Seismic Risk Assessment Survey of Urban Buildings

Haluk Sucuoglu and Ufuk Yazgan

Introduction

The classical engineering approach to seismic safety for building structures is to ensure compliance with seismic design codes. This is a valid approach for new buildings. However the majority of existing buildings in seismic zones do not meet modern building codes. Yet, the percentage of severely damaged and collapsed buildings after a strong earthquake is much less than the percentage of buildings with substandard construction. The difference is significant. Countrywide, some 90 percent of buildings in Turkey have substandard construction. However, as a result of two consecutive earthquakes in 1999, just 20 percent of buildings in Düzce, a city heavily hit by the earthquakes, collapsed (Sucuoglu and Yilmaz, 2001). Similar percentages were observed in Gölcük and Adapazari. A recent loss estimation study for Istanbul (JICA, 2002) revealed that under a scenario earthquake of magnitude 7.4 along the Marmara Sea fault, seven percent of buildings can be expected to collapse. With high numbers of substandard buildings yet a significantly lower percentage of them expected to be severely damaged, a sound risk assessment methodology should be developed to identify the buildings at risk. In this study, a two-stage seismic risk assessment procedure for low to medium-rise (less than 8 stories) ordinary reinforced concrete buildings is detailed. The procedure is based on several building parameters that can be easily calculated during a systematic survey. The main objective of the procedure is to develop a building database and rank the buildings with respect to their expected seismic performance under a defined ground excitation.

Two-Stage Risk Assessment Procedure

Trained observers can conduct stage one of a two-step survey from the sidewalk. In stage two, observers enter a building's basement and ground levels to collect basic structural data. The acquired data is then used to calculate a risk score for each building.

Stage 1: Observations from the Street

The street survey is based on simple structural and geotechnical parameters that can be observed easily from the sidewalk. The time required to collect such data for one building is about ten minutes. Building vulnerability is represented by:

1. The number of levels above ground (1 to 7)
2. Presence of a soft storey (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 on a variable scale under earthquake excitations. The correlation between observed building damage and parameter variation, based on building data from Düzce, allows assessment of the weight of each parameter to be rated for seismic performance. A linear combination rule for the selected parameters was determined in order to predict the damage distribution displayed by the data. Once such a combination rule has been developed, it is possible to rate the seismic performance of reinforced concrete building structures by a simple walk-down survey procedure. The proposed method is similar to the seismic evaluation procedure developed in FEMA-154 (1988). However, it is believed that the method detailed in this paper provides a broader description of seismic risk for multi-storey reinforced concrete buildings that do not comply with modern seismic design and construction code requirements.

The objective of developing a performance scale for existing buildings is to provide a simple tool that can be used easily by building owners and government administration. If an individual building falls in the lower (high-risk) part of the scale, then a more detailed evaluation will be necessary. The performance scale sorts building stock according to seismic vulnerability. 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 should be subjected to further evaluation before final decisions on retrofitting and demolition are made.

Each vulnerability parameter that impacts the damage distribution of the building data collected is discussed in detail in the following paragraphs.

The Number of Stories

Field observations following the 1999 Kocaeli and Düzce earthquakes revealed that there is a strong correlation between a building's number of stories and its vulnerability to damage. If all buildings conformed to modern seismic design codes, then a uniform distribution of damage would be expected. However, if the majority of buildings in an earthquake zone do not conform to building codes, then increasing the number of stories increases seismic forces linearly. After the two earthquakes in 1999, damage distribution and number of floors for all 9,685 buildings in Düzce was obtained. The results are shown in figure 1 below. It can be seen that damage grades shift linearly with the number of stories. As the number of stories increases, the percentage of undamaged and lightly damaged buildings decreases. However, the trend is the opposite for moderately and severely damaged buildings. This is an indication that the number of stories is significant, perhaps the most dominant parameter in determining the seismic vulnerability of typical multilevel concrete buildings in Turkey.

Presence of a Soft Storey

A soft storey usually exists in a building when the ground storey has less stiffness and strength than the upper stories. This mostly arises in buildings located along a main street. The ground floors, level to the street, are used as commercial spaces whereas residents occupy the upper stories.

