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Tuğçe Kazanasmaz Zehra

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The Impact of Planimetric Configuration on Structurally Damaged Residential Buildings

Zehra Tuğçe Kazanasmaz

Department of Architecture, Izmir Institute of Technology, Gulbahce Kampus, Urla, Izmir 35430, Turkey
Corresponding author: Tel: +90 232 7507063; Fax: +90 232 7507012; Email: tugcekazanasmaz@iyte.edu.tr

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Abstract: This study was conducted to determine a significant relationship between planimetric configuration and vulnerability of hazardous buildings located in seismic zones by developing design and construction efficiency indicators. Case study examples were chosen from residential buildings in Bolu, Düzce and Kaynaşlı in Turkey, which were damaged by the 1999 earthquakes. Utilizing field survey drawings, efficiency quotients; compactness quotients; construction efficiency ratios; aspect ratios and height-to-base ratios were defined as planimetric configuration indicators. The significant relationship between these aspects and the damage level of buildings were determined through statistical analyses and scatter charts. Planimetric configuration – including building geometry, cantilever projections and layout of columns – was reviewed according to the Turkish Earthquake Code. Findings revealed certain dependencies for efficiency ratios, which would satisfactorily predict the seismic vulnerability of buildings based on planimetric configuration. Researchers in the field of architecture who are engaged in earthquake-resistant design may use the general methodology. In addition, architects and structural engineers can use this approach presented here to evaluate their design.

Keywords: Earthquakes, Earthquake-resistant design, Planimetric configuration, Residential buildings, Structural damage

Introduction

Architectural design has a direct impact on the structural system of a building especially on its seismic performance (McDonald, 1994; Mendi, 2005; Naeim, 2001; Özmen & Unay, 2007; Toker, 2004). Several design irregularities and faults in building configuration (discontinuity in slabs, re-entrant corners, non-parallel axes of structural elements, discontinuous beams, cantilever projections and columns with broken axis) (Naeim, 2001; Ministry of Public Works & Settlement, 2006), may cause structural damage under earthquake forces (Özmen & Unay, 2007). In addition, inadequately designed building details and non-structural components may lead to deficiencies in structural strength of buildings and may affect their seismic vulnerability. However, not only building configuration but also the density of structural elements (walls and columns) determines the earthquake resistance of buildings. At the base of the building, walls and columns carry both their own lateral load and the shear forces of all structural members in all stories above. The members transmit those loads to the ground. During earthquakes, these elements also resist overturning and torsional moments and as a result, generate greater resisting moment in the structure. This condition creates a need for redundancy in the structural design, which then results in high plan density (Naeim, 2001). Such elements' density is also a function of their efficiency in a broad sense, and the linear amount of wall is not the only architectural determinant for the efficient configuration but the number and spacing of columns (Reitherman, 2005). The first step to analyse these items then would be to assess the degree of their existence in real situations. To this end, an investigation was carried out to assess the dependency of damage level on building configurations of residential buildings structurally damaged by 1999 earthquakes in Turkey.

The Turkish Earthquake Code has been used to design structural elements of buildings and to define their seismic performance over the years. It covers basic guidelines in the field of construction in Turkey. It stipulates standards and rules about the structure by focusing on certain irregularities and building configuration faults in design. According to this code, its main purpose is to make the building remain intact without collapse (Ministry of Public Works and Settlement, 2006).

Several studies related to hazardous buildings, their damage level and types of damage that occurred in various structural elements (Dönmez & Pujol, 2005; Hassan & Sözen, 1997; Lourenco & Roque, 2006; Sucuoğlu, Gür & Günay, 2004) resulted in practical outcomes for the evaluation of seismic performance and seismic vulnerability of buildings. Most of the proposed solutions for seismic design enhancement related to the field of structural engineering. Some quantitative architectural features (number of storeys, height of floors, room dimensions) are mentioned briefly, but only to supply information for structural analysis of buildings. On the other hand, seismic codes such as ASCE 7-05 Standard (American Society of Civil Engineers, 2006) and Turkish Earthquake Code (Ministry of Public Works and Settlement, 2006) mention irregular building configurations. Thus, engineers would take precautions and calculate appropriate load distributions to the structural design according to the code. The benefit of these codes seems to be in the integration of architecture and structure for the most efficient seismic design. The basic differences between them are in the load calculation factors including values of earthquake forces, ground motion values and spectral response acceleration coefficients according to soil and the function of buildings.

Efficient configurations have been basic architectural determinants in seismic design. As an example, a regular configuration (a simple and symmetric structure) leads to a regular distribution of strength, mass and stiffness within the building. This may produce less hazardous effects during and after earthquakes (Reitherman, 2005). To explain this more explicitly, the lateral-force-elements (walls and columns) should be located about the centre of mass and the stiffness by these elements should have a centre of rigidity co-located with this centre of mass. In plan, this causes uniform torsional resistance (Dorwick, 1987; Reitherman, 2005). In another study, Arbabian, (2000) focused on the role of architects in seismic design by analysing the case of traditional Iranian construction methods. The author addressed the geometric plan, building shape and configuration, symmetry in plan and elevation, and symmetrical load distribution as architectural aspects of buildings that affect earthquake resistance. Other studies focused on technical design objectives for seismic performance and seismic design guidelines for reinforced structures (Holmes, Kircher, Petak & Youssef, 2008; Kabeyasawa & Moehle, 2002).

In this study, design efficiency ratios were offered to conduct the assessment for the occurrence of significant relations between damage level and planimetric configurations of hazardous buildings. The approach sought here is simple and fast, being based on a geometric approach for the immediate evaluation of a proposed building (using architectural drawings). Researchers would be aware of this methodology as the utilization of configuration-based ratios (derived from certain building dimensions) and then to apply it for architectural design evaluation processes. This may allow the detection of buildings at possible risks against any earthquake and offer precautions to be taken for possible structural hazard. Architects may benefit from this study by using its method as a design performance tool to assist in their design process. Additionally, structural engineers would be informed and be aware of the degree of architectural impact concern in structural decision making processes, for example, they might decide whether to locate load bearing walls or not according to the existing configurations.

The principal aim of the study was an analysis of hazardous buildings with respect to their design efficiency as a representative tool for their building configuration. This is taken to be a significant indicator of not only their seismic vulnerability (damage level) but also of their potential adaptability under any renovation or retrofit design processes. It is also thought that the outcomes of this analysis would provide much-needed feedback and be of benefit to such designers (architects and structural engineers) who may be seeking better solutions in these areas. It also offers a trial approach in the field of architecture by its implementation to future researchers like a guide.

The specific objectives were the following:

a. To identify relevant attributes for building configuration of hazardous residential buildings,
b. To determine net usable, gross floor and construction areas as well as external surface areas and external perimeter dimensions.,
c. To construct intrinsic floor-area, height-to-base and aspect ratios as building configuration indicators for measuring design efficiency,
d. To determine whether or not these ratios showed any significant difference among hazardous buildings because of different seismic vulnerabilities and their predefined damage level, and
e. To construct scatter charts to show whether there is a relation between seismic vulnerability of buildings and certain building configuration indicators.

