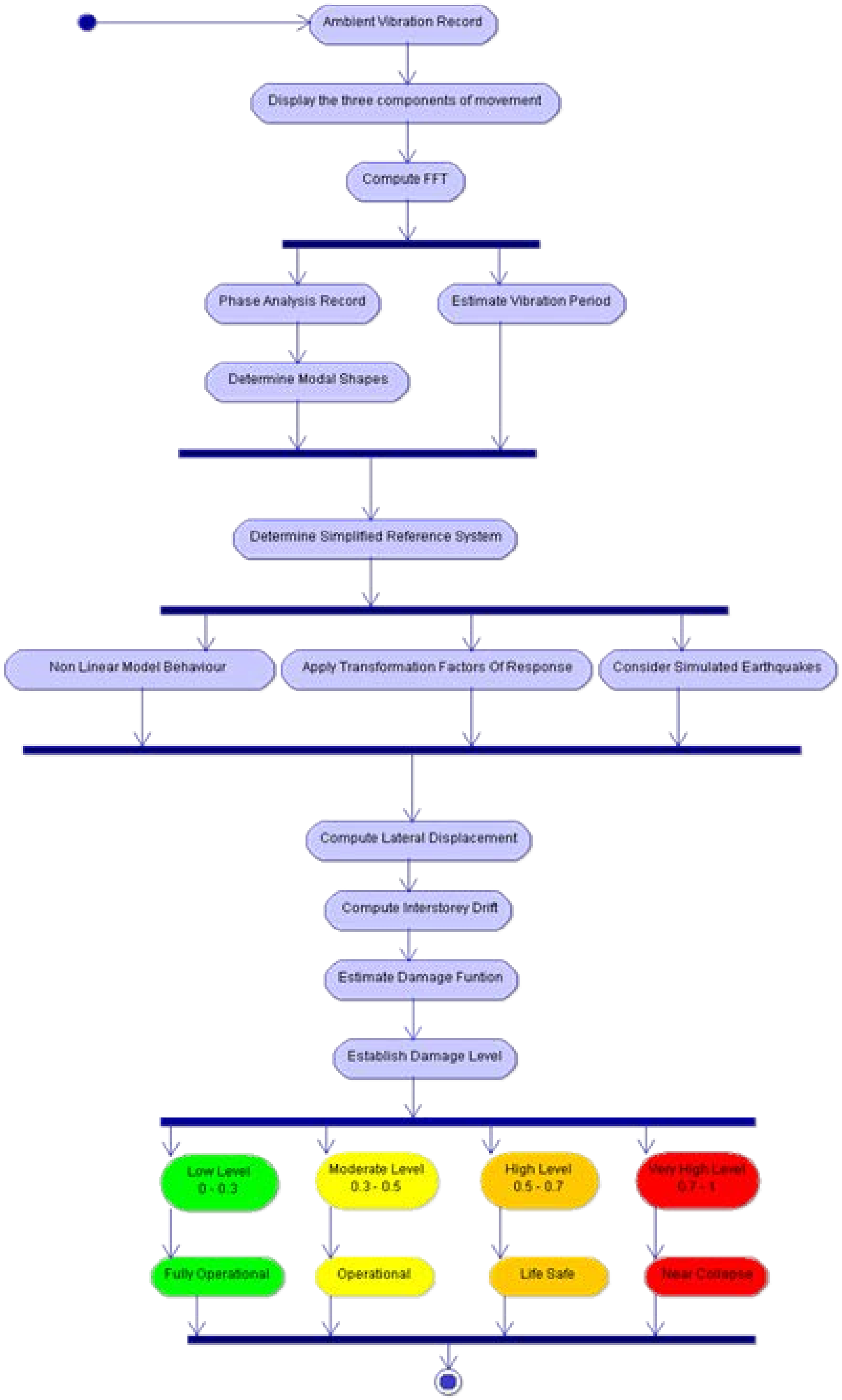



Fig. 5 – Activities diagram to evaluate the Structural Vulnerability Level

## 5. SAVER Sensor Node

The SAVER wireless sensor network bases its functionality in different electronic elements comprising of sensors, combining embedded system and wireless communication to transmit/receive data acquisition. In turn, these elements are arranged in nodes to form specific function components in the network: Sensor Node, Router and Coordinator, the latter being common for all network components.

