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Sensors Placement in Airport Traffic Control Towers for Seismic Health Monitoring

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ABSTRACT: In structural health monitoring systems, it is crucial to distinguish what elements and at which locations need to be monitored. In other words we should decide about number of sensors and their locations. The basic philosophy of recent design codes to take into consideration earthquake loads is to design structures in a way that for specific earthquake hazard levels, all elements comply with special target performance levels. In this research sensor placement for seismic health monitoring will be based on this concept. In other words, sensors will be placed at locations where elements have not satisfied required performance levels for the applied seismic hazard levels. The applicability of this approach was examined by applying it to traffic the control tower of Kerman airport.

Introduction

Structural health monitoring (SHM) is a growing area in structural engineering and is widely being employed for different types of structures. Seismic health monitoring can be considered as one of challenging issues in this field because contrary to static loads in buildings or moving loads in bridges, seismic loads have a complex and usually unknown effects on structures. This characteristic of seismic loads donates remarkable place to seismic health monitoring systems. These systems can provide particular information about the safety of structures after an earthquake which is a big concern for the owners of such buildings. Moreover such information can help authorities to reduce post-earthquake hazards. But apart from direct benefits that result from seismic health monitoring there are some concerns about the application of this system. For example required mechanical devices are often expensive and should be selected precisely. One of these equipments that are widely being applied in SHM systems are Sensors. They play significant role in data acquisition systems and as inseparable part of health monitoring system are costly ones. So reduction in the number of used sensors can directly decrease the total cost of the health monitoring systems. Because in addition to their own cost, by decreasing the number of sensors, the volume of uninformative data will be reduced and consequently data processing needs less time and storage of extra data will be decreased.

A few efforts have been done to optimize sensor placement .As one of these studies Liu et al. (2008) used genetic algorithm for optimal sensor placement. They provided an improved genetic algorithm to maximize obtained data information from spatial lattice structures. Received results showed that proposed method could identify the vibration characteristics of 12-bay plain truss model. In another research Flynn &Todd (2009) by working on Bayes risk theory provided a global optimality criterion to minimize error type I and II during damage detection process. From the test results they represented that placement of sensors depends on performance constrains.

Papadimitriou (2004) presented a formula for optimal sensor placement based on the information entropy measure of parameter uncertainty. In that research, two algorithms for prediction of optimal and worst sensors configurations were proposed. Li et al. (2004) studied optimal sensor locations for structural vibration measurements based on uniform design method.

Skjærbæk et al. (1996) used a measured acceleration response time series to localize the damage in seismically excited reinforced concrete structures. They applied their method on a six-story, two-bay frame and tried to find the optimal locations of sensors. They assumed that measurements are performed at top story and ground surface and tried to find the best locations for one or more sensors in between. It was found that generally, placing sensors at lower parts of the structure provides better results.

Xie & Xue (2006) applied hybrid algorithm using improved reduced system and singular value decomposition for obtaining optimal number and locations of sensors for building structural health monitoring.

One shortcoming of the previous studies is that they did not considered importance of structure in the proposed algorithms for sensor placement. In other words in previous studies optimal sensor locations just depends on geometry and mechanical prosperities of structures whereas for seismic health monitoring it is significant to consider not only the importance of structure but also seismicity of the area where structure is located in. Since in this study we are looking for optimal sensor placement for seismic health monitoring systems, in the next section at first concept and methodology of this approach is discussed and then applicability of such method is confirmed by an example.

Concept and Methodology

The basic philosophy of recent design codes for considering earthquake loads is to design structures in a way that for specific earthquake hazard levels, all elements comply with special target performance levels. In this research sensor placement for seismic health monitoring will be based on the same concept. In other words, sensors will be placed at locations where elements have not satisfied required performance levels for the applied seismic hazard levels. By this definition, optimal sensor placement for seismic health monitoring of structures depends on predefined seismic hazard levels and their corresponding performance levels. A direct benefit of such a concept is that number of sensors for seismic health monitoring will increase if we raise seismic performance level or corresponding earthquake hazard level and will decrease if we disrate them. So for sensor installation not only we consider the importance of building but also the seismicity of the area where structure is located in will be taken into account.