Buildings under Study

The subject buildings in this study were defined to be residential buildings that were structurally damaged during the 1999 earthquakes in Turkey. They were located in the three provinces of Bolu, Düzce, and Kaynaşlı. In this section, these 1999 earthquakes in Turkey are explained briefly. Planimetric configurations of the sample buildings and their structural layout were then analyzed descriptively. Finally, calculated areas and indicator ratios derived from these areas were summarised respectively.

Earthquakes

Two earthquakes occurred in the Marmara region of Turkey in 1999; one on the 17 August, Kocaeli (İzmit) earthquake, (M_w=7.4, USGS, Kandilli Observatory) and the other was the 12 November, Düzce earthquake (M_w=7.2, USGS). Due to these earthquakes, many fatalities and injuries occurred; many commercial and residential structures were damaged and/or collapsed. Several studies were conducted about these earthquakes relating to a number of issues. One study, for example, about the Kocaeli (İzmit) earthquake was related to its geoscientific aspects and their impact on structures as well as the built environment (Scawthorn & Johnson, 2000). Another one focused on the structures—viaducts and tunnels—damaged after the Düzce Earthquake (Ghasemi, Cooper, Imbsen, Piskin, İnal, & Tiras, 2007). Dönmez and Pujol, (2005) pointed out the relation between seismic vulnerability of damaged buildings and number of storeys together with their spatial distribution in the region. In view of recent reports and ongoing research, it was once more noted that many residential buildings constructed as one to six storey reinforced concrete structures with hollow brick infill walls were affected in various degrees by the earthquakes. These buildings were consequently the subject of this study.

Figure 1 shows a detailed photo of a damaged building with a crack on its structural member. Another one is shown with damage to a brick infill wall in Figure 2.

Residential Buildings

The study material itself consisted of ground floor structural plan drawings prepared by field teams comprising representatives from several universities in Turkey and the United States. These constituted a population of 28 hazardous one to six storey-buildings with various floor heights. Field survey teams assigned alphanumeric identity codes for each building. They also noted dimensions and footprint areas of structural elements (reinforced concrete columns, reinforced concrete walls and masonry walls) several overall dimensions


(a)


(b)

Figure 1: *A five-storey hazardous building in Bolu (a) with a structural crack on the column and (b) beam connection inside.*
(Source: Field teams from various universities.http://www.anatolianquake.org)

Figure 2: *Damage occurred on the brick wall in a hazardous building in Kaynaşlı.*
(Source: Field teams from various universities.http://www.anatolianquake.org)

(story heights, spanning dimensions between axes, overhang areas) and ratios to define the damage level for each building. This survey is referred to as the "Hassan Survey" (Hassan & Sözen, 1997) with regard to its data gathering and sampling processes (Dönmez & Pujol, 2005). The observed damage was evaluated by constructing combinations of area-based parameters. These were named "wall index", "column index" and "priority index" with respect to the seismic vulnerability of these buildings. Accordingly, Hassan and Sözen, in their study, formulated ratios as below, respectively:

$$WI = \frac{\left[A_{cw} + \frac{A_{mw}}{10}\right]}{A_f} x100 \qquad (1)$$

where A_{cw} is the footprint area of reinforced concrete walls at base,
A_{mw} is the footprint area of non-reinforced masonry walls at base,
A_f is the total floor area at ground level.

$$CI = \frac{\frac{A_{col}}{2}}{A_f} x100 \qquad (2)$$

where A_{col} is the footprint area of columns at base.

$$PI = WI + CI \qquad (3)$$

In the above equations, first, the wall index (WI) represents the ratio of the effective cross-sectional area of walls to the total floor area at ground level. Second, the column index (CI) is the ratio of the effective cross-sectional area of columns at base to the total floor area at ground level. Third, the priority index (PI) is defined as the summation of wall and column indices to compare a building's seismic vulnerability. A plotting graph with WI and CI values leads to a ranking method that exhibits the observed damage satisfactorily. A building is considered more vulnerable than another building for which the indices have higher values, according to the graph. By summing WI and CI values, priority index is then defined as a single judgment variable. It represents the effective areas of reinforced walls, unreinforced walls and columns. An increase in the value of the priority index indicated reduced damage levels in the ranking process (Hassan & Sözen, 1997).

The data, including these parameters and related photographs, consequently were available for this study. The priority index indicated the vulnerability of buildings against earthquake; and damage levels were classified by field teams as, 'none', 'light', 'moderate', and 'severe' according to the failures and cracks observed on structural members (Dönmez & Pujol, 2005; Hassan & Sözen, 1997; http://www.anatolianquake.org). A scatter chart summarises wall and column indices for the sample buildings, as shown in Figure 3.

Relevant attributes of the planimetric configuration for these buildings are described below:

a. ***Building geometry*** represents all horizontal and vertical building dimensions. In the seismic design processes, however, it is named 'proportion' to define the ratio between height and least depth of the building. Since an earthquake affects a slender building by overturning forces more strongly than a bulky one (Naeim, 2001). In this study, the term has however, a broad meaning because of the inclusion of various plan shapes constituting re-entrant corners. According to The Turkish Earthquake Code, if both

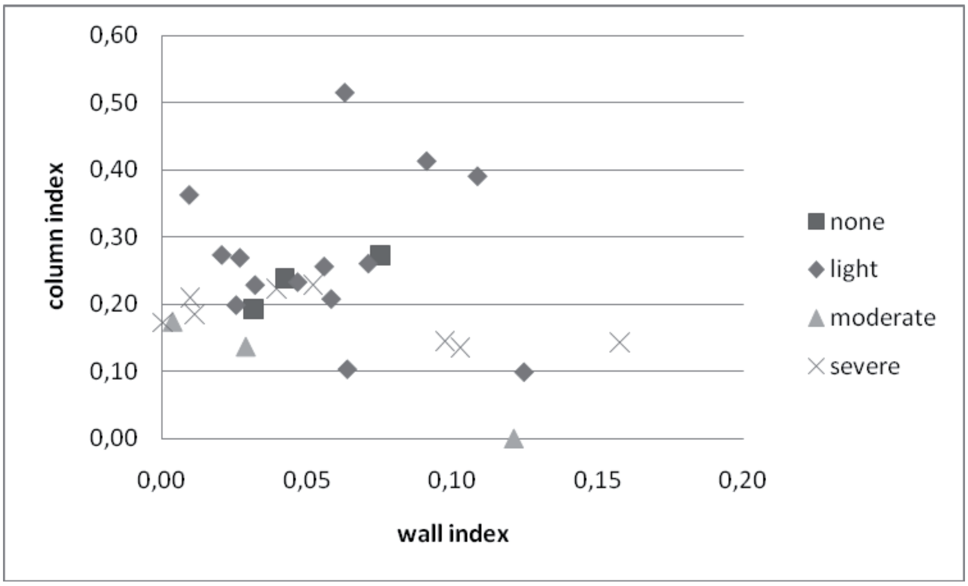
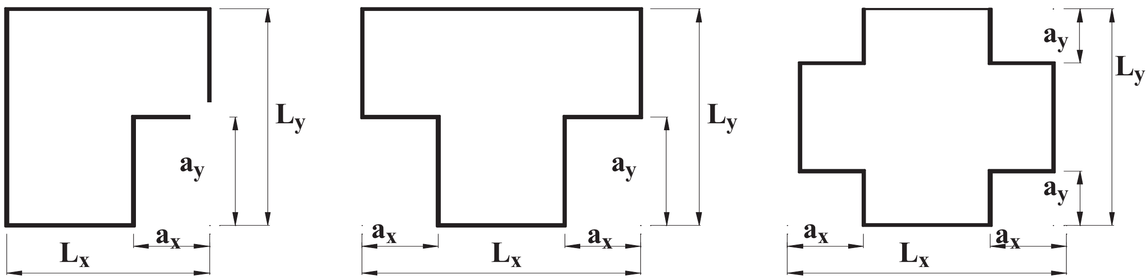