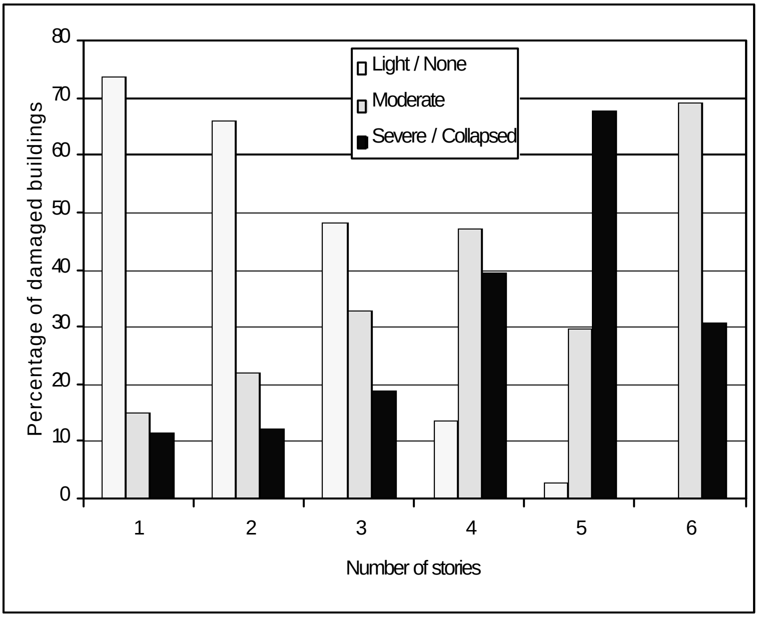

Figure 1. Damage distribution in Düzce after the 1999 earthquakes, with respect to the number of stories

Upper stories benefit from the additional stiffness and strength provided by partition walls, but the lower-level commercial space is often open between frame components. Ground floors also tend to have higher clearances and a different axis system resulting in irregularity. From an earthquake engineering perspective, these negative characteristics result in a 'soft storey.' Worldwide, buildings with soft stories often collapse in a pancake manner during earthquakes.

Presence of Heavy Overhangs

Heavy balconies and overhanging floors in multilevel reinforced concrete buildings shift the mass center upwards, increasing seismic lateral forces and moments for overturn during earthquakes. Balconies with large overhanging cantilever spans and heavy concrete parapets sustained heavier damage than regular buildings during recent earthquakes in Turkey. Since this building feature can easily be observed during a walk-down survey, it is included in the parameter set.

Apparent Building Quality

Material, workmanship and maintenance create a building's quality. A well-trained observer can classify a building's quality as roughly good, moderate or poor. During recent earthquakes in Turkey, a close relationship was observed between apparent quality and building damage. A building with poor apparent quality is expected to have weak material strength and inadequate detailing.

Presence of Short Columns

Semi-filled frames, band windows in semi-buried basements and mid-storey 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 high shear force relevant to their shortened lengths. Short columns can be identified from outside because they usually form along the exterior axes.

Pounding between Adjacent Buildings

As a result of different vibration periods and non-synchronized vibration amplitudes, close buildings knock together during an earthquake. Uneven floor levels aggravate the effect of such pounding. Buildings subjected to pounding receive heavier damage on 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 classify local soil as stiff or soft. In urban environments, geotechnical data provided by local authorities can be used to classify local soil conditions.

Topographic Effects

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

Stage 2: Measurements in the Ground Storey and Basement

When building data are obtained from street surveys and evaluated, it is possible to identify buildings as moderate and high-risk according to their performance scores. Observer teams enter the basements and ground floors of these buildings to collect data for further evaluation. Their first task is the confirmation or modification of the previous grading on soft stories, short columns and building quality. The second and more elaborate task is to prepare a sketch of the framing plan at the ground level and measure the dimensions of columns, concrete and masonry walls. These tasks should take a three-member team two hours to complete. This data is then used to calculate the following parameters:

Plan Irregularity

Irregularity in building plans is a deviation from a rectangular plan and has orthogonal axis systems in two directions. Such deviation from plan regularity leads to irregularities in stiffness and strength distribution, which in turn increases the risk of damage localization under strong ground excitations. In an 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. These frames exhibit inelastic response during earthquakes and suffer from a lack of sufficient redundancy, which leads to localized heavy damage. A normalized redundancy ratio is defined by the following expression (Özcebe et al., 2003).

