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APPLICATION OF A LOCAL MONITORING AND CONDITION ASSESSMENT METHODOLOGY TO BUILDING STRUCTURES

Tuluhan ERGIN[1], Murat Altug ERBERIK[2] and Ozgur KURC[3]

ABSTRACT

Various parties, such as first responders, emergency response teams, and occupants need a wide variety of internal information about facilities, such as building structure, in terms of damage condition, building content and vulnerable locations, during and right after a disaster. Accuracy and reliability of such information and making it available in a timely manner plays an important role in minimizing the number of casualties observed in the aftermath of disasters and emergencies.

Within the context of this study, an integrated model, which has been developed to (1) perform rapid damage and condition assessment in a building structure under the thread of a disaster, (2) guide the occupants to shortest and safest evacuation paths and (3) assist the emergency response teams in rescue operations by pinpointing vulnerable locations where secondary disasters can be triggered, is considered to combine the information obtained from building information model and the sensors deployed inside the building. The integrated model is applied to an existing and large public (school) building with many hallways and exits, which is hypothetically hit by a major earthquake. The analytical model of the building is constructed and time history analyses are performed in order to estimate the condition of the building. Then this information is used by different sensors placed at specific locations within the building in order to determine the blocked or vulnerable locations and assist safe evacuation of the building.

INTRODUCTION

During and after disasters, occupants inside a damaged building should be evacuated rapidly and safely while the first responders outside the building should be informed about the current condition of the building. Obviously, this information should be as accurate as possible and accessed timely in order to speed up the guidance of occupants to safe exits from a building under the effect of hazards. Unfortunately, the absence of such information during evacuation and emergency response operations, which is the common case, result in increased number of casualties. Hence, there arises a need for an approach to determine blocked passages in damaged building structures in order to guide the occupants to the exits safely and timely during evacuation by utilizing the sensor information.

Among many different types of disasters, earthquake is the most hazardous and effective one that may result in loss of many lives and property. Many buildings can experience severe damage during an earthquake and the occupants can easily be trapped in these damaged buildings. The photos in Figure 1 present damaged (but not totally collapsed) buildings, from which people had been rescued by the first responders during the 2011 Van (Turkey) earthquake (M_w=7.1).

[1] Graduate student, Middle East Technical University, Ankara Turkey, tuluhanergin@gmail.com
[2] Associate Professor, Middle East Technical University, Ankara Turkey, altug@metu.edu.tr
[3] Associate Professor, Middle East Technical University, Ankara Turkey, kurc@metu.edu.tr

Figure 1. The photos of the severely damaged buildings caused by the 2011 Van (Turkey) earthquake; taken from a) a commercial building, b) a residential building (courtesy of Murat Ayhan)

This research mainly focuses on a real-time sensor-based blockage assessment for passages of buildings under earthquake hazard. To achieve this, different types of sensors are examined. The selected sensors and video camera are mounted to an experimental model of a pilot building's hallway (corridor) model and a series of damage tests are conducted on the building elements to simulate the effect of a potential earthquake. In order to identify the blocked area in the hallway, image processing technique is used for the video camera data recorded during the experiment. The information gathered through the sensor and video camera data is fused in order to assess the blockage of the passage by decision tree approach. Finally, the decision tree approach is tested on the simulation platform by constructing the analytical model of the pilot building selected for this study and subjecting the analytical model to seismic action. The simulated seismic response is then used to generate the sensor data for the validation of the local monitoring and condition assessment methodology.

FACTORS FOR SENSOR LOCALIZATION IN BUILDING STRUCTURES

Figure 2 presents the building units and the relationships between these units that are used for local monitoring and blockage assessment methodology. Similar definitions have been made by different researchers (Schütz *et al*., 2008; Dibley *et al*., 2011)