Figure 3: *Scatter plot displaying wall and column index of sample buildings according to damage level.*

the projected dimensions of a building for both of the perpendicular axes in the horizontal plane are more than the 20 percent of the total building dimensions on the respective axes, this case is defined as an 'irregularity' and is shown in Figure 4 (Ministry of Public Works & Settlement, 2006). Planimetric layouts of all damaged buildings subjected in this study were rectangular- or square-shaped without re-entrant corners. Thus, this type of irregularity was not observed. In addition, the minimum total floor area was 92,1m^2 and the maximum area was 1069m^2 of one to six storey residential buildings. Proportion values were consequently calculated, and these calculated values, which ranged from 0,01 to 0,11, were obviously below the optimum value of between 3 and 4 as mentioned by Naeim, (2001).

b. ***Cantilever projections in plan*** may be designed either as overhangs to enlarge total usable floor area in upper level floors or as balconies in residential buildings in Turkey. They create irregularity in the floor slab, which may cause large deflections under earthquake motion (Ministry of Public Works & Settlement, 2006; Özmen & Unay, 2007). As displacements occur on slabs under earthquake forces, these are related to the shape and dimensions of the slabs. In the same building, a slab with an overhang, for example on the first floor, will have a certain displacement value, while another slab without any projections, for example the in the ground floor, has an entirely different displacement value. Thus, this may unfortunately lead to a collapse. Following these considerations, it was observed that sample residential buildings had



$a_x > 0.2\ L_x$ *and* $a_y > 0.2\ L_y$

Figure 4: *A schematic view of the irregularity defined in the Turkish Earthquake Code.*
(Ministry of Public Works & Settlement, 2006, pp.9).

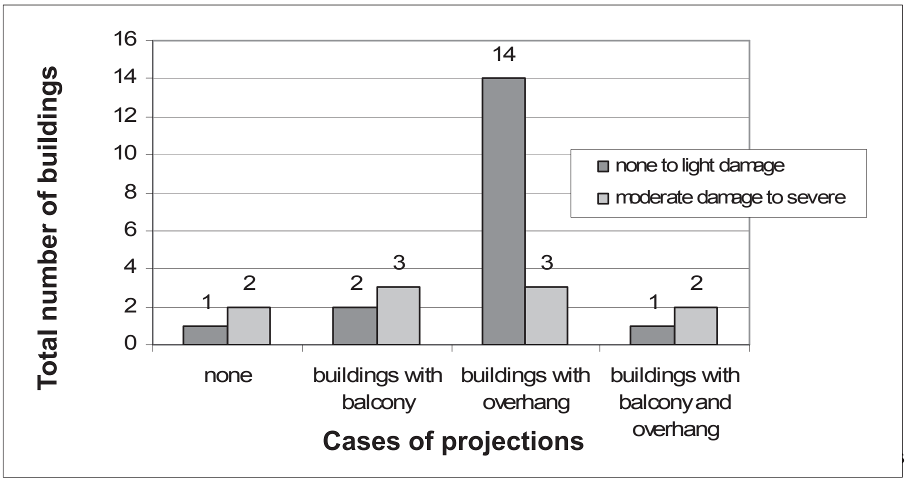


Figure 5: *Distribution by cases of projections of damaged buildings according to damage levels.*

overhangs of varying dimensions. Figure 5 shows the distribution of buildings according to the existence of overhangs and balconies. Among the buildings with overhang, only 18% of them had 'moderate' or 'severe' damage, while for buildings with balconies this was 60%. This meant that earthquakes caused more harmful effect on buildings with balconies than on buildings with overhangs. The literature explains that overhangs are extensions of the total mass, which results in an interrupted vertical structure. Therefore, the rotational inertia increases and stiffness changes. This situation causes undesirable stress concentrations and torsions (Dorwick, 1987). However, a balcony is a cantilever that supports its own weight and its structure creates its own vibration, leading one to conclude that earthquake forces may cause more harmful effect on overhangs. This conflict between the sample buildings and literature may stem from the infills in the balconies. Brick infills may increase the total weight and stiffness of the balconies. Figure 6 shows a building with an overhang and a balcony.

c. ***Planimetric configuration of columns*** is a design issue vital to both structural engineers and architects. Structural engineers decide on the configuration and type of structural elements by certain quantitative calculations according to their seismic resistance, while architects create usable interior spaces by determining the configuration and type of structural elements. The size and density of structural elements and their planimetric configuration have a direct influence on the seismic performance of buildings. If the structural configuration is not a regular one, additional moments on columns and shear walls will occur due to twisting of the building and may lead to cracks or collapse. Non-parallel axes and asymmetrical layout result in imbalanced resistance against earthquake forces in all directions (Dorwick, 1987; Naeim, 2001). In general, the irregularities mentioned above were observed in the sample buildings with few exceptions. Figure 7 displays an irregular plan with columns of various dimensions, while a regular one is shown in Figure 8. In the irregular plan, the lengths of some of the rectangular columns were aligned in one horizontal direction (x-direction), while others were in the other direction (y-direction). Moreover, some columns were laid on discontinuous axes, which can create additional moments under earthquake forces. In the regular plan, however, there is continuity on the axes where all columns and reinforced walls were placed. Of twenty-eight hazardous buildings examined in this study, only six had a regular plan configuration, twenty-two showed irregularities in configuration. The damage level however was noted as 'moderate' or 'severe' in 2 out of 6, and 9 out of 22, respectively, as shown in Figure 9.

Areas calculated from these were the following:

Construction Area: This was the footprint area of all reinforced concrete columns, concrete walls and masonry walls given on the ground floor plan, as shown in Figure 10.

Gross Floor Area: This comprised the overall built area of each typical residential building, calculated from the external dimensions given on ground floor plan.

