Simple Survey Procedures for Seismic Risk Assessment In Urban Building Stocks

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Abstract: Cities under significant seismic risk contain a large number of vulnerable buildings. An effective risk assessment measure is to identify the most vulnerable buildings, which may undergo severe damage in a future earthquake. A two-level risk assessment procedure is proposed here. The first level is based on recording building parameters from the street side. In the second level, these are extended by structural parameters measured by entering the ground story. Statistical correlations have been obtained by employing a database of 477 damaged buildings surveyed after the 1999 Düzce earthquake. The results revealed that the parameters observed from the street and measured at the ground story provide strong guidance for identifying those buildings that jeopardize the life safety of their occupants.

Key words: Seismic risk, assessment, buildings, street survey, damage, score

1. INTRODUCTION

The classical engineering approach for providing seismic safety in building structures is to ensure their conformance to the current seismic design codes. This is a valid approach for new buildings. However majority of the existing buildings in seismic environments do not satisfy modern code requirements. Yet, the ratio of severely damaged or collapsed buildings observed after a severe earthquake is much less than the ratio of substandard buildings. The difference is significant. An optimistic estimation of substandard buildings in Turkey is not less than 90 %, which can be generalized to Istanbul, or other earthquake prone regions in Turkey. On the other hand, the ratio of collapsed or heavily damaged buildings in Düzce after the two consecutive damageable earthquakes in 1999 was 20 % (Sucuoğlu and Yılmaz, 2001). Similar ratios were observed in Gölcük and Adapazarı. A recent loss estimation study for Istanbul (JICA, 2002) revealed that the expected ratio of collapsed buildings under a scenario earthquake of magnitude 7.4 along the Marmara Sea fault is 7 %. Considering these large differences, it may be proposed that a sound risk assessment methodology for effective risk mitigation must be focused on identifying these hazardous buildings in urban environments as the first priority.

A two-level seismic risk assessment procedure is developed in this study for low to medium rise (less than 8 stories) ordinary reinforced concrete buildings. The developed procedure is based on several building parameters that can be easily observed or measured during a systematic survey. The main objective of the procedure is developing a building database, and ranking the buildings in an urban stock with respect to their expected seismic performances under a defined ground excitation.

2. TWO-LEVEL RISK ASSESSMENT PROCEDURE

The first survey level is conducted from the sidewalk by trained observers through walk-down visits. In the second survey level, the observers enter the basement and ground stories of the buildings for collecting the simplest structural data. The acquired data is then processed for calculating a risk score for each building.

2.1 Level 1: Observations from the street

A street survey procedure must be based on simple structural and geotechnical parameters that can be observed easily from the sidewalk. The time required for an observer for collecting the data of one building from the sidewalk is expected not to exceed 10 minutes. The parameters that are selected for representing building vulnerability in this study are the following:

1. The number of stories above ground (1 to 7)
2. Presence of a soft story (Yes or No)
3. Presence of heavy overhangs, such as balconies with concrete parapets (Yes or No)
4. Apparent building quality (Good, Moderate or Poor)
5. Presence of short columns (Yes or No)
6. Pounding between adjacent buildings (Yes or No)
7. Local soil conditions (Stiff or Soft)
8. Topographic effects (Yes or No)

Each parameter reflects a negative feature of the building system under earthquake excitations on a variable scale. Evaluating the correlation between observed building damage and parameter variation by using the building data compiled from Düzce assesses the weight of each parameter in expressing a seismic performance score. It is intended to develop a linear combination rule for the selected parameters in order to predict the damage distribution displayed by the collected data as good as possible. Once such a combination rule is developed, it will be possible to rate the seismic performance of reinforced concrete building structures in Turkey by employing a simple walk-down survey procedure. The proposed method bears some similarities with the seismic evaluation procedure developed in FEMA-154 (1988). However it is believed that this method provides a broader description of seismic risk for the multistory reinforced concrete buildings in Turkey, which do not conform to the requirements of modern seismic design and construction codes.

The objective of developing a performance scale for existing buildings is to provide a simple tool, which can be easily implemented by both the building owners and the public administrations. If an individual building falls on the lower (high-risk) part of the scale, then a more detailed evaluation will be deemed necessary. The performance scale provides an ordering of the seismic vulnerability of a building stock. The scale can be used to classify low, moderate and high-risk buildings. Low-risk buildings may not require a further evaluation, but moderate and high-risk buildings can be subjected to more detailed evaluation procedures before final decisions on retrofitting or removal.

Each vulnerability parameter, which the damage distribution in the collected building data is found sensitive to, is evaluated separately in the following paragraphs.