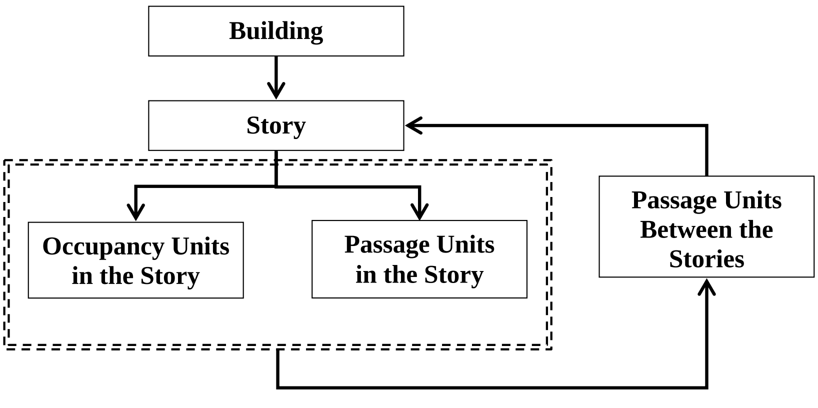


Figure 2. The structural units used for monitoring and blockage assessment

According to the flowchart in Figure 2, buildings consist of one or more stories, which can be regarded as a sub-unit. The units in the story are further divided into two sections: the occupancy units and the passage units. The occupancy units are the places where the occupants stay together. In other words, these places are the room units, which people occupy for different purposes. In post-disaster cases, victims generally get trapped in a room unit. It is extremely essential to know the intended use of the room units in terms of estimating the location where people get trapped and guiding them to the available exits during evacuation.

The passage units in the story (i.e. horizontal passage units) are the units that allow the movement of occupants in the story like hallways. It may not be possible to evacuate people from the blocked passage units in the case of blockage, so; it is essential to monitor the passage units with sensors for the purpose of determining as to whether the passages under consideration are blocked or not and to decide on which path to use during disaster.

The passage units between the stories (i.e. vertical passage units) are the units that enable the people to be transferred between any two stories. These are generally elevators, stairs or ramps. In a post-disaster situation, the unblocked passage units between the stories are important for safe evacuation of occupants. These units should also be monitored with sensors for blockage.

For safe evacuation of occupants, the structural and the non-structural elements to be monitored by sensors should be determined. If the vertical load-bearing elements (e.g. columns and load-bearing masonry walls) are damaged, the structural safety of the building is accepted to be under risk. Partial or total collapse is likely to occur depending on the level of damage. Hence the occupants should not be guided to the locations with moderately or severely damaged load-bearing elements. In the course of decision-making, the information about the structural condition of the building by sensors can help the decision maker to select among different options. On the other hand, if non-structural elements are damaged, the structural safety of the building is not critically threatened, only economic loss may occur. The suspended ceilings, infill walls or partial walls and various types of furniture (e.g. cupboard, bookshelf, etc.) are some examples of non-structural elements. The damage to non-structural elements can cause injuries (e.g. fall of a cupboard on a person) or can block the passage units (e.g. a corridor blocked by damaged infill wall).

In order to determine the locations of sensors in a building, it is essential to examine the seismic response and damage localization in different construction types. For instance, in frame buildings, columns are the most important structural elements because if the columns are severely damaged so that they cannot carry the loads, the vertical stability of the building becomes critical. Hence the sensors that monitor the columns should give detailed information about the present condition of the building. In addition, frame buildings are generally regarded as flexible structural systems. As a result, the probability of being damaged, overturning or failure of a non-structural element is rather high. Selecting and placing the sensors in the light of this information are unquestionably essential. On the other hand, masonry buildings are wall-bearing and rigid structures. Therefore seismic behaviour and failure modes for masonry buildings are totally different from framed structures. The load-bearing walls can be exposed to in-plane and out-of-plane damage. These different behaviour modes can emerge depending on many factors (e.g. the locations of the walls, geometric properties, mechanic properties, the lateral and vertical loads etc.). In these types of buildings, the most important structural elements are the load-bearing walls, so; it is proper to select and place the sensors to monitor the behaviour of these walls.

Occupancy class of the building is another important parameter for choosing the type and localization of the sensors. There are different occupancy classes such as residential, commercial, public, industrial, educational, medical, etc. The passage ways in buildings where people are populated such as shopping malls, public buildings, hospitals or educational buildings should be monitored thoroughly with more sensors by taking the panic and the stampede atmosphere into consideration during the post-disaster situation.

The architectural and structural properties of the buildings also have a prominent role for the localization of the sensors. For instance, while selecting the types and locations of the sensors, irregularities in plan (torsional behaviour) and in elevation (soft or weak story) should be taken into consideration because the occupants should not be guided to potential zones of damage and blockage that may be induced by such structural deficiencies.

This research is focused on low-rise and mid-rise highly populated public buildings with multiple exists. The construction type under consideration is framed structure with columns, beams and floor systems as the structural components.

MONITORING DEVICES (SENSORS) USED IN THIS STUDY

As mentioned in the above section, seismic response and damage of structural and non-structural components in a building structure should be monitored in real time for safe evacuation of the occupants. Different types of monitoring devices (sensors) can be used to achieve this task. The sensors can be broadly classified as physical and chemical sensors depending on the quantities that they monitor. Chemical sensors can monitor temperature, humidity, smoke and different types of gases (especially the toxic ones) and they are out of the scope of this study. Physical sensors monitor physical quantities like distance, direction, movement, acceleration, etc. The physical sensors used in this study are closed cable circuit (CCC), ultrasonic range finder (URF), gyro sensor and accelerometer. Video camera is used with image processing.