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

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 closely 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 level of an existing building is possible, strength ratio SR can be defined as follows (Özcebe et al., 2003).

SR = min (A_{nx}, A_{ny})

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

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.

SI = 0 when SI > 0.0025 : strong

SI = 1 when 0.0015<SI<0.0025 : moderate

SI = 2 when SI < 0.0025 : weak

Evalution of the Düzce Database

A total of 477 buildings were surveyed in Düzce following the two earthquakes in 1999. Building damage was classified into four groups: none, light, moderate and severe/collapsed. A building with light damage required minor repairs after the earthquake. Moderately damaged buildings required structural repairs. For severe damage, buildings were strengthened to upgrade seismic capacity or demolished. The damage distribution of the buildings surveyed and the number of stories is presented in table 1.

The variation of damage in the 477 buildings and survey parameters were obtained independently for each parameter. The Düzce database did not include 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

The Number of Stories

To check whether the surveyed building stock is representative of the Düzce building inventory, the distribution of damage and the number of stories were further considered. The results are shown in figure 2. The trend is similar to that in figure 1, which confirms that building damage is strongly correlated to the number of stories. Accordingly, this parameter was separated from the others. Data for the other parameters was sorted for each storey number separately to eliminate their effect on the other parameters.

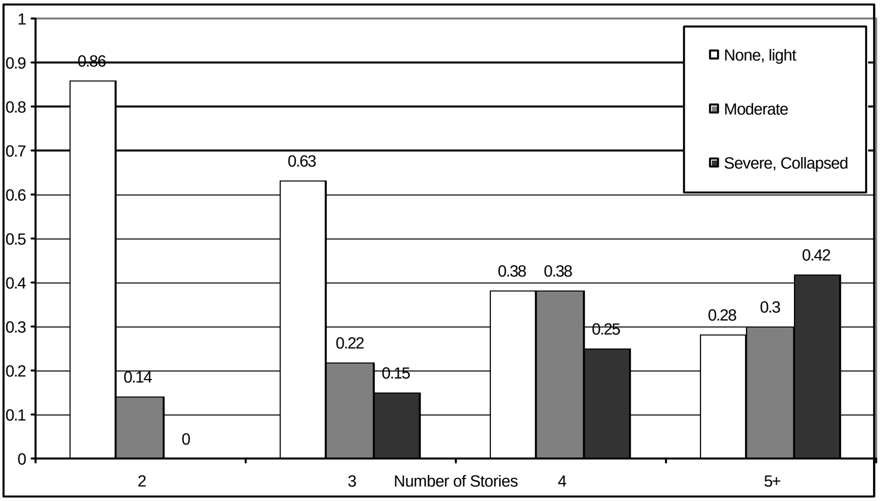

Figure 2. The distribution of damage with the number of stories in 477 buildings

Presence of Soft Storey

Of the 477 buildings surveyed, 234 had soft stories. These buildings are grouped with respect to damage category and number of stories, then this number is normalized relative to the total number of buildings in each group. The results are presented in figure 3. For all storey numbers, it can be seen that buildings with soft stories exhibit higher severe damage/collapse ratios compared to those without soft stories. Notably, almost all severely damaged buildings have soft stories. This is an important observation because if a building with a soft storey is vulnerable to seismic damage, it is highly likely that damage will be 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 consistent variation with the number of stories. Therefore this parameter can be assessed independently from the number of stories.

Apparent Building Quality

The quality classification of the 477 surveyed buildings revealed that 63 were good, 391 were moderate and 23 were poor. These buildings were grouped with respect to the damage categories and number of stories, then their number was normalized relative to the total number of buildings in each class. The results are presented in figure 4. The data for six-storey buildings is meaningless. However the data for three to five-storey buildings reveal that the severely damaged/collapsed buildings are of lower quality than buildings in other damage groups. An increasing effect can also be seen based on the number of stories.

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 477. The number was obtained by normalizing the number of buildings in each category with respect to the total number of buildings with and 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 two to six-storey buildings with the storey number and the presence of overhangs. Accordingly, this parameter should be considered in the seismic risk assessment of buildings with more than 3 stories.