The network's infrastructure will consist of the installation of sensor nodes at strategic points determined by specialists in seismic instrumentation. Sensor nodes send data to a coordinator using the Zigbee protocol in a frequency of 2.4 Ghz. Coordinator will concentrate data from a cluster of sensors. Besides, a mesh network protocol, based on DigiMesh, will seek the fastest way to send data to the main hub, which will have a GPRS connection for uploading data. The Internet speed will be according to the connection available in the location. Each sensor has a SD memory of 8GB. In this memory, each sensor node will save its information in ASCII files. The complete WSN will be installed in a building during a week. At the end of this period the amount of data stored in the memory will be a maximum size of 5Gb. We measured the data loss rate during the storage process. Sensors send their data to a coordinator through the mesh network that is mounted with Xbee. This allows us to send the data from the sensors to the coordinator. Each coordinator is a GPRS (General Packet Radio Service) module (Figure 6) that will transmit data to Ethernet network.


Fig. 6 – Coordinator with a GPRS protocol

The sensor node prototype (Figure 7) is composed of a accelerometer (+ -2g), a magnetometer (+ - 1.3 + - 8.1 to gauss), a barometer pressure and temperature sensor (ranging from -40 to 85 ° C, in a range of 300- 1000 hPa and a resolution of 0.17m), a gyroscope (scale + -250 degrees per second) and a clock. Each node is identified by an unique node code (Sn) and synchronized by the exact local time.

Data acquisition sensors will be processed or acquired by a mbed LPC1768 card based on ARM architecture with 96MHz, 32KB RAM and 512KB of Flash memory. Powered by a source of 5 to 9 Volts, the communication protocol between the card and the sensor is an I2C.

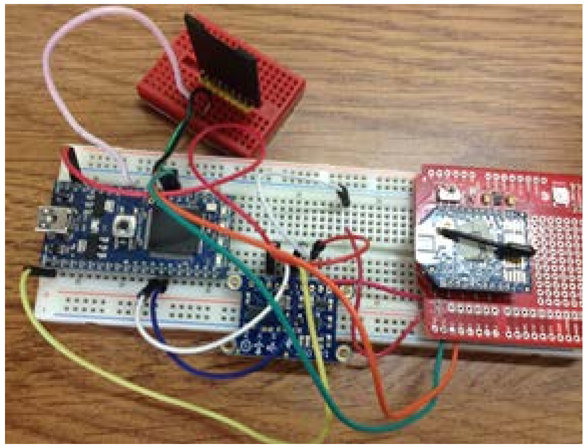


Fig. 7 – SAVER Sensor Node prototype

Free Digi software, XCTU [13] is used to configure the radio devices in order to *talk* in the same network. In the test presented herein devices are in factory defaults. The mesh network is presented in Figure 8.

