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An Efficient and Reliable Structural Health Monitoring System for Buildings after Earthquake

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Abstract

Occupation of buildings of high importance like hospitals and shelters after earthquake is a risky yet vital task for rescue workers. This paper presents a structural health monitoring system to ensure the safety and reliability of the buildings after earth quack. It is understood that ground motion and lateral displacement due to earthquack may cause deformation and thus excessive strain and stress at the main structural elements. Therefore, the building may suddenly goes to failure, requiring a reliable yet efficient health monitoring system. An array of piezoelectric sensors is mounted at desired location to measure the deformation and stress at critical points. The voltage generated by piezoelectric sensors is sent to computer via a data acquisition system. Measuring and monitoring the trend of changing sensors voltages indicate the probability of existing damages and the rate of propagation. The performance-based seismic is reported based on the nonlinear static analysis (pushover) under the influence of the lateral loading and structural behaviour through the Sap2000® software and FEMA356. The proposed model is verified for a three-story steel structure building. The effects of the lateral displacement caused by earthquake forces on strain and sensors voltage are investigated for each main element in each floor. Increasing the strain and displacements at selected elements increases the voltage generated at piezoelectric sensors. Continuous monitoring and analysis of generated signals helps the building manager to apply warning alarm or call for evacuation of the building.

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Keywords: Earthquake, Building, Structural, Health monitoring

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1. Introduction

The important buildings such as hospitals, military bases and emergency shelters should meet the requirement of safety, reliability and serviceability when subjected to natural disasters, such as earthquakes and strong winds. The structural health monitoring (SHM) technology provides a way to evaluate the safety and durability of a structure during and after earthquake to ensure its serviceability and sustainability.

The SHM system consists of sensors, data acquisition and transmission systems, database for effective data management and health diagnosis including, damage detection, safety evaluation and reliability analysis. Farrar and Worden [1] provided a recent survey on structural health monitoring for civil applications. Park and Inman [2] investigated the use of piezoelectric sensors for damage detection of building based on impedance measurements. Recently Ou and Li [3] reviewed the application of SHM for building in China. Atashipour *et al*. [4] investigated the use of guided wave to detect the presence of damage in thick steel beams.

In the present work a SHM system is developed to ensure the safety and reliability of a hospital building during and after an earthquake. Piezoelectric sensors are mounted at desired elements to continuously monitor the deformation, strain and stress at desired elements. Changing the strain and stress at the elements alters the generated voltage at piezoelectric sensors. Measurement and analysis of piezoelectric signals provides an accurate and efficient way to decide on occupation or evacuation the building. A mathematical modeling for a three story building integrated with piezoelectric sensors is considered for numerical study.

2. Mathematical Modeling of the Building

The building is modeled based on the push-over analysis for seismic design. This approach is a computational procedure in which the static-equivalent loading consist of constant gravity loads and monotonically increasing lateral loads, the progressive stiffness/strength degradation of a building framework is monitored at specified performance levels. The multi-degree-of-freedom (MDOF) building structure converted to an equivalent single-degree-of-freedom (SDOF) system. The fundamental mode of vibration of the MDOF system is often selected as the response mode of the equivalent SDOF system. The selected vibration response mode is the basis for estimating the distribution of static-equivalent lateral inertia loads applied over the height of the building [5].

Specified deformation states are often taken as an indicator of the building performance at corresponding load levels. The US Federal Emergency Management Agency (FEMA) [6] identifies operational, immediate-occupancy, life-safety and collapse-prevention performance levels, and adopts roof-level lateral drift at the corresponding load levels as a measure of the associated behavior states of the building. The damage level that buildings experience at the various performance levels is associated with horizontal and ground motion during earthquakes.

The shear force in the lateral direction generated at building due to horizontal ground motion is given by:

$$V = S_a \, \mathrm{W}/g \qquad (1)$$

where g is the gravitational constant, W is the total weight of the building and S_a is the acceleration spectral. The lateral inertia forces F applied at the vertical height of the building is defined as:

$$a)\; F_x = C_{vx}\, V \quad \text{In which} \;\; b)\; C_{vx} = W_x h_x^{k} / \sum W_i h_i^{k} \qquad (2)$$

where F_x is the lateral load applied at story level x, and C_{vx} is the corresponding vertical distribution factor, W_x gravity loads, W_i the portions of the total building weight at story levels x and i, similarly, h_x and h_i indicate the vertical distances and the heights from the base of the building to story levels x and i. The number of stories is given by n; and the value of k depends on the fundamental period of the building.