By considering aforementioned concept, sensor placement can be a step by step procedure. At first, seismic performance level of structure will be determined. This step clarifies earthquake hazard levels and corresponding target performance levels. It should be noted that selection of appropriate seismic hazard levels and target performance levels depend on several factors and needs comprehensive considerations. In the next step, by applying nonlinear analysis, demand and capacity of each element for predefined target performance levels will be calculated. Then by defining usage ratios, as ratio of demand to capacity, those elements that their usage ratios do not satisfy required seismic performance levels will be selected as elements that have the potential for sensor installation. Finally based on the type of selected elements (beam, column…) and their damage mechanism (bending, shear, torsion…) appropriate sensors will be installed. Figure (1) depicts this procedure.

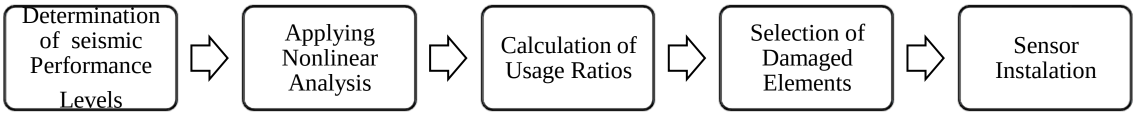


Figure 1. Proposed procedure for sensor installation for seismic health monitoring systems.

ATC Tower Used in this Study

In this study the ATC tower of Kerman International Airport was investigated.Figure2 depicts geometry of the tower. As it can be seen, this tower includes two sections. The first section comprises two concrete shafts which serve as a lateral resistance system to withstand wind and earthquake loads. The total height of this section from foundation level is 26.4m.Thickness of concrete walls at Exterior and Interior shaft is 0.4m and 0.25m respectively. Stairs are located between shafts. Interior shaft serves as a support for lift which travels inside it.

The second section is the place that is occupied by experts and equipment .This section contains steel columns that are connected to each other through steel beams at two different levels. Each Column has box girder cross-section with constant flange thickness of 2.5cm and dimensions of 30x30cm.Columns place on 12 radial concrete beams at level 26.4m and continue up to the level 30.1m, then six columns are cut and the remain continue toward roof level. Concrete beams have a rectangular cross-section with dimensions of 60x30cm. At level 26.4m a 30cm thick slab connects all concrete beams and creates a rigid diaphragm.

Roof comprises 12 radial inclined beams with IPE27 cross section. Twelve I shape girders with height of 35cm surround the roof at level 34m. Flange width and thickness of these beams are 20cm and 2cm respectively.

Besides roof level, columns are connected to each other by six I shape curved beams with height of 30cm at level 30.1m. Flange width and thickness of these beams are 25cm and1.5cm respectively. All beam-column connections are fixed except for deck girders and inclined steel beams.

Figure 2 shows cross-sections of the tower at two different levels. Moreover this figure presents the arrangement of reinforcement, inside cross-sections of the tower. Concrete shafts have a polygonal cross-section. Due to the openings along the height of structure, concrete walls of the exterior shaft are connected to each other via spandrel beams at different levels. All spandrel beams have a rectangular cross-section with dimension of 50x40cm. Table 1 shows rebar ratios along the height of concrete shafts.