Plan Irregularity

The results obtained from the survey data are presented in figure 6 according to number of stories. The number of buildings classified as irregular was 274 of 477. Irregularity in plan does not influence damage distribution in two-storey buildings. In three to six-storey buildings, those with irregular plans have a greater percentage of severe damage or collapse than buildings with regular plans. Therefore plan irregularity should be considered a parameter in determining the seismic risk of buildings higher than two stories.

Redundancy

The majority of buildings in the Düzce database were classified as weakly redundant (315), 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 four to six-storey groups. Weakly redundant buildings do appear among the severely damaged and collapsed buildings that increase with the number of stories. They become notable in five and six-storey buildings.

Strength Index

Only 37 buildings of the 477 were classified as weak in strength. More than half of the five and six- storey weak buildings collapsed or sustained severe damage (figure 8). However, strength index has no influence on the damage distribution of two to four-storey buildings. Therefore this parameter can only be considered when identifying the risk of five and six-story buildings.

Two Stage Seismic Risk Assessment Tools for Istanbul

This section presents a practical risk assessment procedure for Istanbul that is based on the data acquired from the two-stage survey. The weight of each building vulnerability parameter was evaluated statistically based on the Düzce database. Statistical analysis was conducted with the program package SPSS Version 11, using the "Multivariable Stepwise Linear Regression Analysis" procedure. The results were then smoothed and the weights of the parameters for which there was no available data (soft storey, pounding, topography) were assigned using engineering judgment. Local soil conditions and associated ground motion intensity were identical to the case of Düzce. However, different intensity zones were used for Istanbul (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 was considered by applying velocity-based conversion factors as explained below.

Building Performance Score

Once the vulnerability parameters of a building are obtained from two-level surveys and their location is determined, the seismic performance scores for survey levels one and two are calculated using tables 2 and 3, respectively. In these tables, an initial score is given 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:

PS = (Initial Score) - $\sum$(Vulnerability parameter) x (Vulnerability Score)

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

Local Soil Conditions and Ground Motion Intensity

The intensity of ground motion under a building during an earthquake depends upon the distance of the building from the causative fault and local soil conditions. Mapping seismic hazard at a 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 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. 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 in 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 historically, the Prince Islands have not been severely affected by strong 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).

Testing of Risk Assessment Tools for the Düzce Database

Seismic performance of the 477 buildings surveyed in Düzce has been tested with the tools presented in tables 2 and 3. To obtain the best prediction, a cut-off performance score of 50 was calculated for both survey levels through optimization analysis. The results revealed that at the level one survey (street surveys), 72 percent of severely damaged and collapsed buildings and 72 percent of the remaining buildings with lesser damage were identified successfully using table 2. These ratios increased to 75 percent when level two survey results were evaluated using table 3.

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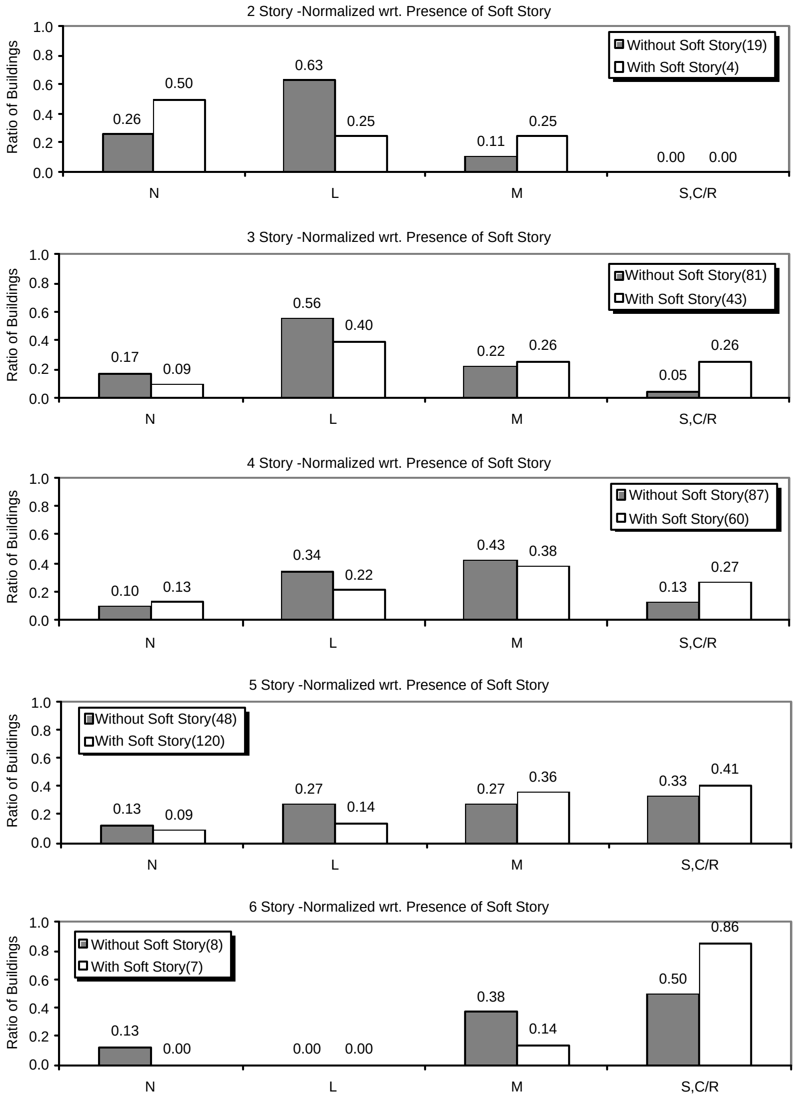