According to ASCE 7-05 section 12.8.6, the drift control of designed steel moment resisting frame should be performed in

$$\Delta = \frac{C_d}{I}(\delta_{e(i+l)} - \delta_{e(i)}) \le \Delta_a = 0.02h, \frac{(\delta_{e(i+1)} - \delta_{e(i)})}{h} \le \frac{0.02I}{C_d} \qquad (3)$$

where δ is elastic displacement computed under strength-level design earthquake force and C_d is the deflection amplification factor for moment resisting frames.

The target displacement is obtained from the following equation:

$$\delta_t = c_\circ c_1 c_2 c_3 s_a \frac{T_e^2}{4\pi^2} g \qquad (4)$$

where C_0 is the first mode contribution chosen based on number of stories as given in FEMA356 (Table 3-2), C_1 is the system's inelastic displacement correction, C_2 is the coefficient indicating the effect of stiffness reduction upon displacement that is obtained from Table 3-3 in FEMA, C_3 is the post yield stiffness, T_e is effective period and S_a is response spectrum acceleration at the effective fundamental period calculated based on IBC 2003 design response spectrum corresponding to 10% probability of occurrence in 50 years (10% in 50 years). All beam sections in the steel frame satisfy $h/t_w \le 418/\sqrt{F_{ye}}$ and $b_f / 2t_f \le 52/\sqrt{F_{ye}}$; so based on FEMA 356, θ_y is rotation limit for Immediate Occupancy (IO), similarly, $6\theta_y$ limit for Life Safety (LS) and $8\theta_y$ indicates limit for Collapse Prevention (CP) performance levels.

When the value of bending moment in the main structural member increases so that all the fiber crosses reaches the point of yield stress, it leads to the formation of plastic hinge in that location. As this location cannot stand any more moment, so it functions as a hinge against the excessive bending moment. This moment that causes the hinge to be formed is called plastic moment (M_p). At first, plastic hinge in structural elements is usually made near the joints. In this study, the plastic hinge location has been considered at a relative distance of 0.05 from the length of span or height of the main structural elements. Thus, the sensors have been installed in the location with high probability of occurrence of the hinge plastic on the main elements.

Tangential strain components (ε) and shear strain (γ) for a bended beam are computed as:

$$a)\ \varepsilon = (dw/ds - u/R) + 1/2(du/ds + w/R)^2 \qquad b)\ \gamma = du/ds + w/R - \theta \qquad (5)$$

where u, w, θ and R represent, radial displacement, tangential displacement, rotation and radius, respectively. The first term in the equation (5a) correspond to the linear area and the second term indicates the nonlinear performance.

When the target displacement of the structure reaches to the collapse prevention performance level, the value of the strain in the hinge plastic location and in each performance level at nonlinear behavior is determined by equation (5a). When the structure shows linear behavior and before it tends to have nonlinear behavior, the amount of strain applied to the sensor is given by:

$$\varepsilon = \delta L/L \qquad \text{where} \qquad \delta L = z\partial w/\partial x \qquad (6)$$

where Z is the distance from the sensor to the neutral axis of section for each main element, $\partial w/\partial x$ is the value of the variation of the displacement element at bottom of the sensor at distance of x between beginning and the end of the sensor on the element, δL is the variation of the length element below the sensor, L is the length of the sensor and ε_{all} is the allowable strain of the main structural element at the sensor location. The electromechanical relation for a piezoelectric sensor is given by:

$$\{\sigma\}=[C]\{\epsilon\} - [e]T\{E\} \quad b) \quad \{D\} = [e]\{\epsilon\} - [g]\ \{E\} \qquad (7)$$

where $\{\sigma\}_{6\times1}$ presents the stress vector, $\{D\}_{3\times1}$ the electric charge and $\{E\}_{3\times1}$ the electric field, $[C]_{6\times6}$ is the stiffness matrix, $[e]_{6\times3}$ the piezoelectric coupling matrix; the piezoelectric constant *e* relates the stress to the electric field E in the absence of mechanical strain, $\{\epsilon\}_{6\times1}$ the strain field and $[g]_{3\times3}$ the permittivity matrix. In equation (7b), *e* relates the electric charge per unit area D to the strain under a zero electric field (short-circuited electrodes); *e* is expressed in $NV^{-1}m^{-1}$ or Cb/m^2.