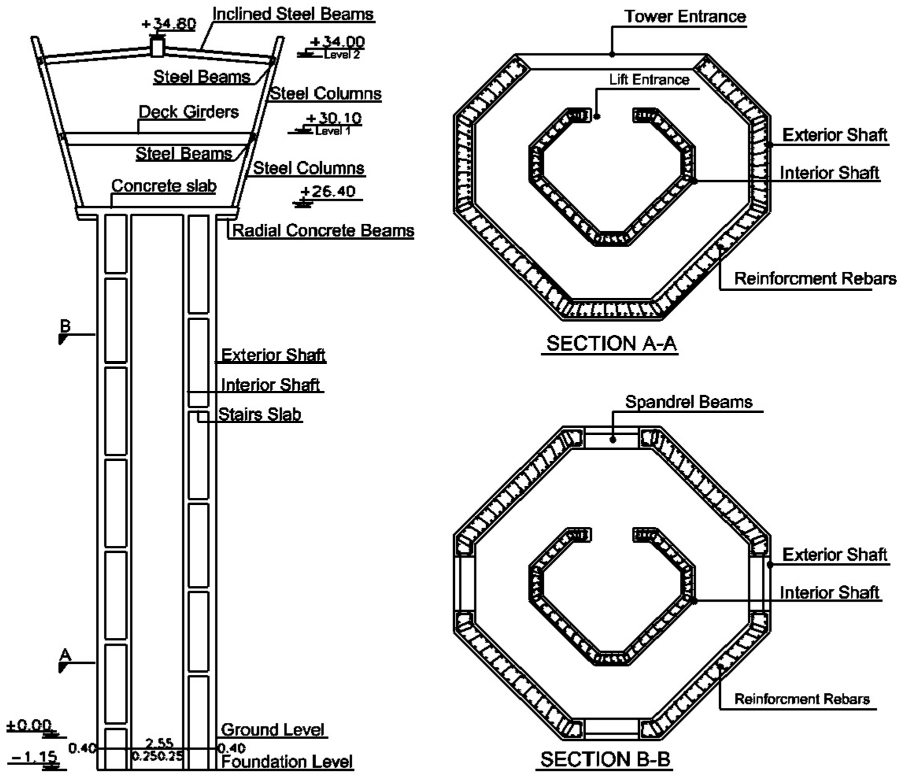


Figure 2. Longitudinal and cross-sections of Kerman ATC tower.

Table 1. Rebar ratios along the height of concrete shafts.

Rebar Ratios (%)		
Height (m)	Exterior Shaft	Interior Shaft
0.0-11.6	1.2	0.84
11.6-21.6	0.79	0.68
21.6-26.4	0.64	0.68

Seismic performance level of the ATC tower

Airports play an essential role in reduction of post earthquake damages and ATC towers as inseparable part of airports must be capable of maintaining their serviceability after an earthquake. Based on this concept, ATC towers must hold higher seismic performance level in comparison with common buildings. For Kerman ATC tower, seismic performance levels were determined as below:

1) Capability for maintaining immediate occupancy (IO) level for design base earthquake (DBE).

2) Capability for maintaining Collapse Prevention (CP) level for Maximum probable earthquake (MPE).

IO and CP levels are defined according to FEMA356 (2000).The return period of DBE and MPE are 474 and 2475 years, respectively .Based on local seismic map, PGA for DBE and MPE equals to 0.3g and 0.45g, respectively. For nonlinear time history analysis six consistent earthquake records were utilized. All records were scaled to satisfy PGA of seismic hazard levels. Figure (3) depicts earthquake records which were applied in nonlinear time history analysis.