Closed cable circuit, or shortly CCC, is a closed circuit which conducts electricity. If the cable is cut off, transmitted signal changes (if electricity is conducted, the signal is transmitted as “1”, otherwise “0”). It is a very simple and cost-effective sensor which can be mounted on both structural and non-structural elements. However the information obtained from CCC should be interpreted in a careful manner since it is not a sophisticated sensor.

Ultrasonic range finder, or shortly URF, is a monitoring device that measures the distance between a target and the sensor by calculating the reflection time of the ultrasonic sound and change in the voltage. The basic types of URF are used in automotive applications for park assist technology. The URF used in this study is able to measure distances between 0.3 m - 6 m and it is mounted on non-structural elements only. The technical details (beam width, dowel radius, etc.) of the URF used in this study can be found elsewhere (Ergin 2013).

Gyro sensor is also known as angular rate sensor or angular velocity sensor. It is a device that monitors angular velocity. The present status of the target objects in a building structure, especially structural elements, could be assessed by using this information. In this study, gyro sensor is used to assess column damage in building structures.

In addition to the aforementioned sensors, accelerometer is also proposed as a monitoring device in this study. Floor acceleration is measured with accelerometer to detect as to whether vibration of the building can cause any damage (or blockage) in terms of predefined performance limits or not.

The last monitoring device proposed in this study is video camera. This device is different from the other sensors in terms of use. In other words, the sensors, except for accelerometer, are used to assess the damage status of a component to estimate blockage. However the estimation of blockage is enabled in a direct manner with a video camera through an image processing tool. As a result, the information is provided directly through video camera.

The measurement and validation tests for all monitoring devices were carried out on a simple experimental model, for which the details are provided by Ergin (2013).

The proposed real-time monitoring system in this study for building structures is shown in Figure 3. As a crucial component of this monitoring system, microcontrollers enable the communication with the sensors located at different parts of the building and a server is used to store and process the multi-sensor data. The connection between microcontrollers and server computer is provided through universal serial bus (USB) port. The power of the microcontrollers and the sensors are supplied from the server computer. Video camera, unlike other sensors, is connected to the server computer directly via IEEE 1394 port, known as firewire port. Data can be transferred faster with this port from USB, which is essential for video camera.

EXPERIMENTAL STUDIES

In accordance with the scope of this study, the selected pilot building is the Faculty of Fine Arts in Nevsehir University, Turkey. It is a building composed of two different blocks separated by dilatation. The building is complicated in the sense that there are several exits and many passage ways within or between floors (see Figure 4). Hence it becomes a challenge to determine the shortest safe path to exit in the pilot building by using the proposed sensor-based approach.