The number of stories

Field observations after the 1999 Kocaeli and Düzce earthquakes revealed that there is a very significant correlation between the number of stories and the severity of building damage. If all buildings were conforming to modern seismic design codes, then such a distribution would not occur, and a uniform distribution of damage would be expected. However if the majority of buildings in the earthquake stricken region lack this basic property, then the increasing number of stories increase seismic forces linearly whereas the seismic resistances do not follow in adequate proportions. Accordingly, damage increases almost linearly with the number of stories. After the two earthquakes in 1999, damage distribution for all 9685 buildings in Düzce is obtained with respect to the number of stories. The results are shown in Figure 1 below, where the number of damaged buildings is normalized with the total number of buildings at a given story number. It can easily be observed from

Figure 1 that damage grades shift linearly with the number of stories. As the number of stories increases, the ratio of undamaged and lightly damaged buildings decreases steadily whereas the ratio of moderately and severely damaged buildings increases in an opposite trend. This is a clear indication that the number of stories is a very significant, perhaps the most dominant, parameter in determining the seismic vulnerability of typical multistorey concrete buildings in Turkey.

Presence of a soft story

Soft story usually exists in a building when the ground story has less stiffness and strength compared to the upper stories. This situation mostly arises in buildings located along the side of a main street. The ground stories, which have level access from the street, are employed as a street side store or a commercial space whereas residences occupy the upper stories. These

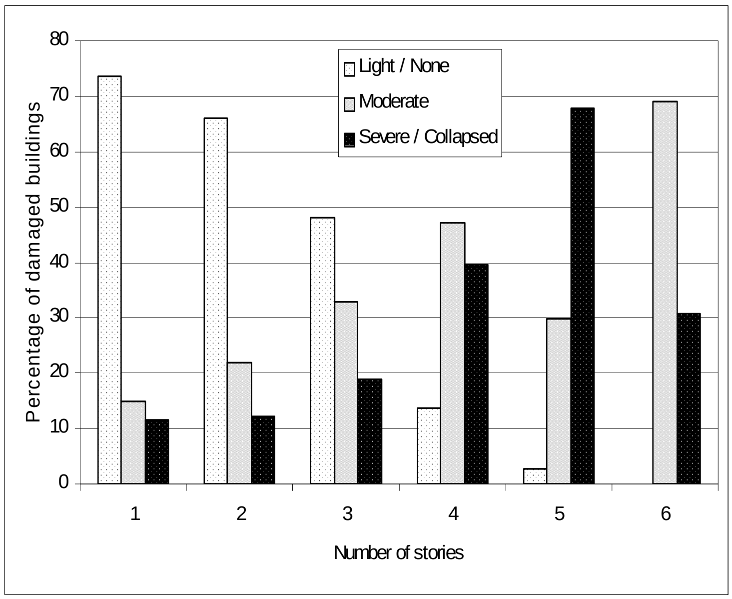

Figure 1. Damage distribution in Düzce after the 1999 earthquakes, with respect to the number of stories

upper stories benefit from the additional stiffness and strength provided by many partition walls, but the commercial space at the bottom is mostly left open between the frame members, for customer circulation. Besides, the ground stories may have taller clearances and a different axis system causing irregularity. The compound effect of all these negative features from the earthquake engineering perspective is identified as a soft story. Many buildings with soft stories were observed to collapse due to a pancaked soft story in the past earthquakes all over the world.

Presence of heavy overhangs

Heavy balconies and overhanging floors in multistory reinforced concrete buildings shift the mass center upwards; accordingly increase seismic lateral forces and overturning moments during earthquakes. Buildings having balconies with large overhanging cantilever spans enclosed with heavy concrete parapets sustained heavier damages during the recent earthquakes in Turkey compared to regular buildings in elevation. Since this building feature can easily be observed during a walk-down survey, it is included in the parameter set.

Apparent building quality

The material and workmanship quality, and the care given to its maintenance reflect the apparent quality of a building. A well-trained observer can classify a buildings apparent quality roughly as good, moderate or poor. A close relationship had been observed between the apparent quality and the experienced damage during the recent earthquakes in Turkey. A building with poor apparent quality can be expected to possess weak material strengths and inadequate detailing.

Presence of short columns

Semi-infilled frames, band windows at the semi-buried basements or mid-story beams around stairway shafts lead to the formation of short columns in concrete buildings. These captive columns usually sustain heavy damage during strong earthquakes since they are not originally designed to receive the high shear forces relevant to their shortened lengths. Short columns can be identified from outside because they usually form along the exterior axes.

Pounding between adjacent buildings

When there is no sufficient clearance between adjacent buildings, they pound each other during an earthquake as a result of different vibration periods and consequent non-synchronized vibration amplitudes. Uneven floor levels aggravate the effect of pounding. Buildings subjected to pounding receive heavier damages at the higher stories.

Local soil conditions

Site amplification is one of the major factors that increase the intensity of ground motions. Although it is difficult to obtain precise data during a street survey, an expert observer can be able to classify the local soils as stiff or soft. In urban environments, geotechnical data provided by local authorities is a reliable source for classifying the local soil conditions.

Topographic effects

Topographic amplification is another factor that may increase the ground motion intensity on top of hills. Besides, buildings located on steep slopes (steeper than 30 degrees) usually have stopped foundations, which are incapable of distributing the ground distortions evenly to structural members above. Therefore these two factors must be taken into account in seismic risk assessment. Both factors can be observed easily during a street survey.