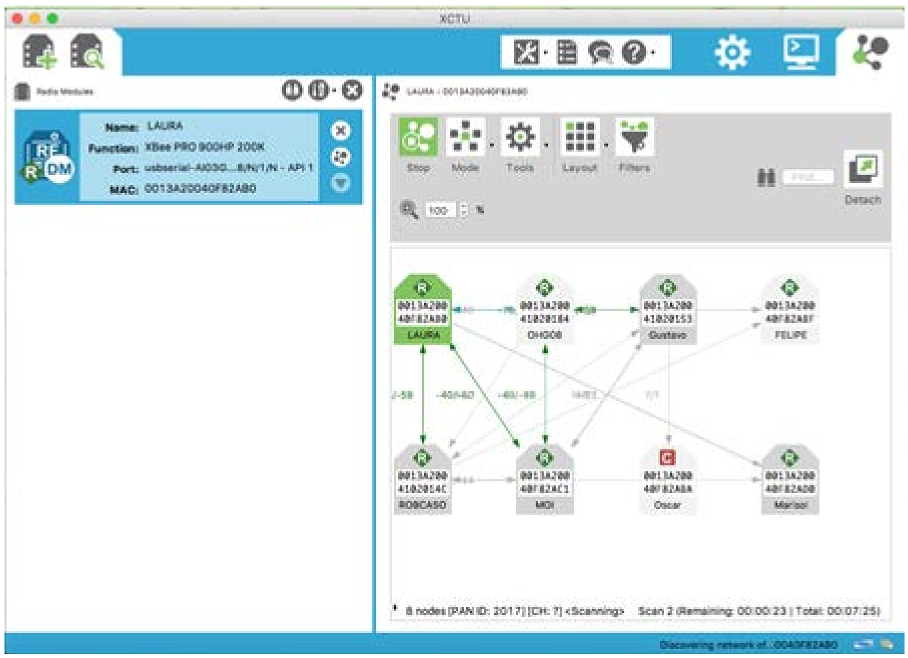



Fig. 8 – Mesh network with 8 Sensor Nodes.

Once the connection is established, XCTU allows monitoring the packages sent and received from the selected node. The API packets can also be shown with details of the frames. XCTU [13] results in a valuable tool for configure and monitor a working network. It also allows studying the devices wireless propagation for optimizing a network.

## 6. WSN Deployment in a Building

In this project we pretend to provide the necessary information to implement methods of vulnerability analysis on buildings such as hospitals or schools.

SAVER project will be validated in the building T (Figure 9) of UPAEP University. The building T is located in the Central Campus of UPAEP University, Puebla City Mexico, and was built in 2007. In plan the building has rectangular geometry which dimensions are 24 x 35 m. The building has six levels with a height of 3.15 m each one; the total height is around 19 m. The building has not regular configuration in plan and elevation; because it presents openings and overturning along its height. The using of the building is mixed. There are two restaurants; twelve lecture rooms; a computer room; three meeting rooms; several office areas and twelve classrooms.

The structural system is based on steel resisting-moment frames (columns and beams). Some columns have circular cross sections and the other have squared cross section. The beams are based on W standard shapes. The floor systems are based on thin composite steel-concrete with 0.12 m thickness. The non-structural elements (internal walls) are based on drywalls with 0.10 m thickness. The external walls are based on masonry with 0.15 m thickness. The predominant material on the facade is glass.

We are planning to install 14 sensor nodes, each one with a temperature and humidity sensor, a triaxial acceleration sensor and a gyroscope (see Section 5). The spatial distribution of the sensors is established from the geometry of each building. But it is necessary to deploy each node at least one in the geometric center of each level, and one sensor on the corner of the roof. If the longitudinal dimension of the building is large, it is suggested deploy some sensors in one border of the building. It is important also monitor the ground response using a free field sensor. The influence of the number of sensors on the building can be explored and it is part of the implementation of our WSN. On the other hand, there is not a specific criterion for establishing a minimum number of sensors on buildings, but it is clear that this number must be established according to the cost and the desirable approximation level in the final results. In general, few sensors increase the uncertainty in the computation process. In order to overcome these problems, more routers will be placed and radios will be equipped of an omnidirectional antenna. Besides, we will improve fade margin through coding gain and we will use a retransmissions protocol for blocks of code. Figure 10 shows a view of the WSN in building T.

Fig. 9 – Building T at the UPAEP University

Some results of modal analysis from building T are described below. Ambient vibration records in three points were obtained on the building, P01 and P02 which correspond to the geometric centroid and the corner at the roof of the building, respectively; P03 corresponds to the geometric centroid at the ground floor of the building. For each point four records were taken considering 15 minutes. A triaxial accelerometer (Kinemetrics Basalt Accelerometer) was used as instrument for obtaining the records. Frequencies and periods were determined for the first three modes: longitudinal (L), transversal (T) and rotational (R). For this the Amplitude Fourier Spectrum (AFS) for each record was obtained, in this way, the horizontal components of the movement (longitudinal and transversal) are only considered for computing the spectral ratios. The procedure for each of the mode is described below. Longitudinal mode (L), the numerator corresponds to the AFS in the longitudinal component obtained in the geometrical centroid at the roof level, and the denominator corresponds to the AFS in the longitudinal component obtained in the geometrical centroid at the ground floor. A similar procedure was used for transversal and rotational modes. Figure 11 shows the spectral ratios estimated for the building using ambient vibration.