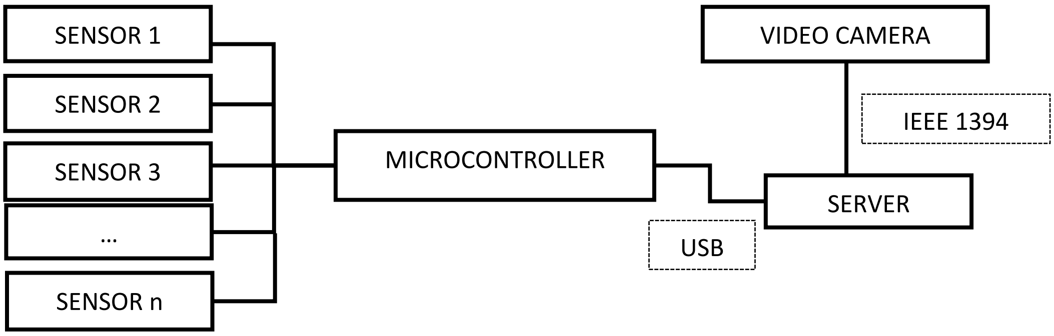


Figure 3. Connections between monitoring devices and server

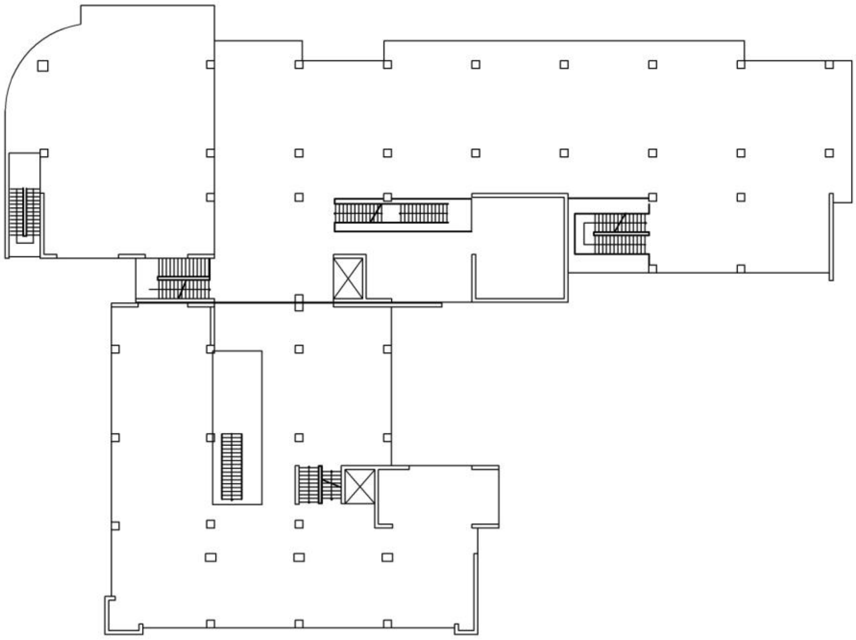


Figure 4. Plan view of the pilot building

First the real-time sensor based approach is tested by constructing the experimental model of a typical hallway from the pilot building (Figure 5). This is a one-third scale model of a three-span hallway composed of structural components (columns, beams) and non-structural components (infill wall, suspended ceiling, furniture). The scaled model is 1.2 m high, 0.9 m wide and 4 m long. The frame elements (i.e. beams and columns) are constructed by using wooden profiles and they are connected to each other and the base board by L-shaped aluminium sheets and profiles. The infill walls on sides of the specimen are made from clay bricks with dimensions of 60 x 80 x 100 (all in mm). The suspended ceiling is simulated by using 4 mm thick cardboards that have been strengthened with thin wooden bars. Bookshelves made of wooden planks are placed on either side of the experimental model to simulate non-structural objects that can block the hallway in the case of seismic action.

Among the selected monitoring devices in this study, only CCC, URF and video camera are used in the experiments. The main reason for not using gyro sensor and accelerometer is the fact that the tests conducted have no dynamic nature. Actually, manual damage is applied to the experiment model in various ways (connections of suspended ceiling are detached, infill walls, infill walls are knocked down, bookshelves are overturned, etc.).

If the structural elements, especially columns, are severely damaged in a specific location of the building during seismic action, it is obvious that the occupants should be kept away from such critical zones. Considering this fact, it has been decided to monitor only the non-structural components for real-time blockage assessment. Hence 29 sensors of two types (i.e. CCC and URF) are mounted on infill walls, suspended ceilings and bookshelves and the video camera is placed at one end of the experimental model to monitor the entire passageway. The placement of sensors is presented in detail in Ergin (2013).