2.2 Level 2: Measurements at the ground story and basement

After the building data is acquired from street surveys and evaluated, buildings falling into the moderate and high risk levels can be identified with respect to their performance scores as explained in the following sections. Observer teams enter into the basements and ground stories of these buildings for collecting more data for further evaluation. Their first task is the confirmation or modification of the previous grading on soft stories, short columns and building quality, through closer observation. The second and more elaborate task is to prepare a sketch of the framing plan at the ground story and measuring the dimensions of columns, concrete and masonry walls. These tasks are expected to consume about two hours of a team consisting of three members. This data is then employed for calculating the following parameters.

Plan irregularity

Irregularity in building plan is a deviation from a rectangular plan, having orthogonal axis systems in two directions. Such deviation from plan regularity leads to irregularities in stiffness and strength distributions, which in turn increase the risk of damage localization under strong ground excitations. In earthquake resistant design, regularity in plan is encouraged.

Redundancy

When the number of continuous frames or number of bays in a building system is insufficient, lateral loads may not be distributed evenly to frame members. Especially those frames exhibiting inelastic response during earthquakes suffer from lack of sufficient redundancy, which leads to localized heavy damages. A normalized redundancy ratio is defined by the following expression (Özcebe et al., 2003).

$$\mathrm{NRR} = \frac{A_{tr}(n_{fx} - 1)(n_{fy} - 1)}{A_{gf}} \tag{1}$$

Here, A_{tr} is the tributary area for a typical column, A_{gf} is the area of ground floor, n_{fx} and n_{fy} are the number of continuous frames in x and y directions, respectively. Three redundancy scores (NRS) are assigned accordingly.

NRS = 0 when NRR>1 : Redundant

NRS = 1 when 0.5<NRR<1 : Semi-redundant

NRS = 2 when NRR < 0.5 : Weakly redundant

Strength index

The lateral strength of a building is strongly related to the size of its vertical members, among other factors including material strengths, detailing and frame geometry. Since measuring the sizes of vertical members at the ground story of an existing building is possible, a strength ratio SR can be defined as follows (Özcebe et al., 2003).

$$\mathrm{SR} = \min(A_{nx}, A_{ny})$$

$$A_{ni} = \frac{\Sigma(A_{col})_i + \Sigma(A_{sw})_i + 0.1\Sigma(A_{mw})_i}{\Sigma A_f} x100 \tag{2}$$

where

$$(A_{col})_i = k_i \,.\, \mathrm{A}_{\mathrm{col}}$$

$$(A_{sw})_i = k_i \,.\, \mathrm{A}_{\mathrm{sw}}$$

$$(A_{mw})_i = k_i \,.\, \mathrm{A}_{\mathrm{mw}}$$

Here, *i* stands for x or y, k_x is 1/2 for square columns, 1/3 and 2/3 for rectangular columns in weak and strong directions respectively, and 1.0 for concrete and masonry walls in x-direction, k_y=1-k_x. A_{col}, A_{sw} and A_{mw} are the cross section area of each column, shear wall and masonry infilled wall, respectively. A stiffness index SI is described by classifying the strength index SI.

SI = 0 when SI > 0.0025 : strong

SI = 1 when 0.0015<SI<0.0025 : moderate

SI = 2 when SI < 0.0025 : weak

3. EVALUATION OF THE DÜZCE DATABASE

A total of 477 buildings were surveyed in Düzce, which survived the 17 August 1999 Kocaeli and 12 November 1999 Düzce earthquakes with some levels of damage. Building damages were classified in four grades, namely none, light, moderate and severe or collapsed. A building with light damage can be occupied with minor repairs after the earthquake whereas a moderately damaged building requires structural repairs. If there is severe damage, then such a building must either be strengthened to upgrade its seismic capacity, or demolished. The damage distribution of the investigated buildings with the number of stories is presented in Table 1.

The variation of damage in 477 buildings with survey parameters is obtained independently for each parameter. Düzce database was not representing all parameters. Short columns and pounding effects were not surveyed. Moreover, soil conditions were uniform and topography was flat. Therefore these four parameters are not included in the following evaluation.

Table 1. Damage Distribution of the Investigated Buildings in Düzce

	Damage Observed				
Number of stories	None	Light	Moderate	Severe, Collapsed	Total
2	7	13	3	0	23
3	18	62	29	15	124
4	17	43	60	27	147
5	17	30	56	65	168
6	1	0	4	10	15
Total	60	148	152	117	477

3.1 The number of stories

An investigation is conducted on the 477 surveyed buildings in Düzce, to check whether the surveyed building stock represents Düzce building inventory, considering the distribution of damage with the number of stories. The results are shown in Figure 2. The trend in this figure is quite similar to that in Figure 1, which confirms that damage is strongly correlated with the number of stories. Accordingly, it is decided to uncouple this parameter from the others. The data for the other parameters is sorted for each story number separately in order to remove its effect on the other parameters.