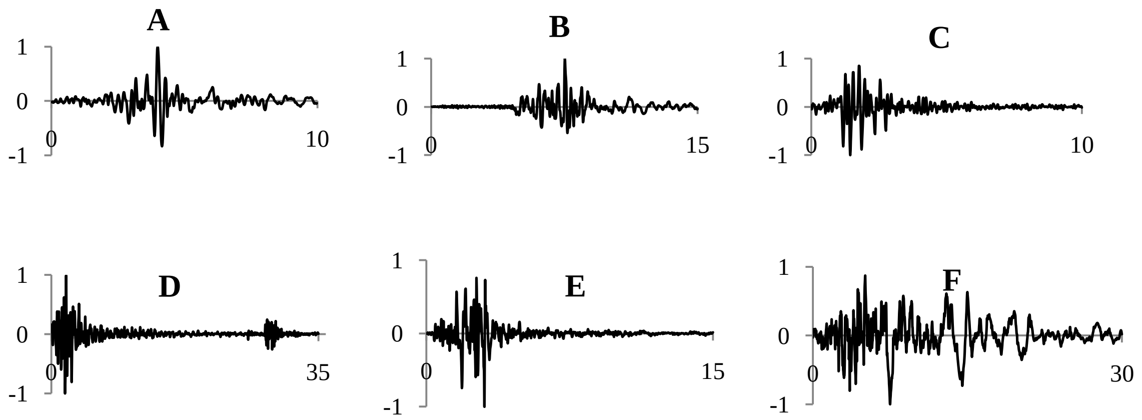


Figure 3. Applied earthquake records for nonlinear time history analysis.

Modeling Parameters and Acceptance criteria

In the finite element model all significant primary and secondary elements were considered. Since in this research we followed FEMA356 guidelines, modeling parameters and acceptance criteria for beams and columns were selected according to proposed values in FEMA356. For slabs, unlike beams and columns, instead of assigning hinges to elements, flexural and shear capacities were compared with the demand values of seismic hazard levels. Furthermore, nonlinearity of concrete shear walls was considered according to fiber method. More detail about this approach can be found in Miao et al. (2006). Out of plane bending of shear walls assumed to remain elastic during the analysis. Table (2) and (3) show modeling parameters and acceptance criteria of concrete and rebars for shear walls elements.

Table 2. Modeling parameters of concrete and Rebars

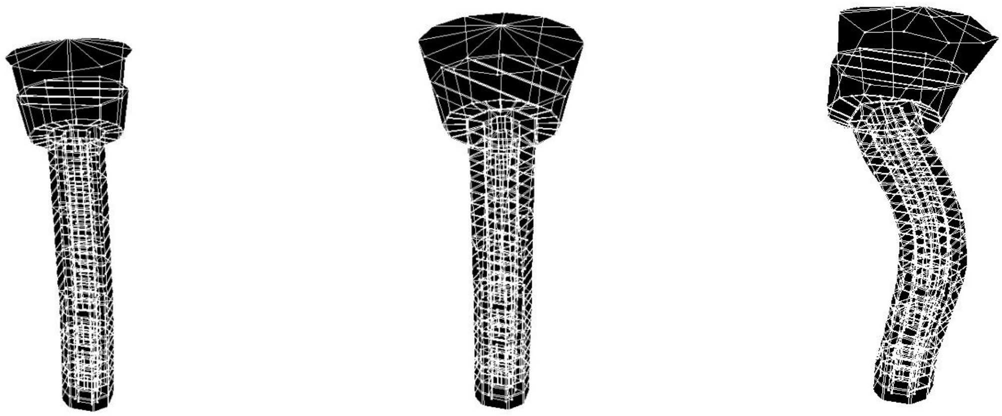
	Ultimate Comparison Strain	Ultimate Tension Strain
Concrete	0.005	-
Rebars	0.02	0.05

Table 3. Acceptance Criteria of Concrete and Rebars

	Strain at IO Level	Strain at CP Level
Concrete	0.0005	0.004
Rebars	0.0015	0.045

Nonlinear Time History Analysis

To consider effect of openings on the dynamic response of structure, tower was excited in three different directions. At first tower was excited through both principal directions and then it experienced ground acceleration with 45 degree deviation from principal directions. So totally 36 different nonlinear time history analysis were carried out. The first 20 modes of the tower was taken into account in the analysis. For each mode, damping was calculated according to Rayleigh method. Alpha and beta in equivalent Rayleigh damping formula were calculated based on the algorithm proposed by Chowdhury (2003).Figure (4) shows first, third and sixth mode of the tower. As it can be seen first and sixth modes are flexural modes and the third one is a rotational mode.