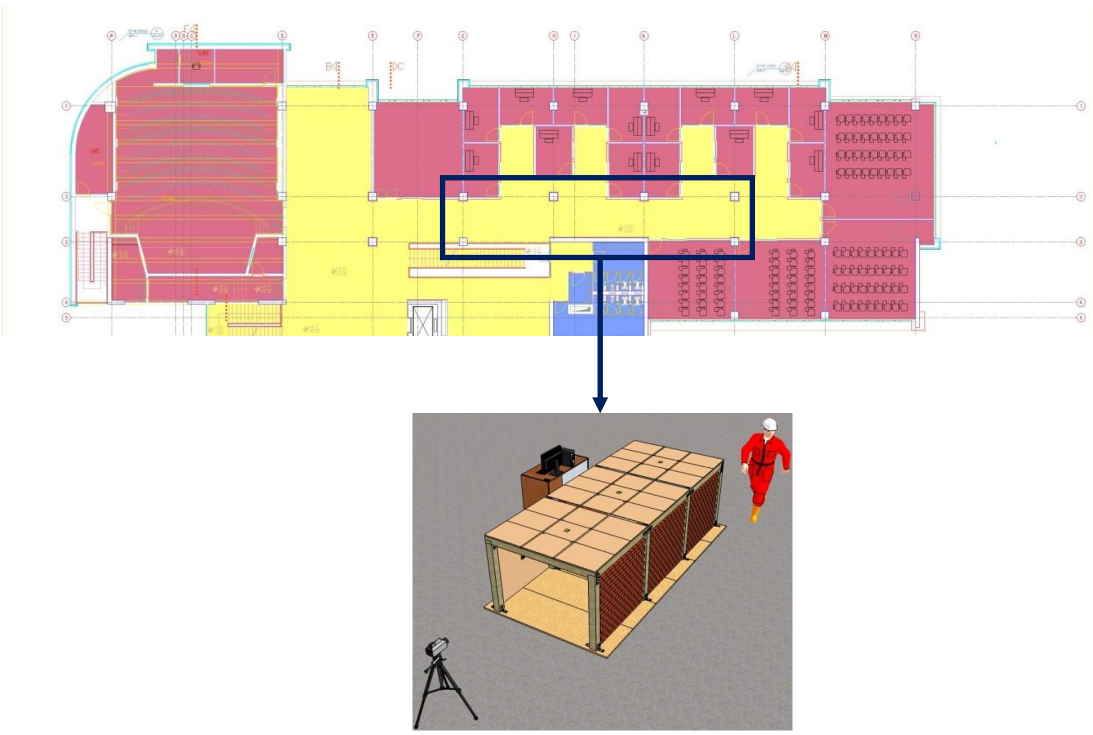


Figure 5. The selected hallway from the plan of the pilot building and 3-D view of the experimental model

In total, 56 experiments are conducted by damaging the non-structural components of the experimental model manually to simulate different levels of damage and blockage in the hallway. During each experiment, all data from the sensors and the video camera are collected and fused to determine the level of blockage in the hallway of the experimental model. The data obtained from CCC sensor is binary, i.e. it is “0” in the case of no cable connection (this means there exists damage) and “1” in the case of cable connection (this means no damage). URF sensor provides data in terms of distance. If there is a change in the distance of the object that the sensor monitors, this means there exists damage, otherwise there is no damage. The video camera is different from the other sensors in the sense that it can monitor the whole passageway while other sensors are able to yield information about a single non-structural component that they are mounted on. Hence the snapshots obtained from the camera are evaluated by using a CAD software to determine what percent of the passageway has been blocked in that specific experiment.

Actual levels of blockage in each experiment have been determined in accordance with the definitions given in Table 1. This information is then used to fuse sensor data, to evaluate the validity of video camera data and to construct a decision tree as the final product of the proposed methodology. Sample photos for each blockage class from the experimental program are presented in Figure 6.

VALIDITY OF SENSOR DATA FOR BLOCKAGE ASSESSMENT

To assess the validity of sensor data for detecting hallway blockage status, the performances of individual and fused (combined) sensor data are compared with the actual condition of the elements in the experimental model (in other words, ground truth). Ground truth has been obtained by gathering the expert opinion regarding the blockage status of the hallway specimen in each experiment. This leads to the development of a decision tree that depicts how data from sensors should be integrated. The decision tree is created by using an inductive learning algorithm, named as the C4.5 algorithm. The decision tree implementation is carried out by using the Weka software, which is an open-source Java implementation. The performance of the created decision tree is examined in terms of precision (proportion of the predicted positive cases that are correct) and recall (proportion of positive cases that are correctly identified) values and the results reveal that these values are rather high. Hence it can be stated that created decision tree is successful in integrating sensor data for blockage assessment in buildings. The details of the created decision tree and its generation procedure are given in Ergin (2013). The next and the final phase is to implement the real-time blockage assessment methodology as a case study to the pilot building.

Table 1. Classes and definitions of blockage levels

Class	Blockage Level	Definition
A	No	Passage is totally clear
B	Low	Some minor blockage but passage is not really prevented
C	Moderate	No comfortable passage. It is closed for disabled occupants
D	High	Occupants with no disability can pass through with great effort
E	Complete	Complete blockage for passing through