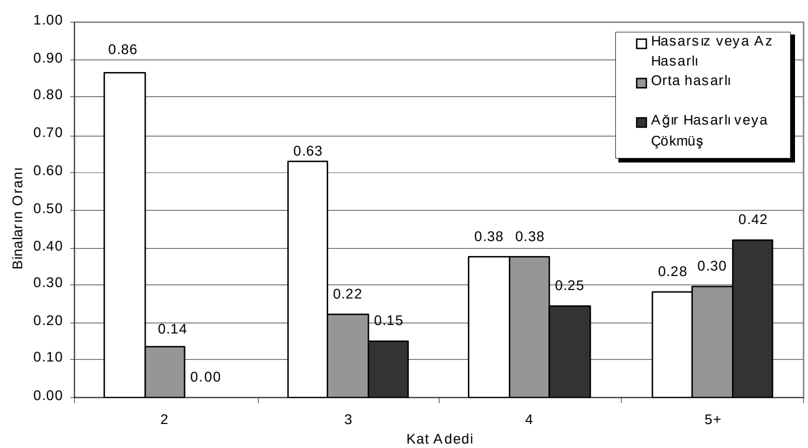

Figure 2. The distribution of damage with the number of stories in 477 buildings

3.2 Presence of soft story

Among the 477 surveyed buildings, 234 buildings had soft stories. These buildings are grouped with respect to the damage grades and the number of stories, and then their number is normalized relative to the total number of buildings in each group. The results are presented in Figure 3. For all story numbers, it is evident that the buildings with soft stories exhibit higher severe damage/collapse ratios compared to those with no soft stories. Notably, almost all severely damaged buildings have soft stories. This is an important observation because if a building with a soft story is vulnerable to seismic damage, it is very likely that this damage will be either moderate or severe, especially when the number of stories exceeds two. It can also be observed that damage distribution among buildings with soft stories does not have a consistent variation with the number of stories. Therefore this parameter can be assessed independently from the number of stories.

3.3 Apparent building quality

The quality classification of 477 surveyed buildings revealed that 63 were good, 391 were moderate and 23 were poor. These buildings are grouped with respect to the damage grades and the number of stories, and then their number is normalized relative to the total number of buildings in each class. The results are presented in Figure 4. The data for 6 story buildings is meaningless. However the data for 3-5 stories reveal that the severely damaged/collapsed buildings have lesser quality than the other damage groups. An increasing effect can also be observed with the number of stories.

3.4 Presence of heavy overhangs

The distribution of damage in buildings with and without heavy overhangs is presented in Figure 5. There were 97 buildings with heavy overhangs among the total of 477. The building ratios are obtained by normalizing the number of buildings in each category with respect to the total number of buildings with or without overhangs for each number of stories. All of the undamaged buildings were free of heavy overhangs. There is a consistently increasing trend in the severely damaged/collapsed building ratios of 2 to 6 story buildings with the story number, with regard to the presence of overhangs. Accordingly, this parameter should be considered in the seismic risk assessment of buildings having more than 3 stories.

3.5 Plan irregularity

The results obtained from the survey data are presented in Figure 6, separately for each number of stories. The number of buildings classified as irregular was 274 among 477. Irregularity in plan does not influence damage distribution in 2 story buildings. In 3 to 6 story buildings, those with irregular plan have a larger share among the severely damaged/collapsed buildings than the ones with regular plan. Therefore plan irregularity should be considered as a parameter in determining the seismic risk of buildings taller than 2 stories.

3.6 Redundancy

The majority of buildings in the Düzce database were classified as weakly redundant (315), whereas 85 were semi-redundant and 77 were redundant. The normalized results are shown in Figure 7. This parameter can only separate the severely damaged and collapsed buildings in the 4 to 6 story groups. Weakly redundant buildings have a share among the severely damaged and collapsed buildings that increases with the number of stories, and becomes notable in 5 and 6 story buildings.

3.7 Strength index

Only 37 buildings among 477 were classified as weak in strength. More than half of the 5 and 6 story weak buildings were collapsed or sustained severe damages according to Figure 8. However strength index has no influence on the damage distribution of 2-4 story buildings. Therefore this parameter can only be considered for identifying the risk of 5 and 6 story buildings.

4. TWO-LEVEL SEISMIC RISK ASSESSMENT TOOLS FOR ISTANBUL

A practical risk assessment procedure for Istanbul is presented herein, which is based on the data acquired from the two levels of surveys conducted from the street and the ground stories of buildings, respectively. The weight of each building vulnerability parameter is evaluated by statistical procedures, based on the Düzce database. Statistical analysis is conducted by the program package SPSS Version 11, using the "Multivariable Stepwise Linear Regression Analysis" procedure. The results are then smoothed, and the weights of the parameters for which there was no available data (soft story, pounding, topography) are assigned by using engineering judgement. Local soil conditions and associated ground motion intensity in Düzce was uniform. Different intensity zones are described for Istanbul however (JICA, 2002), based on the distribution of peak ground accelerations (PGA) or velocities (PGV) during the scenario earthquake. The effect of ground motion intensity expected in different zones is considered by applying velocity-based conversion factors as explained below.