Figure 3. Correlation of damage with the presence of soft story

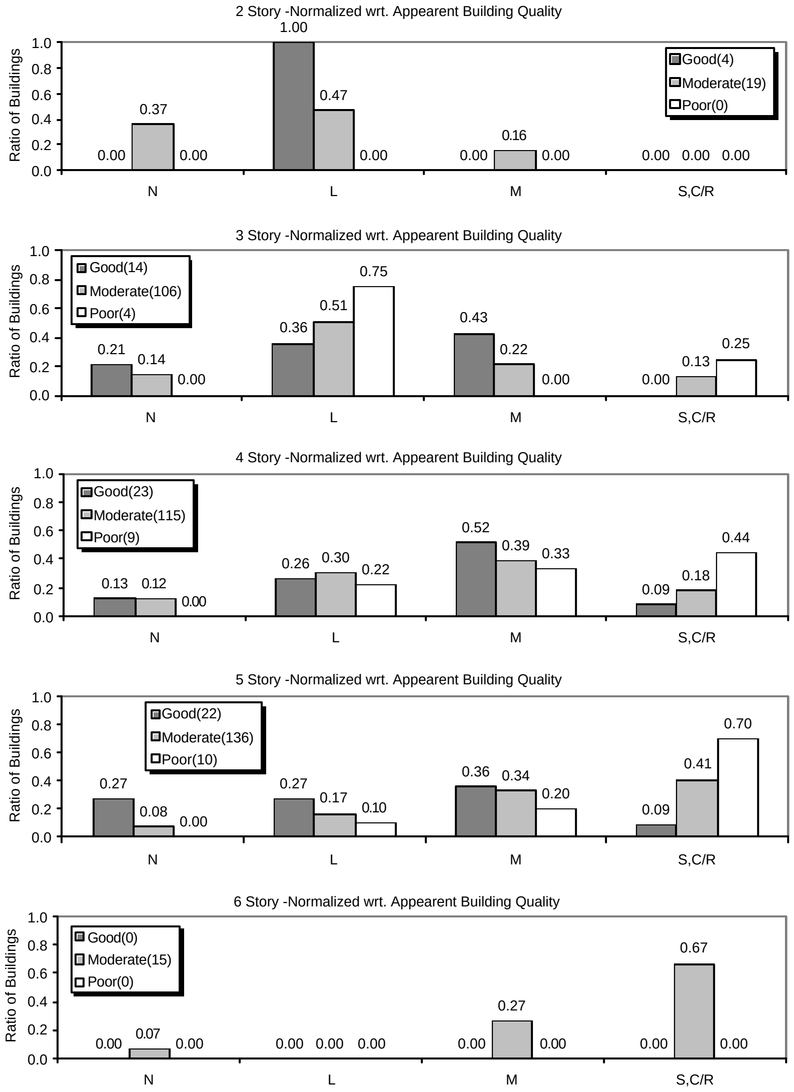

Figure 4. Correlation of damage with the apparent building quality

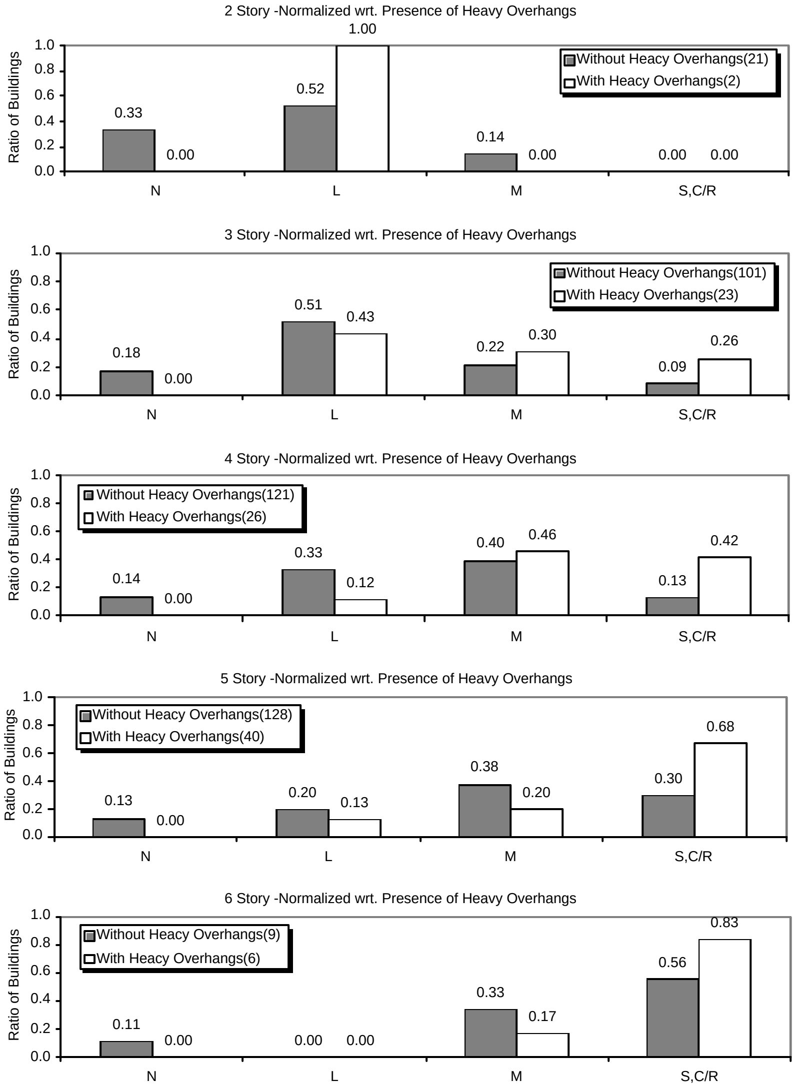

Figure 5. Correlation of damage with heavy overhangs

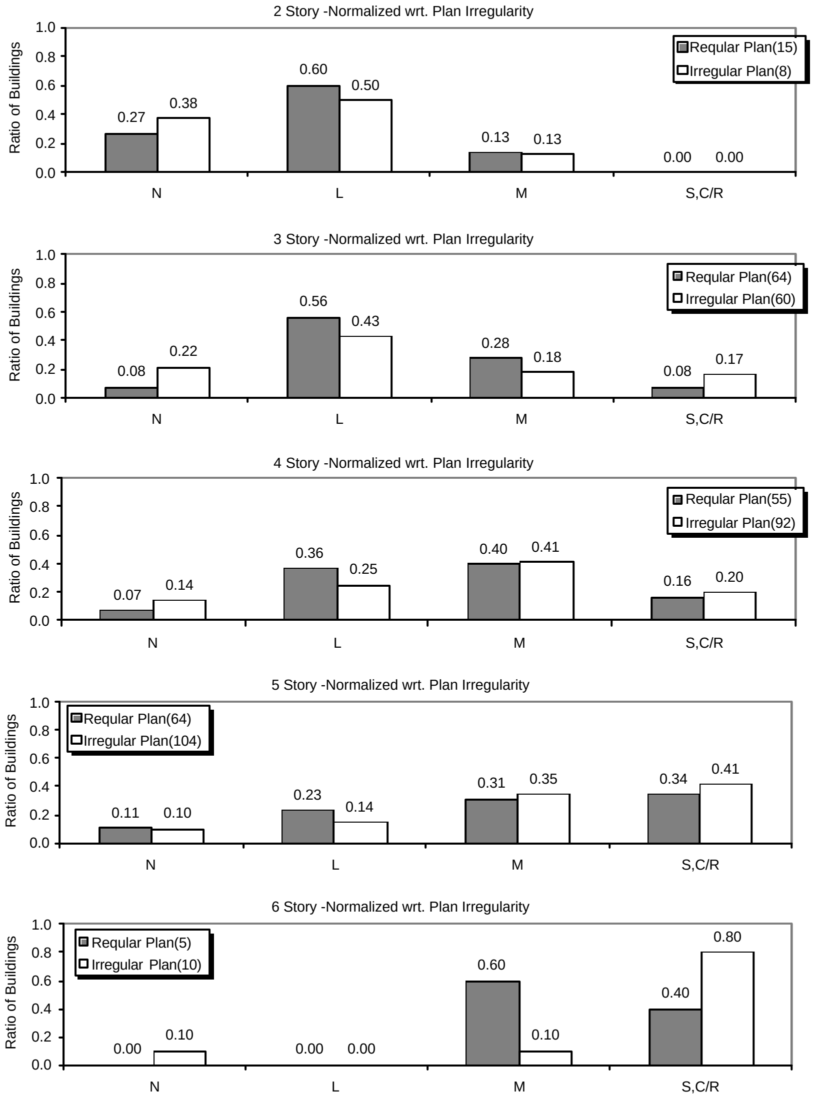

Figure 6. Correlation of damage with plan irregularity