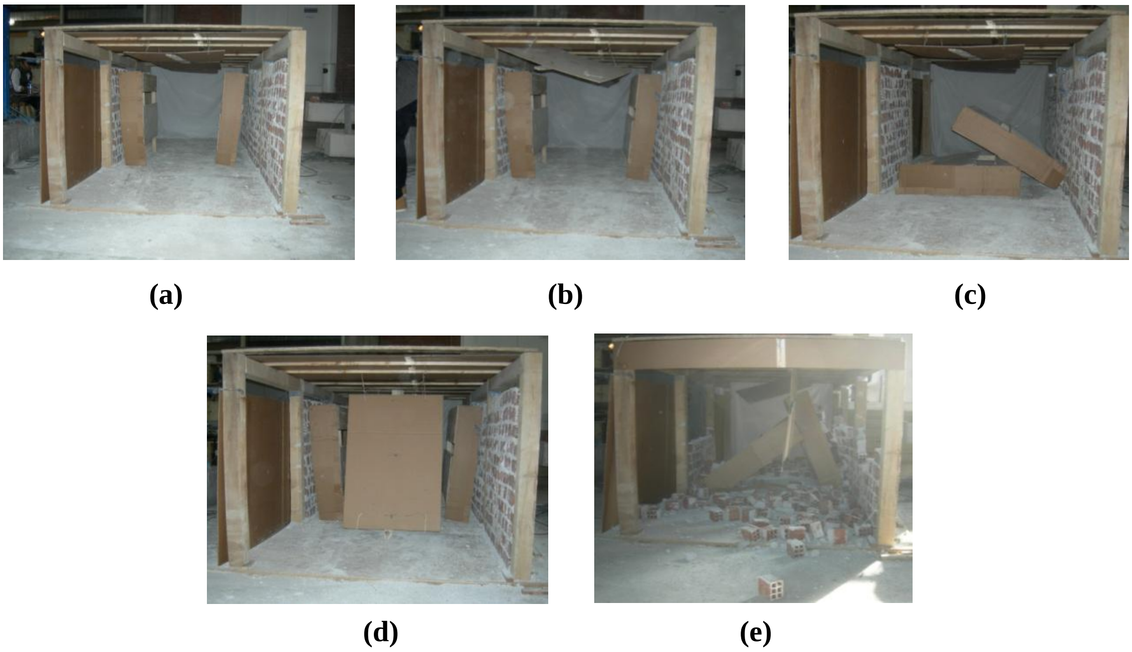
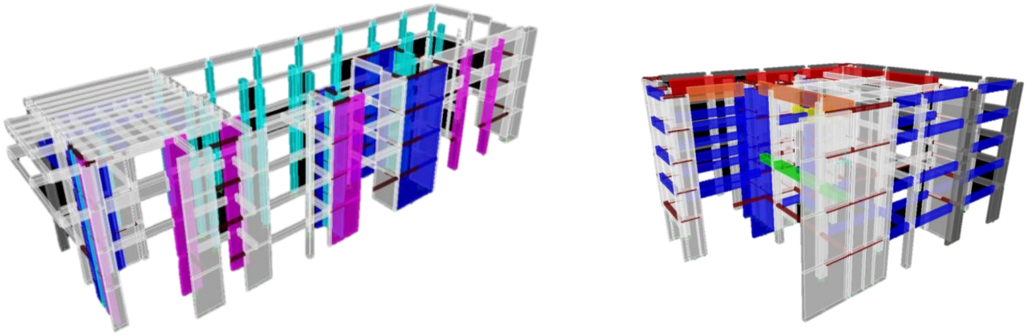


Figure 6. Sample photos for each blockage level; (a) class A, (b) class B, (c) class C, (d) class D and (e) class E

IMPLEMENTATION OF THE METHODOLOGY TO THE PILOT BUILDING

This section presents an implementation of the blockage assessment methodology with sensor fusion, which is provided by the decision tree approach. The case study is focused on the pilot building. The first step is to model the structural system of the pilot building by using SAP2000 analysis platform. Then two selected acceleration records, which represent moderate and severe levels of ground shaking, are applied to the building separately. Through time history analyses, the damage statuses of the components of building are simulated. The next step is to generate the sensor data for two different damage levels with the assumption that the sensors work flawlessly. Finally, the decision tree is employed for both of the seismic analyses and the results are discussed.

The computer models of the two blocks of the pilot building are presented in Figure 7. Each block has been modelled separately. The structural system of both blocks is reinforced concrete frame structure without beams (i.e. flat slab). The rigid diaphragm approach is used instead of shell elements for slabs and the structural loads are distributed by tributary area approach. The vibration periods of the first three modes are provided in Table 2.



(a) (b)

Figure 7. 3-D image of the analytical model of the pilot building; (a) block A, (b) block B

Table 2. Vibration periods of the modelled blocks for the first three modes

Modes	Periods in seconds	
	Block A	Block B
1	0.44	0.69
2	0.29	0.58
3	0.25	0.42

The ground motion records used for time-history analysis are selected from two different stations of the 17 August 1999 Kocaeli, Turkey earthquake (M_w=7.4). These two stations are Düzce and Gebze stations. The ground acceleration record of Düzce station represents severe shaking intensity whereas the Gebze station represents a moderate shaking intensity. The major ground motion characteristics of the records are listed in Table 3. In the table, CD, PGA and PGV stand for closest distance to ruptured fault, peak ground acceleration and peak ground velocity, respectively.