Net Usable Floor Area: This simply being the difference of the two areas cited above. It was inclusive of all internal areas left out from footprint area of structural elements.

External Surface Area: Obtained from the overall external perimeter length and the floor to ceiling height of a residential building floor. It is a simple surface measure.

Specific ratios were determined from these calculated areas and building dimensions noted on floor plans. These ratios are considered analogue indicators to understand design and construction efficiency.

a. ***Ratio of net usable floor area to gross floor area:*** This ratio was used to investigate design efficiency in hospitals in several studies (Düzgünes, 1982; Hardy & Lammers, 1986). This was here viewed as the basic indicator for the level of planimetric design efficiency. Since it is divorced of any functional distinctions, it

(a) (b)

Figure 6: *Views from a damaged residential building with (a) an overhang and (b) a balcony.*
(Source: Field teams from various universities.http://www.anatolianquake.org)

reflects the basic architectonic outlook. It is referred to as efficiency quotient, just for simplicity.

b. ***Ratio of external surface area to gross floor area:*** This ratio was used to define design efficiency indicators to understand the compactness of residential buildings in a study (Düzgüneş, 1982). The objective was to determine the degree of the potential load imposed on such surfaces in filtering out negative effects of external environment. This ratio indicates the amount of construction materials constituting the building exterior surface. It also reflects the architectonic outlook cited above and the building's absolute size having effects on the seismic performance of buildings. It is also referred to as *compactness quotient.*

c. ***Ratio of construction area to gross floor area:*** This is an indicator to define the density of structural members (Naeim, 2001) so it is highly related in the cost efficiency of construction (Hardy & Lammers, 1986). In this study, this was viewed as the basic complementary indicator for the level of design efficiency. Higher value for the efficiency quotient results in lower value for this ratio. It also reflects the density of construction elements, which has potential effect on seismic design and construction costs. In addition, for simplicity, it is referred to as *construction efficiency quotient.*

d. ***Ratio of external shorter depth dimension to longer depth dimension:*** This was viewed as the indicator for plan configuration, describing how long or how compact the building is. It reflects the building proportion in horizontal plane. It is also called *aspect ratio.*

e. ***Ratio of height to least depth dimension:*** This is an indicator of the building configuration that shows how slender a building is (Naeim, 2001). The objective here was determining the building configuration also in the third dimension in affecting overturning of the building under earthquake forces. It reflects the degree of slenderness for the building. It is now called *height to base ratio*.

Methods

The study was designed and conducted in accordance with due statistical methods. Analyses were based on a procedure consisting of single-factor Analyses of Variance (ANOVA) and distributions were based on scatter charts.

A data table listing all quantitative and descriptive features derived from the material for each sample element was first constructed. Relevant data also included in the table were location, number of stories, and height of first floors, wall indexes, priority indexes, external dimensions and damage levels. Thus, areas and derived ratios cited above were recorded.

The relations between variables, namely, efficiency quotients and compactness quotients, the construction efficiency quotients, aspect ratios, height-to-base ratios and

Table 1: Sample data description.

Sample ID	Location	Number of stories	efficiency quotient	compactness quotient	construction efficiency quotient	aspect ratio	height to base ratio
B-C-27-01	Bolu	5	0,98	1,06	0,02	0,76	0,11
B-C-27-02	Bolu	4	0,98	0,70	0,02	0,53	0,05
B-C-27-03	Bolu	6	0,98	0,64	0,02	0,64	0,06
B-C-27-04	Bolu	5	0,98	0,70	0,02	0,69	0,06
B-C-27-05	Bolu	5	0,97	0,86	0,03	0,53	0,08
B-C-28-01	Bolu	5	0,98	0,87	0,02	0,81	0,11
B-C-28-02	Bolu	6	0,97	0,43	0,03	0,94	0,03
B-C-28-03	Bolu	4	0,98	0,85	0,02	0,64	0,07
B-C-29-01	Bolu	4	0,98	0,87	0,02	0,75	0,08
B-C-29-02	Bolu	3	0,97	0,72	0,03	0,49	0,04
B-C-29-03	Bolu	6	0,98	0,47	0,02	1,00	0,04
B-C-29-04	Bolu	3	0,98	1,04	0,02	0,72	0,07
D-C-18-01	Duzce	3	0,99	0,42	0,01	0,86	0,01
D-C-22-01	Duzce	5	0,98	0,70	0,02	0,50	0,05
D-C-25-01	Duzce	4	0,97	1,02	0,03	0,63	0,07
D-E-18-1	Duzce	2	0,98	0,32	0,02	0,67	0,01
D-E-20-1	Duzce	4	0,96	1,02	0,04	0,55	0,06
D-E-20-2	Duzce	4	0,96	1,12	0,04	0,63	0,08
K-C-23-01	Kaynasli	2	0,95	1,58	0,05	0,54	0,05
K-C-23-02	Kaynasli	2	0,96	0,90	0,04	0,93	0,04
K-C-24-01	Kaynasli	2	0,98	0,90	0,02	0,83	0,04
K-C-24-02	Kaynasli	1	0,98	0,89	0,02	0,91	0,02
K-C-24-03	Kaynasli	1	0,98	1,10	0,02	0,85	0,03
K-C-24-04	Kaynasli	3	0,97	0,70	0,03	0,89	0,05
K-C-24-05	Kaynasli	3	0,97	1,11	0,03	0,84	0,08
K-C-26-01	Kaynasli	3	0,96	0,94	0,04	0,91	0,07
K-C-26-02	Kaynasli	2	0,97	0,87	0,03	0,92	0,04
K-C-26-03	Kaynasli	2	0,96	0,87	0,04	0,92	0,04

the damage level were tested by single-factor ANOVA. The MS EXCEL software program was used in conducting these tests and in the preparation of tables displaying results. Four factors were analyzed by ANOVA at a 5% level of significance (α=0.05). These were:

i) The difference between efficiency quotients and compactness ratios;
ii) The difference between the damage level and construction efficiency quotients;
iii) The difference between the damage level and aspect ratios; and
iv) The difference between the damage level and height-to-base ratios.

The scatter plots were derived from paired values of variables, namely, priority index (showing vulnerability of buildings), construction efficiency quotients and aspect ratios were analysed. These were constructed to understand, first, the relation between the priority index and the construction efficiency quotients; and second, the relation between the priority index and the aspect ratio.

Results

The results of single-factor ANOVA according to four variables cited are presented below with their tabular forms for each given in Tables 2 through 5.

The first null hypothesis was H_0: $\tau_i = 0$; i.e. there is no relation among efficiency quotients according to their compactness ratios. Accordingly, H_0 was rejected at 5% level of significance (α=0.05), meaning that the compactness quotients varied significantly according to efficiency quotients.

The second null hypothesis was H_0: $\tau i = 0$; i.e. there is no relation among the level of damage according to the construction efficiency quotients. Accordingly, H_0 was rejected at 5% level of significance (α=0.05). It was

Table 2: Single factor ANOVA for compactness ratios, among efficiency quotients.