4.1 Building performance score

Once the vulnerability parameters of a building are obtained from two-level surveys and its location is determined, the seismic performance scores for survey levels 1 and 2 are calculated by using Tables 2 and 3, respectively. In these tables, an initial score is given first with respect to the number of stories and the intensity zone. Then, the initial score is reduced for every vulnerability parameter that is observed or calculated. A general equation for calculating the seismic performance score (PS) can be formulated as follows.

$$\text{PS} = (\text{Initial Score}) - \sum(\text{Vulnerability parameter}) \times (\text{Vulnerability Score})$$

The vulnerability scores are given in Tables 1 and 2, and the vulnerability parameters are defined under the tables.

4.2 Local soil conditions and ground motion intensity

The intensity of ground motion under a building during an earthquake predominantly depends on the distance of the building to the causative fault, and the local soil conditions. Mapping of seismic hazard at micro scale considers both variables. Seismic hazard, or ground motion intensity is mapped in terms of PGA and PGV in the JICA report. PGV usually reflects the effect of soil conditions very well during a large magnitude earthquake (Wald et al., 1999). The correlation of PGV and shear wave velocities of local soils can easily be observed from the associated maps given in the JICA report. Accordingly, PGV is selected to represent the ground motion intensity in this study.

The PGV map in the JICA report has contour increments of 20 cm/s2. The intensity zones in Istanbul are expressed accordingly, in terms of the associated PGV ranges.

Zone I : 60 < PGV < 80 cm/s2

Zone II : 40 < PGV < 60 cm/s2

Zone III : 20 < PGV < 40 cm/s2

The superiority of PGV over PGA can be best observed at the Prince Islands, which are bedrock outcrops. They are in PGV zone II. However if PGA were employed, they would be in zone I due to their proximity to the Marmara fault. It is well documented that the Prince Islands were not severely affected from the strong historical earthquakes.

The differences in ground motion intensities at three PGV zones are reflected in the initial scores given in Tables 2 and 3, according to a study conducted by Akkar and Sucuoglu (2003).

4.3 Testing of risk assessment tools for the Düzce database

Seismic performances of the 477 buildings surveyed in Düzce have been tested with the tools presented in Tables 2 and 3. A cut-off performance score of 50 has been calculated for both survey levels through an optimization analysis to obtain the best prediction. The results revealed that at the level-1 survey (street surveys), 72 % of the severely damaged and collapsed buildings, and 72% of the remaining buildings with lesser damages are identified successfully by using Table 2. These ratios increased to 75 % when level-2 survey results are evaluated by using Table 3.

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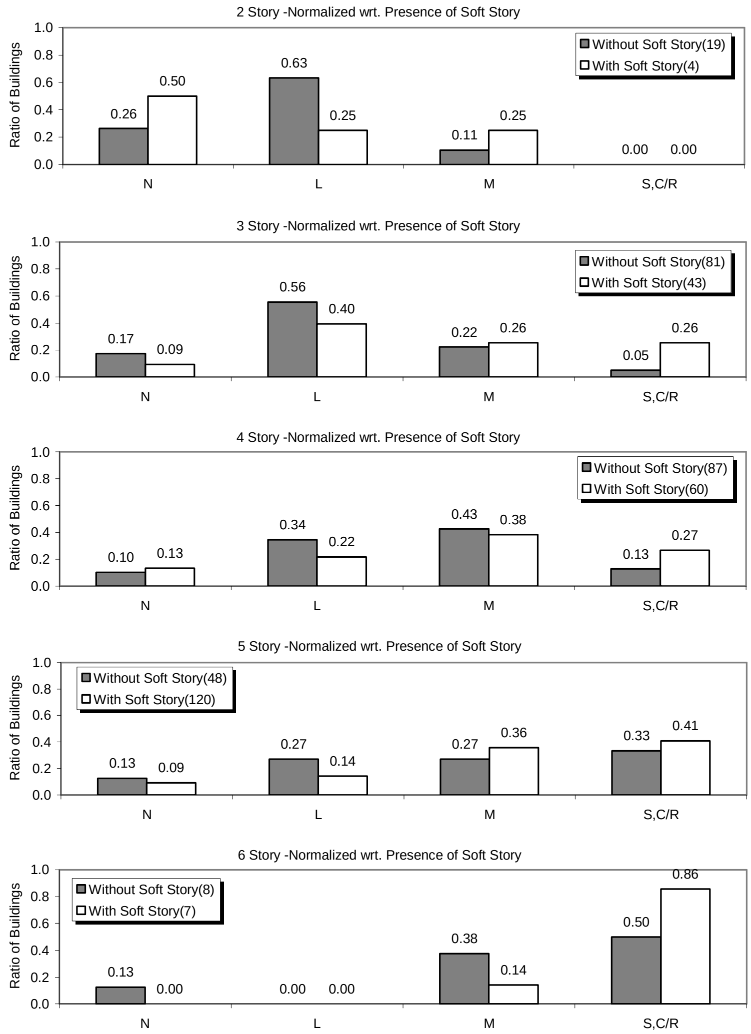