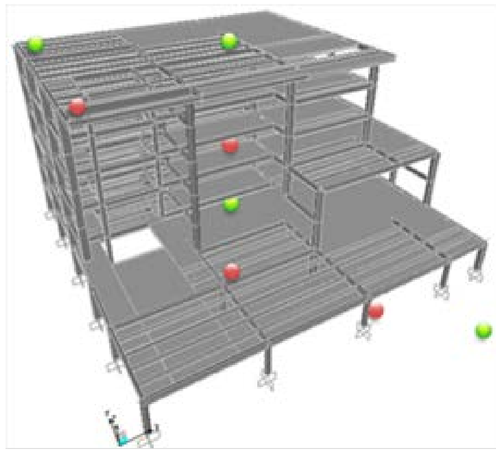
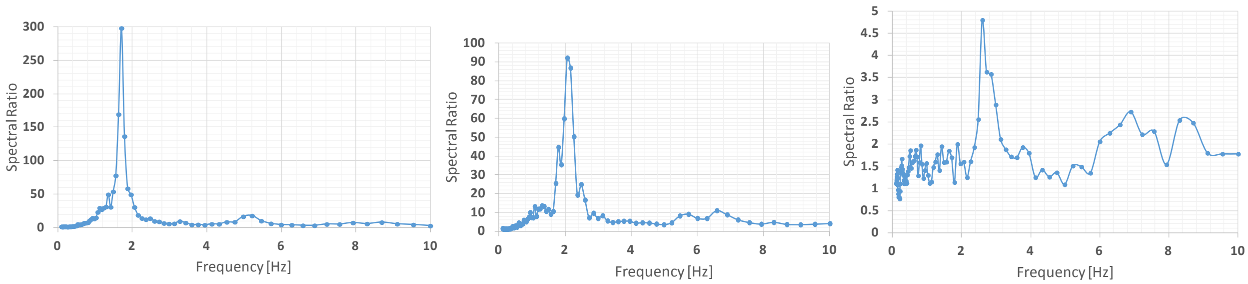


Fig. 10 – Lateral view of the WSN in the building T.




a) b) c)

Fig. 11. Spectral ratios estimated for the building using ambient vibration; a) Longitudinal mode, b) Transversal mode, and c) Rotational mode

## 7. Conclusions and Future Works

This paper presents the SAVER project. This multidisciplinary project proposes a monitoring platform that aims at estimating the structural vulnerability level of buildings through wireless sensor networks. This platform will offer a low-cost technology for monitoring and determining the structural health of buildings. The preliminary results of SAVER project, that have been obtained so far, were presented. In particular: i) the SAVER architecture; ii) the sensor node; iii) Web platform; and; iv) the structural vulnerabilities analyzer module. This project provides two main advantages comparing to commercial solutions: i) a low-cost, not intrusive, and flexible monitoring system; and; ii) a platform to estimate the structural vulnerability level. This has a paramount importance since, this platform will provide useful tools and information to increase knowledge and reduce uncertainty about the buildings' performance and behavior to seismic events. Thus, with this platform we can mitigate seismic risk in them.

Finally, the following steps (in short-term) of this research that are intended to carry out are:

- Test MBed boards to compare manageability with the sensors;
- Compare and implement different accelerometers sensors and test humidity in locations where SAVER nodes will be located;
- Implement SAVER sensor network and test under worst-case scenario conditions;
- In relation to the Structural Vulnerabilities Analyzer module is intended to extend its functionality and implement the transfer functions between the sensor nodes. Likewise, we intend to implement the remaining modules SAVER platform. Develop and implement the models using simplified reference systems.

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