It is noted that the stress can be known through measurement of the strain initiated by external force. Neglecting actors and considering only piezoelectric sensors is the system, the voltage obtained for a multi-degree- of freedom system can be determined through displacement measurement U as:

$$\{\Phi\} = -[K_{\Phi\Phi}]^{-1}[K_{\Phi U}]\{U\} \tag{8}$$

In which the displacement due to seismic force is given by:

$$[M]\{\ddot{U}\} + [K_{UU}]\{U\} = \{F\} \tag{9}$$

where *M* is the element mass, K_{UU} is stiffness, $K_{U\Phi}$ is piezoelectric coupling matrix and the second term in the right hand side represents the equivalent piezoelectric loads. For more detail on displacement and voltage measurement one may consult the Ref. [7]

3. Algorithm for Reliability Analysis

The push-over analysis proposed by this study is based on the post-elastic analysis procedure. The structure data describes the dimensions and numbers of bays and stories (*L, h, n,* etc.) and the types of connections and supports (fixed, pinned, etc.) in the building. The member data describes the cross-section properties for the beams, columns and other structural components of the building ($A, E, I, S, Z, m, \sigma_y, \Phi_y, \Phi_p, \Phi_u$, etc.). The load data describes the gravity loads and building weight (*w, W),* as well as the distribution of incremental lateral inertia loads ΔF pre-calculated through Equations.(1), (2b) for arbitrarily small spectral acceleration S_a and prescribed exponent *k* The performance data describes the parameters that quantify the performance levels for the building. The operational performance level is associated with the onset of initial yielding.

The immediate-occupancy, life-safety and collapse-prevention performance levels are associated with the building reaching corresponding target roof-level lateral displacements δ_{IO}, δ_{LS} and δ_{CP} respectively. The gravity loads on the building remain constant for the analysis. The lateral loads are progressively increased through the different performance levels until the lateral displacement at the roof level of the building reaches the target value associated with the collapse-prevention level ($\delta_{roof} = \delta_{CP}$), at which point the pushover analysis terminates[5].

In this study, the lateral load increases until the structure reached to the level of collapse prevention performance and as long as the results are achieved. The voltages generated by the sensors are sent to a PC for further signal processing and decision making.

4. Case study Frame and Analysis

A three-story hospital building modeled in 2-D steel moment resisting frame with three bays is shown in Fig.1. The frame sections are shown in Table 1. The frame is designed for a highly seismic region. The seismic design of frame followed the International Building Code 2003 (IBC, 2003), assuming the frame are located in site class *D* and stiff soil, with mapped spectral accelerations S_2 =1.5 g and S_1 = 0.72g for 5% damping ratio.

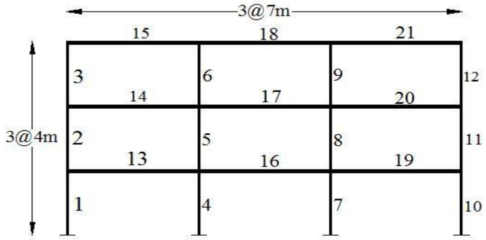

Fig. 1. Frame Configuration

The frame is assigned to seismic group *I* and seismic design category *D*. Columns and beams are designed based on AISC-LRFD (AISC-LRFD 1999). The frame are pre-designed using the program SAP2000 considering that the joints are rigid. The term C_d is assumed to be 4.9. The factor *I* is the importance factor and *h* is the story height for used frame, drift control is presented in Table 1.