Source of Variation	SS	df	MS	*F*	*P-value*	*F crit.*
Between Groups	0,397743374	2	0,19887169	3,493952036	0,045912	3,385196
Within Groups	1,422970929	25	0,05691884			
Total	1,820714302	27				
H_0 was rejected with 95% confidence.						

Table 3: Single factor ANOVA for construction efficiency quotients among the levels of damage.

Source of Variation	SS	df	MS	*F*	*P-value*	*F crit.*
Between Groups	0,000376	1	0,000375504	4,8006	0,037608	0,037608
Within Groups	0,002034	26	7,82202E-05			
Total	0,002410	27				
H_0 was rejected with 95% confidence.						

concluded that the construction efficiency quotients varied significantly according to damage level, meaning that there existed a relation between the construction efficiency ratios and the damage level.

The third null hypothesis was H_0: $\tau i = 0$; there is no relation among the level of damage according to aspect ratios. Accordingly, H_0 was accepted at 5% level of significance (α=0.05). It was concluded that aspect ratios did not varied significantly according to the level of damage. This did not give an indication that the aspect ratio of a building with a specific damage was higher or lower than another building with other damage levels. This was also considered to indicate that there was no significant difference in horizontal ratios of the building according to the level of damage. In short, the damage level was independent of aspect ratios.

The fourth null hypothesis was H_0: $\tau i = 0$; there is no relation among the level of damage according to height-to-base ratios. Accordingly, H_0 was accepted at 5% level of significance (α=0.05). It was concluded that height-to-base ratios did not varied significantly according to the level of damage. However, this did not give an indication that the height-to-base ratio of a building with, for example, a light damage was higher or lower than another building with other damage levels; the damage level was independent of height-to-base ratios.

The results of scatter plots according to four variables cited are presented below:

The relation between the damage level and the compactness quotient of damaged sample buildings is shown in Figure 11. Plotting the values for compactness quotient (y-axis) and damage level (x-axis) resulted in a fine scattering pattern. However, no relation between these variables was found to be statistically significant.

The relation between the damage level and the construction efficiency quotient of damaged sample buildings is shown

Table 4: Single factor ANOVA for aspect ratios among the levels of damage.

Source of Variation	SS	df	MS	*F*	*P-value*	*F crit.*
Between Groups	0,066872	1	0,066872	2,902241	0,100382	4,2252
Within Groups	0,599075	26	0,023041			
Total	0,665947	27				
H_0 was accepted with 95% confidence.						

Table 5: Single factor ANOVA for height-to-base ratios among the levels of damage.

Source of Variation	SS	df	MS	*F*	*P-value*	*F crit.*
Between Groups	2,29933E-05	1	2,3E-05	0,033295	0,85663	4,2252
Within Groups	0,017955362	26	0,000691			
Total	0,017978355	27				
H_0 was accepted with 95% confidence.						

in Figure 12. Plotting the values for construction efficiency quotient (y-axis) and damage level (x-axis) resulted in a fine scattering pattern. It was concluded that the damage level was matching to high values when construction efficiency had lower values, thus providing evidence of a reasonable relationship between damage level and construction efficiency quotients.

The relation between the damage level and the aspect ratios of damaged sample buildings is shown in Figure 13. Plotting the values for the aspect ratios (y-axis) and damage level (x-axis) resulted in a fine scattering pattern. As the aspect ratios ranged from 0.6 to 1.0 and all damage levels were within that range, no relation between these ratios and the damage level were noted as significant.

The relation between the damage level and the height-to-base ratios of damaged sample buildings is shown in Figure 14. Plotting the values for the height-to-base ratios (y-axis) and damage level (x-axis) resulted in a fine scattering pattern. As the height-to-base ratios ranged almost from 0.02 to 0.08 and all damage levels were within that range, no relation between these ratios and the damage level were noted as significant.

The relation between the damage level and the efficiency quotient of damaged sample buildings is shown in Figure 15. Plotting the values for efficiency quotient (y-axis) and damage level (x-axis) displayed similar dependency as the one found for damage level on construction efficiency quotient.

The relation between the priority index and the construction efficiency quotients of damaged sample buildings is shown in Figure 16. Plotting the values for the priority index (y-axis) and construction efficiency quotients (x-axis) resulted in a fine ranking procedure according to damage levels. This process is not meant to be a method to predict damage levels. It is simply an objective method to rank buildings with respect to their vulnerability and the density of vertical structural members, then, to define their relative relation for the sample

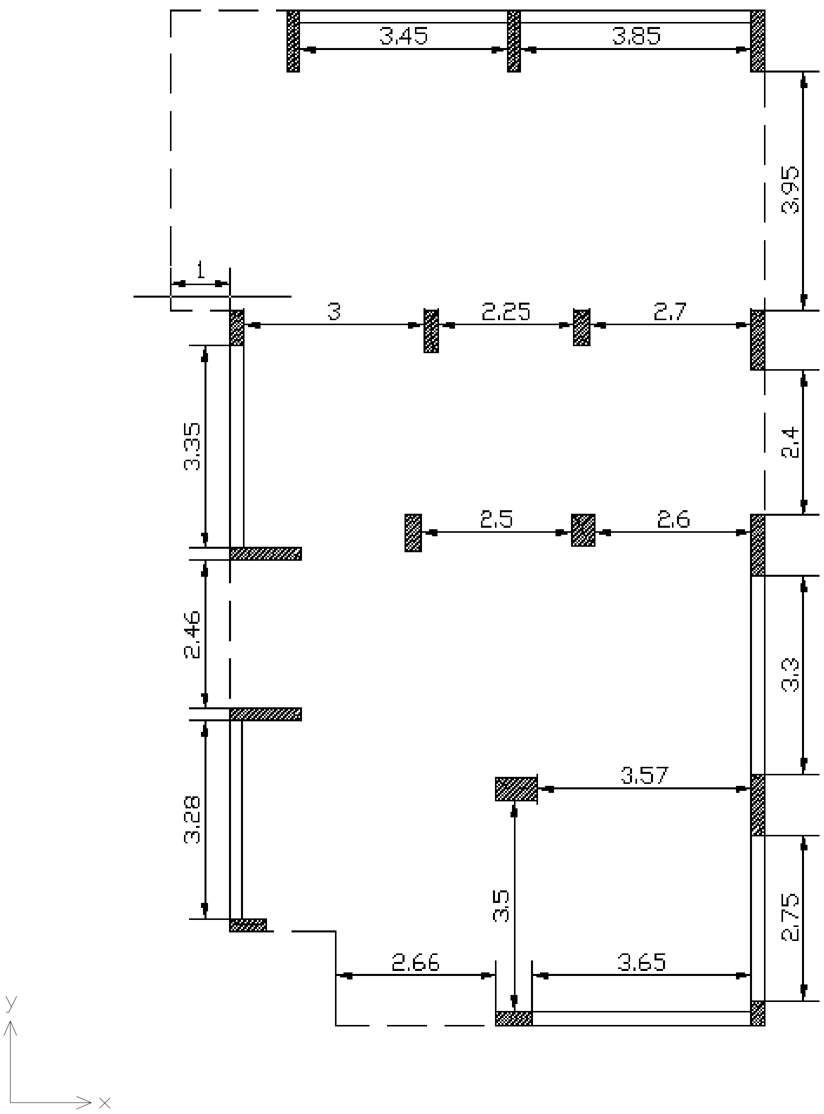


Figure 7: *A plan drawing showing irregular layout of columns.*
(Source: Field teams from various universities.http://www.anatolianquake.org)

buildings. It was concluded that the damage level was high when construction efficiency had lower values, thus providing evidence of a reasonable relationship between priority index and construction efficiency.