Figure 3. Correlation of damage with the presence of soft story

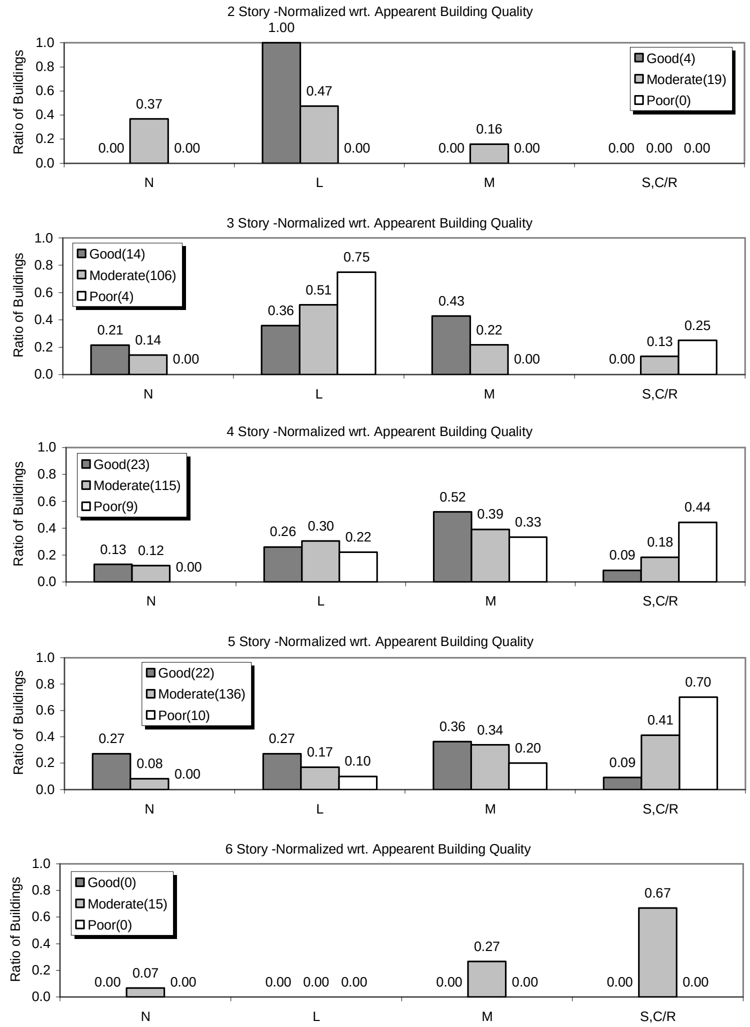

Figure 4. Correlation of damage with the apparent building quality

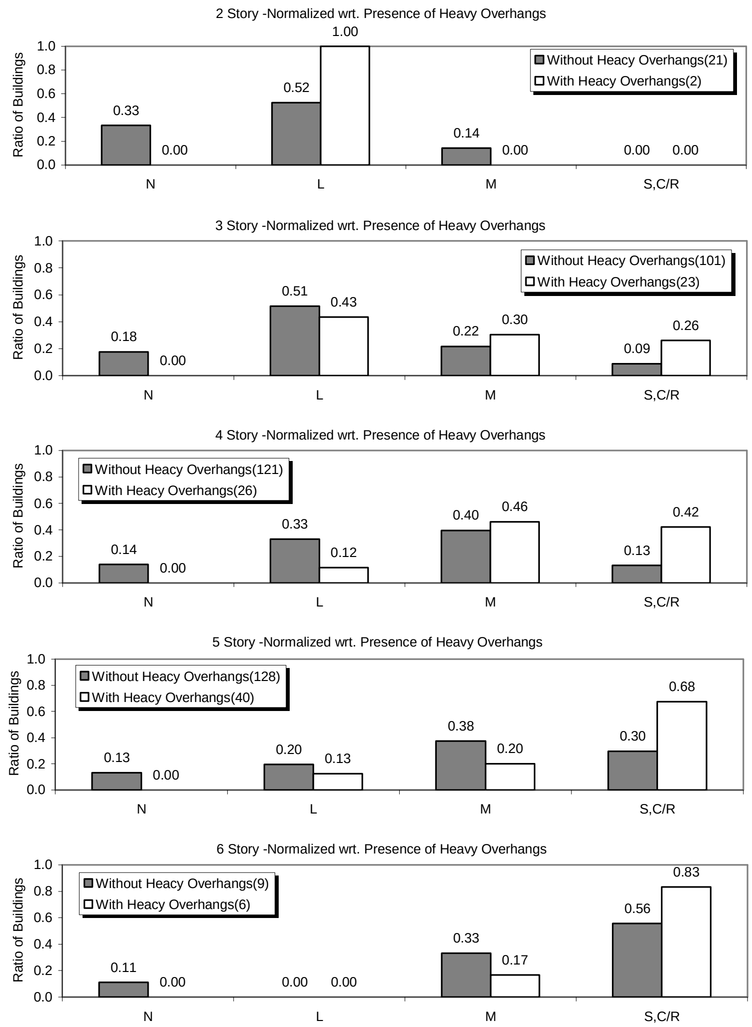

Figure 5. Correlation of damage with heavy overhangs

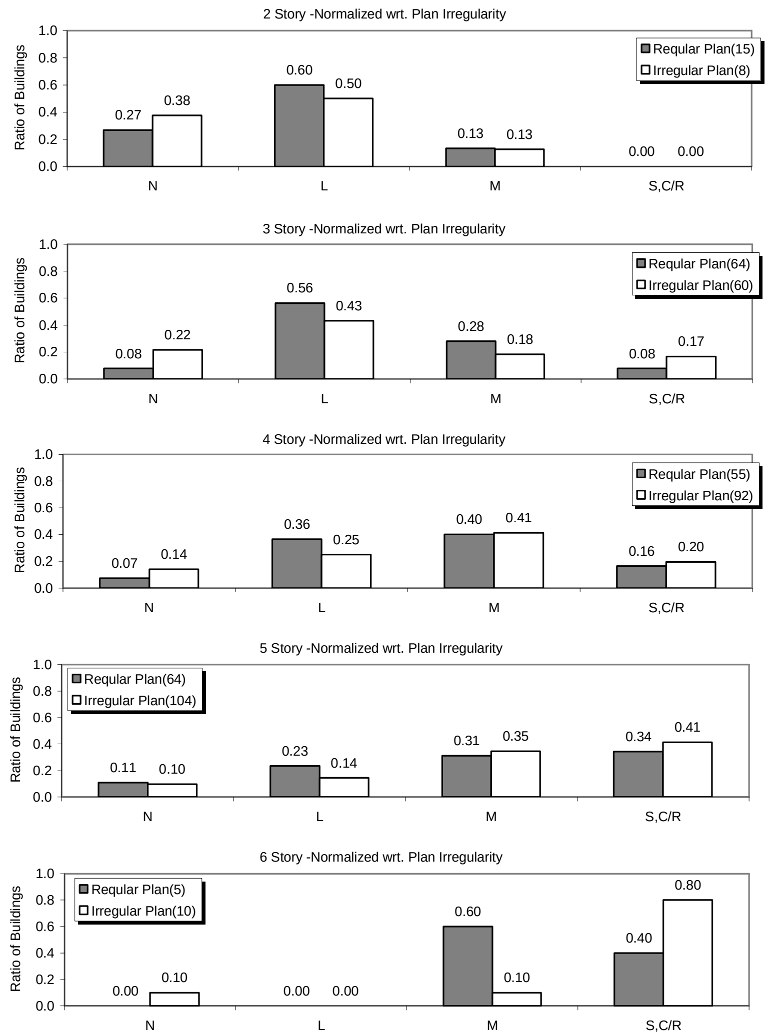

Figure 6. Correlation of damage with plan irregularity

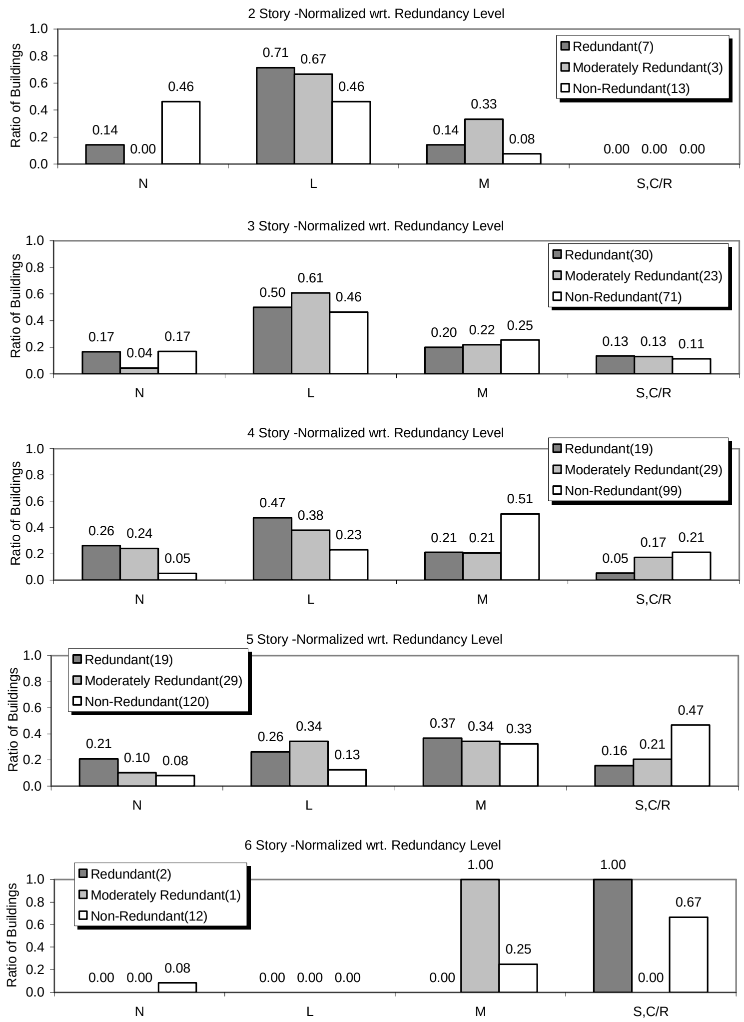

Figure 7. Correlation of damage with redundancy

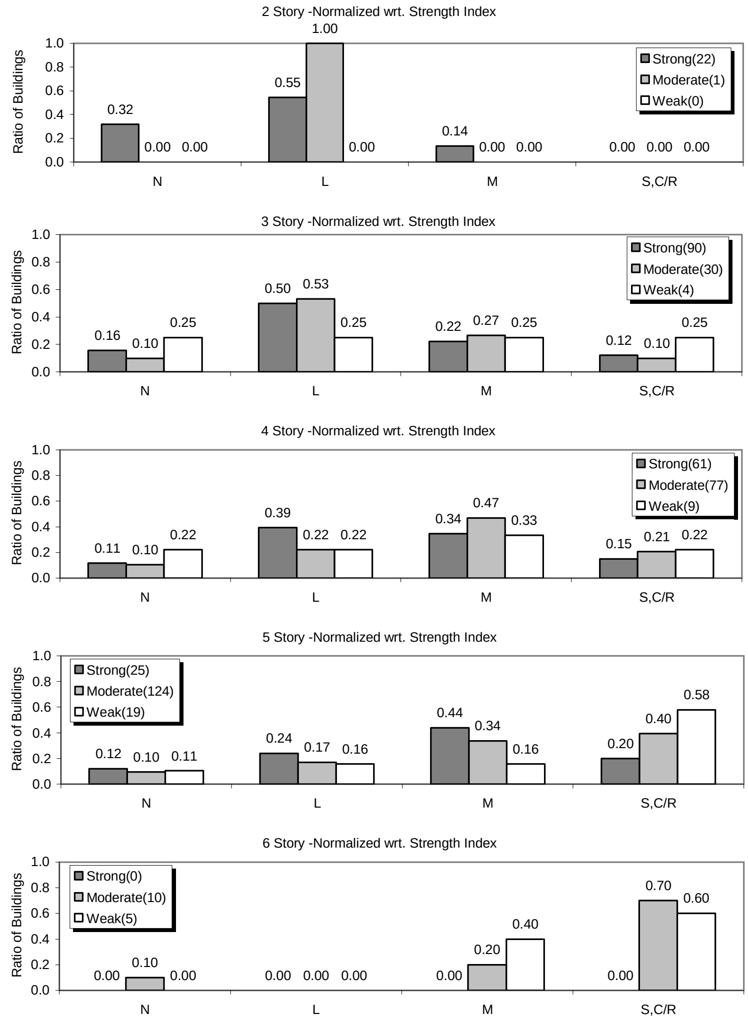

Figure 8. Correlation of damage with the strength index

Table -3. Initial and Vulnerability Scores for Level-2 Survey of Concrete Buildings