Table 1. Frame Sections and Drift Control for Steel Frame

Story/ Section	Beam	INT column	EXT column	Drift	$m = 0.02I/C_d$	Drift $\leq$ m
1 st	IPE 360	IPE 750 ×185	IPE750×161	0.001512	0.004082	O.k.
2 nd	IPE 400	IPE 600	IPE 600	0.003245	0.004082	O.k.
3 rd	IPE 360	IPE 500	IPE 450	0.003380	0.004082	O.k.

4.1 Seismic Performance of the Building

The FEMA 356 is used to assess the seismic performance of the steel moment resisting frame based on the nonlinear static analysis.

Structural performance levels in FEMA 356 include Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP). Structures at IO should have only minor damage. Structures at LS may have sustained significant damage, but still provide an appreciable margin against collapse. Structures at CP are expected to remain standing, but with little margin against collapse. In FEMA 356, the Basic Safely Objective (BSO) is defined as LS performance for the Basic Safety Earthquake I (BSE -1) earthquake hazard level and CP performance for the BSE-2 earthquake hazard level. BSE-1 is defined as the smaller of an event corresponding to 10% probability of occurrence in 50 years (10% in 50 years) and BSE-2 which is the 2% probability of occurrence in 50 years (2% in 50 years) event [8].

According to FEMA 356 two different load distributions patterns should be considered in pushover analysis. In this study the frame considered under both triangular and uniform load pattern. The uniform load pattern results in higher stiffness and capacity in comparison with the triangular distribution as expected. Therefore, the triangular load pattern is considered to evaluate the overall behavior of steel moment resisting frame at LS performance level.

The parameters corresponding in Eq. (4) are determined for the case under study and given in Table 2. The target displacement δ_t of case study steel frame and base shear V_t corresponding to target displacement are also provided in the table.

Table 3 provides displacement of the roof level step by step when Collapse Prevention performance level happens after target displacement at Life Safety performance level ($\delta_{\text{roof}} = \delta_{\text{collapse prevention}} = 0.3749$m). It shows the base force at the displacement in each step.

Table 2. Performance point specifications & yield Strength of steel moment resisting frame ($\delta_{roof} = \delta_{Ls}$)

Frame	C_0	C_1	C_2	C_3	S_a	T_e(s)	δ_t(m)	V_y(KN)*	V_t(KN)**
3 story	1.3	1	1	1	1.25	0.862	0.298	1281.92	1650.94

*yield strength of steel frame
** Base shears corresponding to target displacement

Table 3. Displacement & Base Force of Roof level Step by Step at CP Performance Level

Step	0	1	2	3	4	5	6	7	8	9	10	11
Displacement (m)	0	0.037	0.062	0.102	0.139	0.177	0.219	0.240	0.250	0.288	0.3225	0.3749
Base force (KN)	0	330	553	821	1075	1289	1457	1537	1561	1606	1652	1701

Material properties of the piezoelectric sensors are given in Table 4.

Table 4. Material properties of PVDF sensor

PVDF (Polyvinylidene fluoride)	Young Module (E1)	G_{12}	Density (ρ)	d_{31}	e_{33}	Length	Thickness
	4.6 Gpa	2.66 Gpa	1610	-20×10^{-12} m/V	$1.5\text{x}10^{-10}$ F/m	25 mm	0.1 mm

4.2 Results of the Analysis

For an efficient SHM system, it is required to decrease the number of piezoelectric sensors on the main structural elements. Based on the results of the strain after analysis, the sensors are installed on the most critical main elements on each floor. Fig 2 shows the schematic diagram for the system showing the location of sensors installed at critical main elements. The system provides important information on the structural health of the building. After an earthquake, its near-real-time data analysis capabilities help to rapidly assess the building safety.

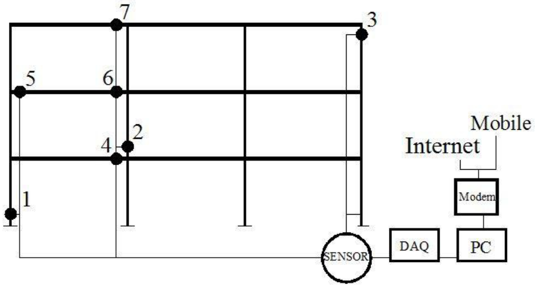

Fig. 2.Schematic diagram for the monitoring system and location sensors

Table 5 provides information for the installed sensors elements in each floor. Table 6 illustrates the amount of allowable strain for linear behavior of the structure and amount of strain in each performance level of the structure for the critical main structural elements in each floor.