Discussion

The analyses of variance and scatter charts were applied to determine relation between planimetric configuration ratios and damage level of hazardous buildings. Plotted values were also used to rank these buildings according to their vulnerability. Constructing building configuration ratios, the dependency of damage level (vulnerability of buildings) on these ratios were summarised in Results.

A number of results about planimetric configuration ratios and their relationship with damage levels were considered as noteworthy on their own merit. One was that the damage level was independent of aspect ratios and height-to-base ratios, despite literature (Atımtay, 2001; Naeim, 2001; Özmen & Unay, 2007) showing distinct impact of building configuration on seismic performance. Two conditions may indicate such an anomaly. One is that the study included a limited number of sample buildings. The other one is that these buildings are similar according to their bulky shape and square-form-plan configurations. In other words, two indices, for the compactness and slenderness of buildings, require further investigation to check their dependency on seismic performance. The scatter plots exhibited similarly the independency of aspect ratio and height-to-base ratios from the damage level. The literature (Dorwick, 1987; Naeim, 2001) describes the performance of extremely long and large buildings subject to earthquake forces. Such buildings act with greater variations during earthquakes. This means that opposite ends of long buildings behave differently due to ground movement. In addition, a large building acts as one big unit whose large lateral spans then may have difficulty to resist large lateral forces. As a rule, when the aspect ratio

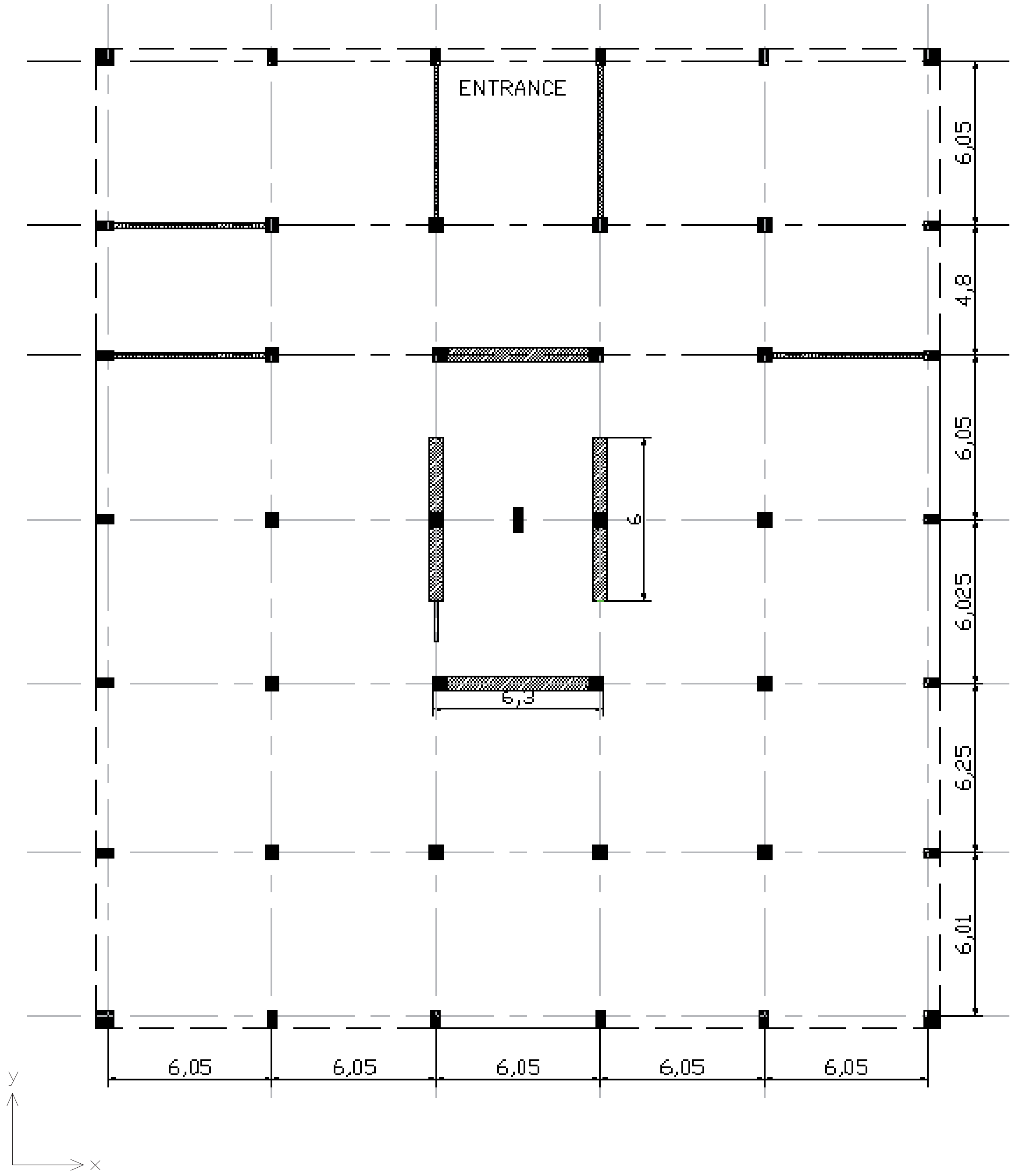


Figure 8: *A plan drawing showing regular layout of columns.*
(Source: Field teams from various universities.http://www.anatolianquake.org)

value is almost 1/6, vertical structural members with non-symmetrical layout might be affected due to unbalanced load distribution. Further investigations including a large set of sample buildings may be carried out to determine quantitative values for aspect ratio boundaries. They may be used to define classifications of buildings whether they are long or not. Then earthquake engineers may apply additional earthquake resistance calculations that are specific to each classification.