Table 3. Ground motion characteristics of the records used in this study

Code	Earthquake	Station	Site Class	CD (km)	PGA (g)	PGV (cm/s)
EQ1-NS	17 August 1999 Kocaeli earthquake (M_w=7.4)	Gebze	Stiff soil	15	0.27	45.6
EQ1-EW			Stiff soil	15	0.14	34.7
EQ2-NS		Düzce	Soft soil	11	0.34	60.6
EQ2-EW			Soft soil	11	0.38	49.6

Using the aforementioned ground motion records that represent two different levels of ground shaking, nonlinear time history analyses are conducted on the analytical model of the pilot building and the seismic response is obtained in terms of floor accelerations and interstory drifts. Eventually, the values obtained in the case of Düzce earthquake are more critical. Then using some predefined performance and limit state definitions these response values are interpreted in terms of seismic damage for both structural and non-structural components. The limit state definitions of the components are determined as follows:

Columns: Default hinge properties of SAP2000 are employed in the analysis, hence the performance limits of the columns are in accordance with the FEMA-356 (2000) document in terms of deformation of the columns. If the deformation demands obtained through analyses exceed the predefined limits, then the columns are assumed to fail in satisfying the related criteria and they are assumed to be damaged to some extent.

Infill walls: Both in-plane and out-of-plane damage of infill walls are considered. The assessment of in-plane damage in the walls can be estimated from the floor drift ratios. By considering the studies of Bayülke (1992), Kuran (2006), and Bal et al. (2008), the limits of the floor drift ratios with respect to slight, extensive and heavy (or collapse) damage states are given as 0.0025, 0.005 and 0.01, respectively.

The out-of-plane damage is assumed to have been caused by the earthquake acceleration. The floor acceleration is assumed to be the average acceleration of the base and the ceiling of the floor. The criterion to determine the out-of-plane damage can be given as (Ergin 2013)

$$\psi\, f_{\max} < \frac{0.75\,\gamma\, a\, H^2}{t} \tag{1}$$

where f_{max} is the flexural capacity of the wall that can be taken between 200-500 kN/m^2 in accordance with Eurocode 6 (CEN 2003), γ is the density of the masonry unit, a is the horizontal floor acceleration, H is the height and t is the thickness of the infill wall. Parameter ψ is a factor that considers the combined effect of in-plane and out-of-plane damages of the infill wall since if the wall experiences in-plane damage, out-of-plane resisting capacity should be reduced to some extent. This parameters takes the values of 1.0, 0.75 and 0.5 for in-plane states of slight, extensive and heavy damage, respectively.

Non-structural objects: A non-structural object can block a passage way in two ways: overturning and/or sliding. These conditions are dependent on the acceleration of the component. In this study, the shape of the non-structural object is assumed to be a rectangular prism for simplicity. The accelerations at the instants of overturning and sliding can be simply calculated by considering the rigid-body dynamics principles. The minimum of these two acceleration values is critical and determines whether the object is to overturn or slide first. Then these limiting values are compared with the floor acceleration that were obtained from the time history analyses to see if the object blocks the hallway by moving or not.

Suspended ceilings: According to HAZUS methodology (FEMA 2009), suspended ceiling is assumed to be damaged in case floor acceleration is greater than 1g. In this study, the limits of floor accelerations with respect to slight, extensive and heavy (or collapse) damage states are given as 0.4g, 0.8g and 1.2g, respectively.

It is assumed that the pilot building is equipped with a large number of hypothetical sensors for real-time monitoring of the seismic response under the aforementioned ground excitations. There are four main components to be monitored in the case study building: infill walls, suspended ceilings, non-structural objects (these can be cupboards, bookshelves or any other furniture or equipment) and columns. The locations of columns and infill walls in the building are definite in accordance with architectural drawings. Each column is equipped with a hypothetical gyro sensor and all the infill walls are equipped with 2 CCCs and 1 URF. Unlike these components, the suspended ceilings and the non-structural objects are intentionally placed in the most proper locations of the building. All the suspended ceilings in the passage ways of the building are assumed to be monitored with 4 CCCs and 1 URF whereas the non-structural objects are assumed to be equipped with 2 CCCs. In addition, it is assumed that there exists an accelerometer at each floor of each block to measure the floor response and also video cameras are located in the critical areas and in specific locations to monitor the passage ways in the pilot building.

The analytical response obtained from time history analyses is compared with the limit state definitions of the building components to predict the damage state of the pilot building. The comparison reveals that there is no significant damage in columns neither at moderate nor at severe shaking intensities. However other elements, i.e. infill walls, suspended ceilings and non-structural objects seem to be damaged or dislocated, especially at the upper stories due to the increased amplitudes of oscillations. The detailed damage distribution can be seen in Ergin (2013). Then the sensor data is generated from the predicted damage distribution. As a result, the sensor data is used as the input attributes for the decision tree to decide the blockage classes of the passage units.