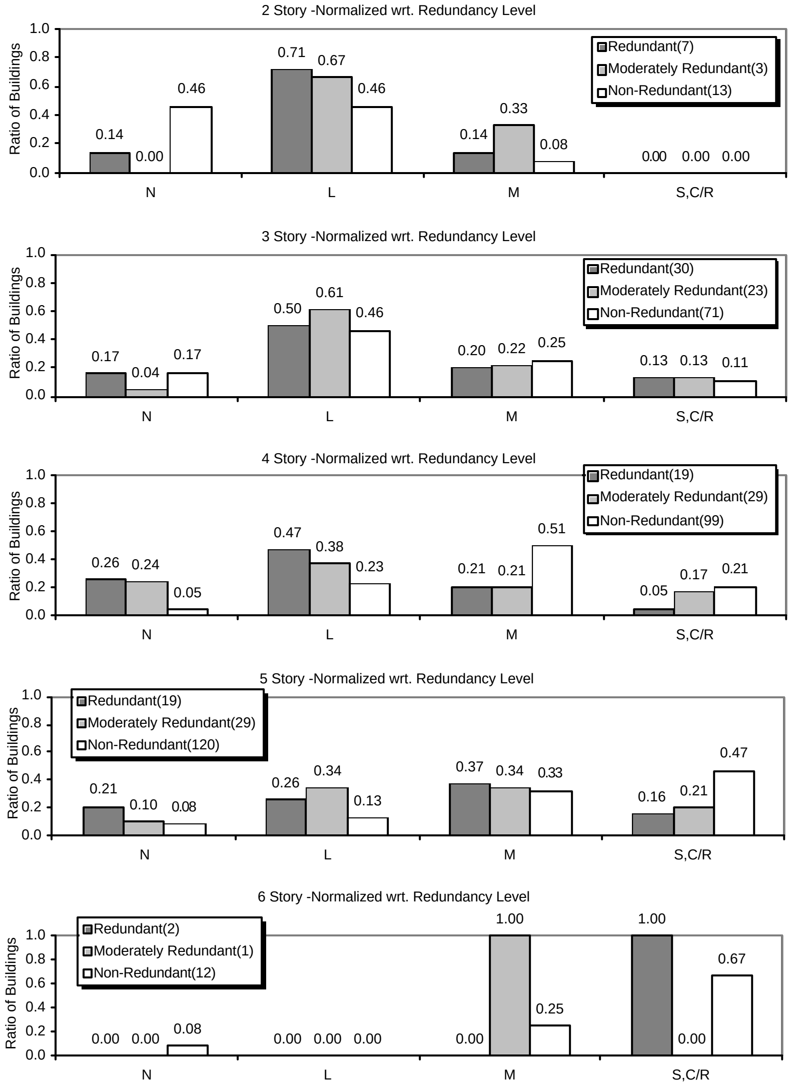

Figure 7. Correlation of damage with redundancy

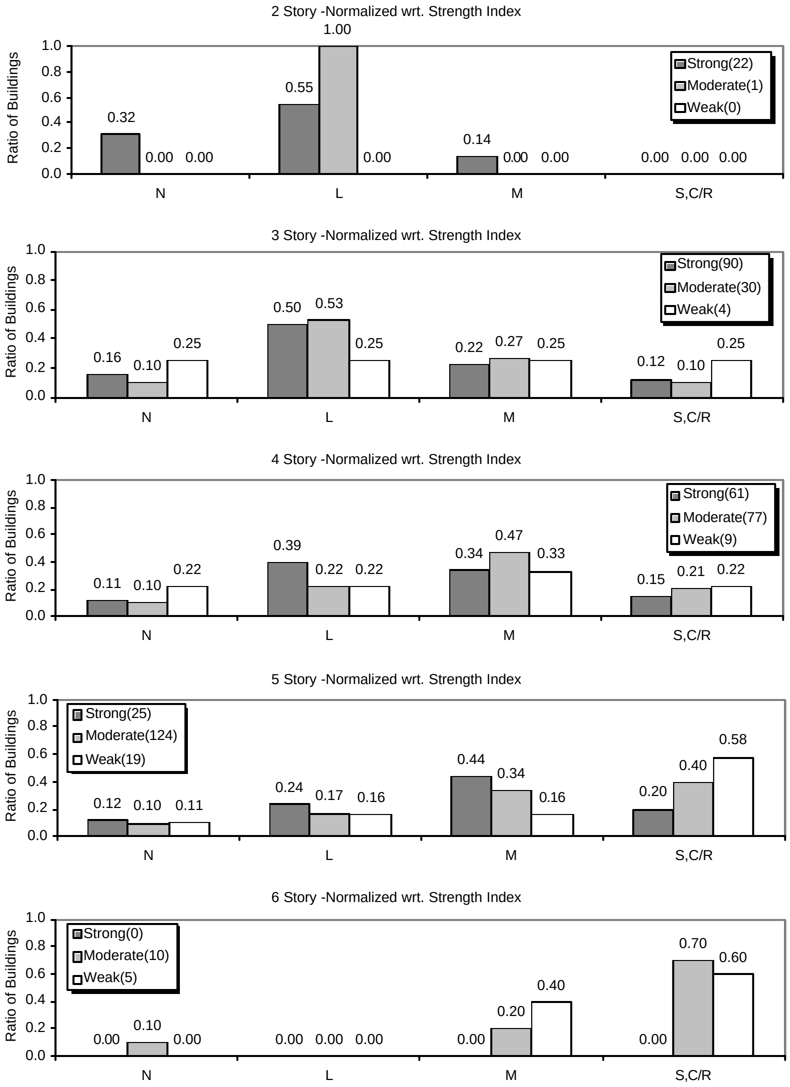

Figure 8. Correlation of damage with the strength index

Table 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	Pounding	Topographic Effects
1, 2	90	125	160	0	-5	-5	-5	0	0
3	90	125	160	-10	-10	-10	-5	-2	0
4	80	100	130	-15	-10	-10	-5	-3	-2
5	80	90	115	-15	-15	-15	-5	-3	-2
6, 7	70	80	95	-20	-15	-15	-5	-3	-2

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)

Table 3. Initial and Vulnerability Scores for Level-2 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	Pound.	Topog. Effects	Plan Irreg.	Redundany	Strength Index
1, 2	95	130	170	0	-5	-5	-5	0	0	0	0	-5
3	90	125	160	-10	-5	-10	-5	-2	0	-2	0	-5
4	90	115	145	-15	-10	-10	-5	-3	-2	-2	-5	-5
5	90	105	130	-15	-15	-15	-5	-3	-2	-5	-10	-10
6, 7	80	90	105	-20	-15	-15	-5	-3	-2	-5	-10	-10

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)
Plan irregularity : No (0); Yes (1)

Redundancy : Redundant (0), Semi-redundant (1), Weakly redundant (2)

Strength Index : Strong (0), Moderate (1), Weak (2)