Another noteworthy observation was the dependence found on the construction efficiency quotient. The scatter charts show this dependency. Moderate and severe damage were mostly found in buildings whose construction efficiency values were lower than 0.03. This should not, however, be generalized for all buildings. Although this value should not be taken as a threshold to determine buildings seismic resistance, it displays an indicative value that may be specific within this sample. Sources (Hassan & Sözen, 1997; Lourenco & Roque, 2006; Reitherman, 2005) cite such quantitative studies based on structural plan density to be taken as seismic resistance indicator. However, sample buildings were compared relatively and approximate relationships were defined between

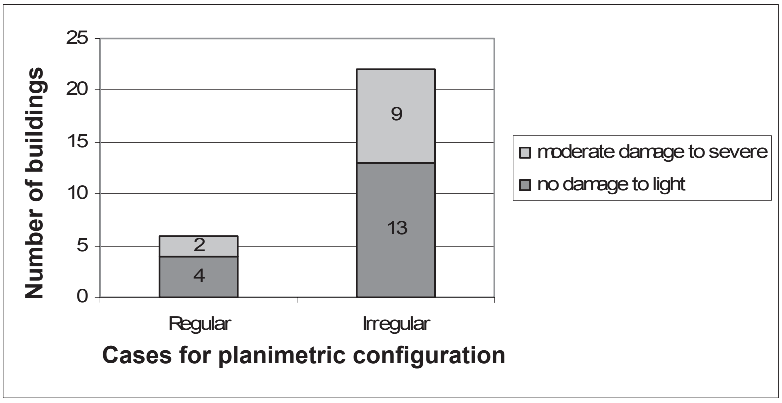


Figure 9: *Distribution by plan configuration of damaged buildings showing the level of damage.*

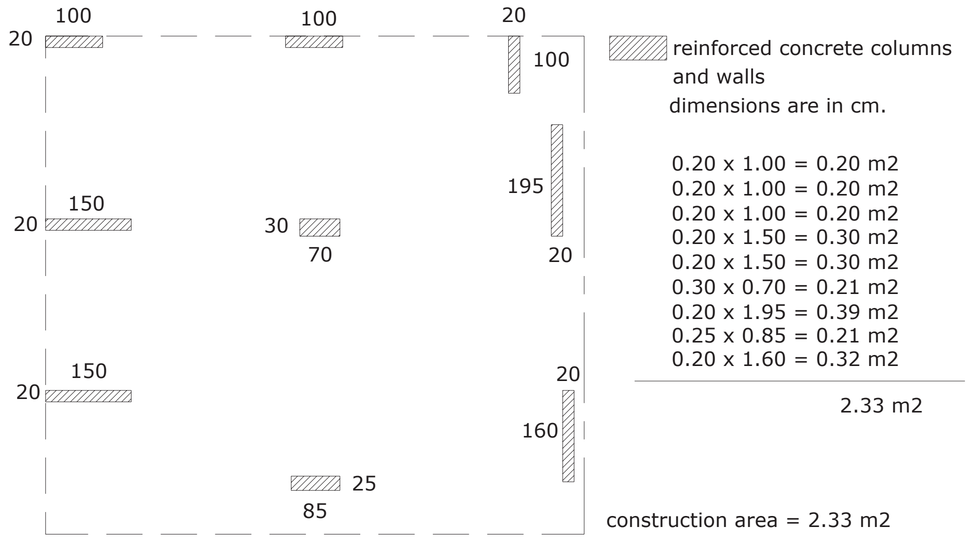


Figure 10: *A sketch displaying the construction area.*

the ratios of floor areas to areas of structural elements. Further investigations including larger numbers of buildings, consequently, may seek to determine such a threshold value to indicate a relationship between the structural density and the extent of damage.

The relation between efficiency quotient and compactness quotient was determined to be significant among these buildings. Considering that efficiency quotient represents the density of structural elements, this was further evidence that the compactness of the building indicates how efficiently its structural elements are designed.

Basic planimetric configuration items such as building geometry, cantilever projections and configuration of columns referred to by the Turkish Earthquake Code (Ministry of Public Works & Settlement, 2006) were not tested by statistical analysis but analysed through photographs and plan drawings. These items were compared according to certain requirements in the Turkish Earthquake Code. Outcomes might be useful to construct feedback information for architects and structural engineers. Including structural analysis methods, the Code serves structural engineers. However, it also defines irregular buildings specific for seismic regions, specific calculation methods for each irregularity and internal earthquake forces adopted in each calculation.

Sample buildings' geometry was in accordance with the requirements of the Turkish Code. These low-rise concrete buildings were almost in square plan form without any re-entrant corner irregularity (Ministry of Public Works & Settlement, 2006) as defined by code. If such an irregularity exists, the Earthquake Code will recommend that the uniform load transmission among structural members should be satisfied with extra load combinations in specific regions. However, the use of overhangs is restricted due to the existence of both torsional irregularity and vertical geometric irregularity. Precautions might be taken during design to increase the forces due to torsional irregularities in sample buildings with

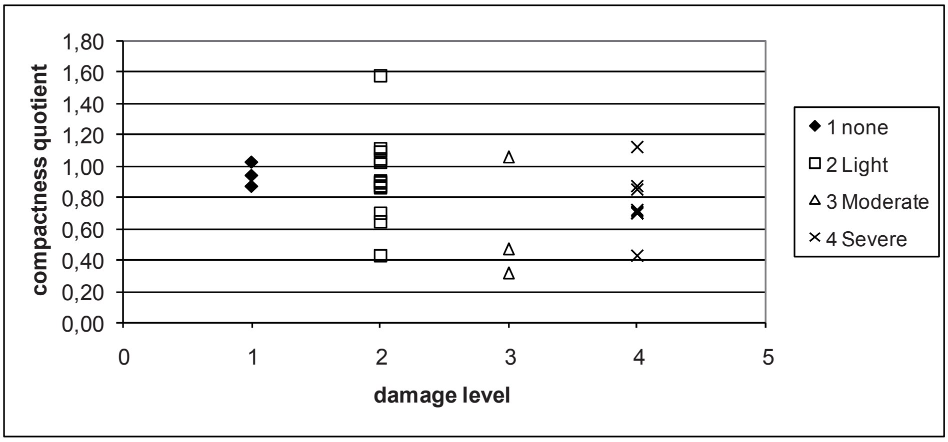


Figure 11: *Scatter plots for compactness quotient and damage level.*

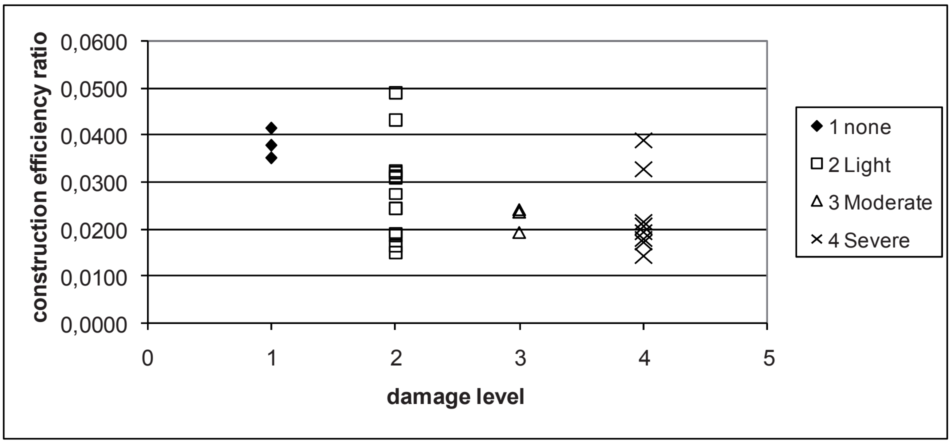


Figure 12: *Scatter plots for construction efficiency quotient and damage level.*