According to the range of the voltage of the sensors, Table 7 provides the sensor voltage which indicates the performance level of the building. Due to importance of columns in the structure and considering the data provided in Table 7, when the first, second and third sensors reaches to 5 volts, non-structural elements need to be controlled and repaired. Similarly, if these voltages reach to lower than 8.5 volts the building is in the Safe Zone performance or IO, however, the main elements in the second and third floor need to be closely investigated by technicians.

The evacuation alarm functions when the voltages of the third sensor is greater than 8.5 volts or the second sensor is greater than 9 volts and / or the voltage of the first sensor goes above 22 volts. Similarly, Safe Zone or IO indicates when the voltage for sensors mounted on the beams is between 0.3 and 0.4 volts and warning alarm is activated if this voltage is greater than 0.4.

Tbale 5. Frame Section & Number of Sensors of Critical Main Structural Elements

Section	Column 1 IPE750×161	Column 5 IPE 600	Column 12 IPE 450	Beam 13 IPE 360	Beam 14 IPE 400	Beam 14 IPE 400	Beam 15 IPE 360
Story	Story 1	Story 2	Story 3	Story 1	Story 2	Story 2	Story 3
Location	Down Plastic Hinge	Down Plastic Hinge	Up Plastic Hinge	Right Plastic Hinge	Left Plastic Hinge	Right Plastic Hinge	Right Plastic Hinge
Number of Sensors	1	2	3	4	5	6	7

Table 6. Amount of Strain in the Location of the Installed Sensors

NO. Sensors		1	2	3	4	5	6	7
Linear Behavior	ε_{all} (m)	9.51×10^{-7}	4.51×10^{-7}	2.26×10^{-7}	7.31×10^{-8}	5.58×10^{-8}	6.15×10^{-8}	7.78×10^{-8}
Non-Linear Behavior	ε_{IO} (m)	3.33×10^{-6}	1.21×10^{-6}	9.81×10^{-7}	2.15×10^{-7}	0.62×10^{-7}	8.85×10^{-8}	1.11×10^{-7}
Performance Level	ε_{LS} (m)	4.42×10^{-6}	1.83×10^{-6}	1.69×10^{-6}	-	-	-	-
	ε_{CP} (m)	-	-	1.72×10^{-6}	-	-	-	-

Table 7. Amount of Voltage in each Sensor

NO.Sensors		1	2	3	4	5	6	7
	$E\varepsilon all$ (V)	4.75	2.25	1.13	0.36	0.28	0.31	0.39
Electrical	$E\varepsilon IO$(V)	16.65	6.05	4.9	1.07	0.31	0.44	0.55
Field (V)	$E\varepsilon LS$(V)	22.1	9.15	8.45	-	-	-	-
	$E\varepsilon CP$(V)	-	-	8.6	-	-	-	-

Table 8. Performance level of the Building

No. Sensors	5(V) ≤ E ≤ 8.5(V)	E ≥ 8.5(V)	E ≥ 9(V)	E ≥ 22(V)
1	Safe Zone	Warning Alarm	Warning Alarm	Evacuation Alarm
2	Safe Zone	Warning Alarm	Evacuation Alarm	-
3	Safe Zone	Evacuation Alarm	-	-

5. Conclusion

A 3-story hospital building is considered for design a structural health monitoring system to ensure the safety and reliability of the structure after earthquake. The building is modeled in 2D frame and the strain and displacement are determined using a nonlinear push-over approach. The stains and displacements are then measured using piezoelectric sensors mounted at the desired locations. The voltage generated by the sensors indicates the level of damage, as safe zone, warning alarm and evacuation call. The proposed method may significantly improve the reliability and serviceability of the building with high level of importance such as hospital, military bases and emergency shelter and save lives in natural disasters like earthquake and storms.

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