Topog. Effects	Plan Irreg.	Redundancy	Strength Index
0	0	0	-5
0	-2	0	-5
-2	-2	-5	-5
-2	-5	-10	-10
-2	-5	-10	-10

Soft story : No (0); Yes (1)
Heavy overhangs : No (0); Yes (1)
Apparent quality : Good (0); Moderate (1); Poor (2)
Short columns : No (0); Yes (1)
Pounding effect : No (0); Yes (1)
Topography effect : No (0); Yes (1)
Plan irregularity : No (0); Yes (1)
Redundancy : Redundant (0), Semi-redundant (1), Weakly redundant (2)
Strength Index : Strong (0),

Table -2. Initial and Vulnerability Scores for Level-1 Survey of Concrete Buildings

Story #	Zone I 60<PGV<80	Zone II 40<PGV<60	Zone III 20<PGV<40	Soft Story	Heavy Overhang	Apparent Quality	Short Column
1, 2	90	125	160	-5	-5	-5	-5
3	90	125	160	-10	-10	-10	-5
4	80	100	130	-10	-10	-10	-5
5	80	90	115	-15	-15	-15	-5
6,7	70	80	95	-15	-15	-15	-5

Vulnerability Parameters

Soft story : No (0); Yes (1)
Heavy overhangs : No (0); Yes (1)
Apparent quality : Good (0); Moderate (1); Poor (2)
Short columns : No (0); Yes (1)
Pounding effect : No (0); Yes (1)
Topography effect : No (0); Yes (1)

Story #	Zone I 60<PGV<80	Zone II 40<PGV<60	Zone III 20<PGV<40	Soft Story	Heavy Overhang	Apparent Quality	Short Column	Pound.
1, 2	95	130	170	0	-5	-5	-5	0
3	90	125	160	-10	-5	-10	-5	-2
4	90	115	145	-15	-10	-10	-5	-3
5	90	105	130	-15	-15	-15	-5	-3
6, 7	80	90	105	-20	-15	-15	-5	-3