In the final phase, generated sensor data is used as the test set to obtain recall and precision rates for validation of the created decision tree and the proposed blockage assessment methodology. The values are presented in Table 4 for moderate and severe shaking intensities.

Table 4. Precision and recall rates for both levels of seismic intensity

Blockage class	Moderate shaking intensity		Severe shaking intensity	
	Precision (%)	Recall (%)	Precision (%)	Recall (%)
A	95.65	100.00	93.75	100.00
B	100.00	100.00	100.00	100.00
C	85.71	100.00	100.00	100.00
D	58.54	88.89	57.14	53.33
E	100.00	10.00	100.00	14.29
Weighted average	88.61	83.97	90.01	90.00

The results reveal that all cases in blockage classes A, B and C have been detected by the decision tree approach since the recall rates are 100% for both moderate and severe shaking intensities. Hence these classes seem to be the most successful blockage classes detected by the decision tree. For blockage class D, the recall rate is still high for moderate intensity, but it gets lower for severe intensity of shaking. Blockage class E seems to be the most problematic blockage class with recall rates of 10% for moderate and 14% for severe intensities of shaking although both have precision rates of 100% (i.e. this class is not confused with the other classes). This shows that the decision tree approach has some difficulty to detect this blockage class. This is also reflected by relatively low precision values of blockage class D. The issue seems to be the interpretation of the fused sensor data to identify the blockage classes D and E. The main reason for that is the lack of sufficient number and type of experiments for these blockage classes. However, even this situation does not influence the overall results significantly. Both of these blockage classes are configured to response to the shortest way algorithm as blocked passage (Birgönül et al., 2012). This indicates that the reliability of the blockage assessment procedure that can be used in order to guide the occupants to the safest path while evacuating the building in a safe and rapid manner.

CONCLUSIONS

In this study, a methodology for real-time, sensor-based local monitoring of blockage in building structures is proposed. This methodology can provide blockage information of passage units by combining the sensor and image processing data. First, the damage indicators of buildings which can cause blockage are examined in order to achieve the aim. After that the sensors are selected and their capabilities are reviewed. Considering the sensor properties and damage indicators, the localization rules of the sensors are determined.

By using these localization rules, series of experiments are conducted on a test specimen, which is a one-third scaled hallway model. In these experiments, non-structural components (infill walls, suspended ceilings and non-structural objects) are monitored for blockage information by using the CCC and the URF. In addition, a video camera is used to view the hallway during experiments. Blockage classes are identified and employed in order to evaluate the final condition of the hallway specimen after each experiment. Image processing approaches are also taken into account for video camera recordings to assess the blockage.

By using the results of the experiments, sensor fusion is carried out with the decision tree approach. In this approach, sensor data obtained from the experiments is considered as an input attribute to the C4.5 algorithm. The input attributes are also ranked to the influence on the decision tree by attribute class in Weka. The blockage condition of the experiment is also entered as an output attribute to the same algorithm. In the final stage, a decision tree is generated through the algorithm. It should be noted that the outcome of this decision tree is limited to the types, numbers and locations of the sensors and also the components used in the experiment.

In order to test the decision tree, a case study is carried out as the last step of the study on the pilot building. The analytical model of the pilot building is constructed and then exposed to two different levels of ground shaking: moderate and severe. Then non-structural component damage of the case study building is predicted by using the floor acceleration and interstory drift data obtained from the time-history analyses. It is assumed that the sensors are located according to the previously defined localization rules and they run flawlessly. In the next step, the simulated sensor data is used as an input for the decision tree approach. The results are discussed in accordance with the precision and recall rates. It is concluded that the decision tree is successful in detecting the first three blockage classes (A, B, C) but is problematic in detecting the last two blockage classes (D, E). It is perceived that the reason for the confusion of the blockage classes after running the decision tree is the lack of sufficient number of experiments. More detailed experiments should be carried out with more various types of components in future studies. This would increase the precision and recall rates. However, it can be stated that this issue does not influence the overall results significantly since both of these blockage classes are configured to response to the shortest way algorithm as blocked passage. This encourages the use of the proposed blockage assessment procedure that can be used in order to guide the occupants to the safest path while evacuating the building in a safe and rapid manner.

This research, despite the discrepancies in some of the results, is a novel study in this research area and it can be a guideline for future studies that will be focused on real-time blockage assessment of building structures by using multiple sensor information. It is highly probable to improve the proposed methodology with the aim of mitigating the fatal consequences of other disasters (i.e. blast, fire, terrorist attack, etc) by making use of the outcomes of this study.

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