First mode Period: 0.78 sec. Third mode Period: 0.44 sec. Sixth mode Period: 0.11 sec.

Figure 4. First, third and sixth mode of vibration of Kerman ATC tower.

Sensor placement based on seismic performance levels

From the results of time history analysis, those elements that satisfy required seismic performance levels can be determined. These elements will not be considered for sensor installation because they already could withstand applied seismic excitations and will play their role after earthquake properly. For the rest of elements, based on their types and locations, a plan for sensors installation was provided.

In order to distinguish intact elements from those which have experienced damage easily, all elements based on their types and locations were categorized in the specific groups as shown in table (4).Tables (5) and (6) represent maximum and minimum obtained usage ratios for IO and CP levels of each group.

Table 4. Categorization of elements into different groups.

Group 1:	Circular steel beams at level 34.0 m
Group 2:	Circular steel beams at level 30.1 m
Group 3:	Inclined steel beams at roof level
Group 4:	Radial Concrete beams at level 26.4 m
Group 5:	Steel columns between level 26.4 m and 30.1m
Group 6:	Steel columns between level 30.1 m and 34.0 m
Group 7:	Exterior concrete shaft
Group 8:	Interior concrete shaft
Group 9:	Concrete slabs
Group 10:	Spandrel concrete beams between level -1.5 m and 26.4 m

Table 5. Maximum Usage Ratios for IO and CP levels.

	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8	Group 9	Group 10
IO	10.2	9.9	0.4	1.85	42	18	37.5	18.1	7.5	4.7
CP	0.8	1.1	0.04	0.4	4.8	3.8	12.1	9.4	4.2	0.6

Table 6: Minimum Usage Ratios for IO and CP levels.

	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8	Group 9	Group 10
IO	0.45	0.77	0.12	0.08	3.6	0.33	2.32	1.4	3.7	0.28
CP	0.2	0.25	0.02	0.15	1.9	0.07	0.35	0.27	1.9	0.29

From table (5) and (6) following results can be concluded:

1-Groups 5 and 9 are the most critical groups in comparison with other groups and for sensor installation priority should be given to these groups because according to table (6), obtained usage ratios indicates that they experience great damages for all applied earthquake records.

2-Group 3 could comply with all required performance levels thus it does not need to be considered in the sensor installation plan.

3-Although group 4 did not satisfy IO level but according to table (5), obtained usage ratios for their CP level shows that this group will experience little damage. Moreover, since we will monitor group 9 at the same level, this group can be removed from the sensors installation list.

4-Obtained usage ratios for Groups 7 and 8 shows that like groups 5 and 9, these groups will experience remarkable damage. Based on the usage ratios, from table (5) it can be inferred that severity of damage for groups 7 and 8 will be greater than groups 5 and 9 however probability of damage occurrence for groups 5 and 9 is unavoidable. The best locations of sensor installation for groups 7 and 8 according to obtained results from nonlinear time history analysis are between foundation level and the height of 1.6m also between the height of 4m and the height of 8.2m, where damage starts developing.

5-Based on the obtained results for CP level, groups 1 and 10 will experience moderate damage during earthquake. Since groups like 5, 7, 8 and 9 which maintain gravity loads experience more damage; groups 1 and 10 can be omitted from the sensors installation list because these two groups have a negligible role in carrying gravity loads.

6-There is no need to monitor group 6 because columns below this level (Group5) will be monitored. Furthermore table (5) shows that group 2 is prone to experience sever damage and can be considered in sensor installation plan.

Conclusions

Optimal sensor placement is a challenging matter in seismic health monitoring of structures. This is important to know how many sensors and at which locations should be installed. To overcome this issue a step by step approach based on seismic performance levels was proposed. This method considers the seismicity of the area where structure located in, and the importance of the structure. Applicability of this method was confirmed by applying it to the control tower of Kerman airport.

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