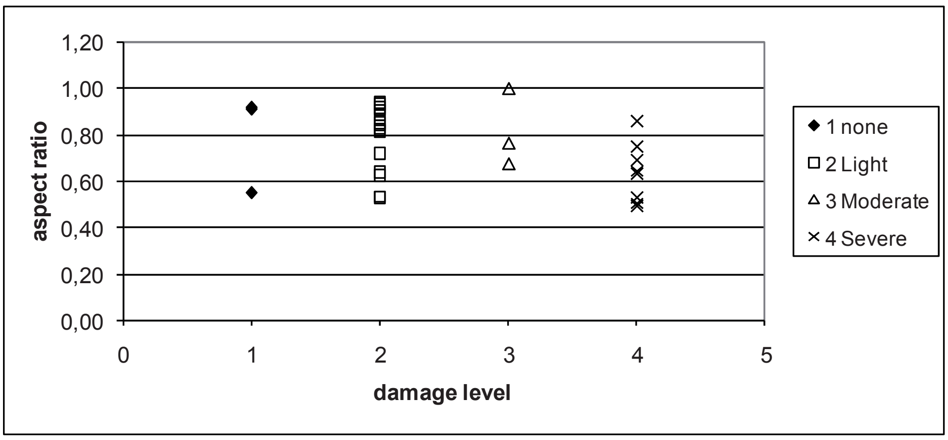


Figure 13: *Scatter plots for aspect ratio and damage level.*

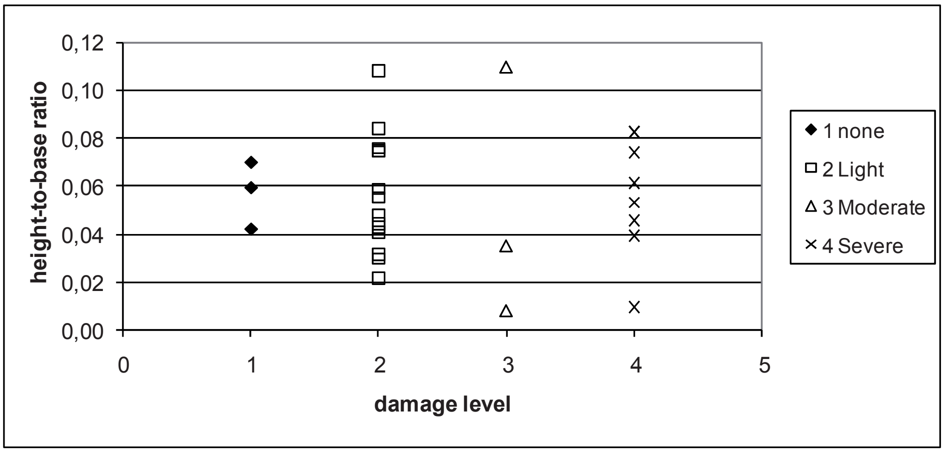


Figure 14: *Scatter plots for height-to-base ratio and damage level.*

Figure 15: *Scatter plots for efficiency quotient and damage level.*

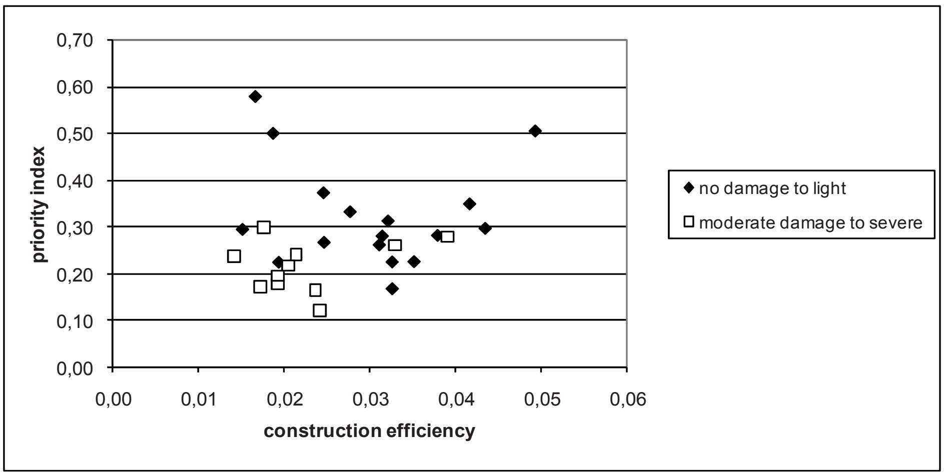


Figure 16: *Scatter plots for priority index and construction efficiency quotients.*

balconies. Furthermore, specific seismic calculations might be applied (Ministry of Public Works & Settlement, 2006). Irregularity in planimetric configuration of columns exists when there is discontinuity in column axes and their layout directions. The Earthquake Code recommends to increase forces due to torsional irregularity then to apply specific extra calculations. In this study, sample buildings with such an irregularity might be hazardous due to the lack of such calculations utilizing additional force factors.

Of course, an aspect of interest should be the complexity of both other intrinsic and extrinsic factors having impact on the damage occurrence in a building. The former includes all structural elements' resistance against earthquake, detailing and ground soil properties, while the latter is most likely to be the quality of construction, the budget, workmanship, and maintenance of the building. Any of these effects may exist in any building that has been damaged or collapsed due to an earthquake. This is also valid for the residential buildings that were the subject of this study. Therefore, these results were considered noteworthy within this study of limited scope with few numbers of data obtained, excluding factors mentioned above. On the other hand, it is also expected that other investigations with larger quantities of data, also including these aspects may be conducted to display relevant evidence for the impact of planimetric configuration on seismic design.

Conclusion

This trial study, based on analyses of field-survey drawings, dealt with the planimetric configuration of damaged residential buildings and then concentrated on the relation between their configurations and their damage levels. Planimetric configuration indicators were developed to determine this relation through statistical analysis and scatter charts. Findings showed significant deficiencies in configuration of damaged buildings. In addition, their damage levels were dependent on their construction efficiency but not on their aspect ratios and height-to-base ratios. Basic planimetric configuration items such as building geometry, cantilever projections and configuration of columns were also analysed and compared according to requirements by the Turkish Earthquake Code (Ministry of Public Works & Settlement, 2006).

Structural engineers benefit from the Earthquake Code when designing the structural members of a building. The Earthquake Code defines earthquake forces, load combinations, irregular buildings and calculation methods as well. In the case of any irregularity, engineers increase relevant forces for the new calculations and redesign the structure. The purpose of this is to construct a building with the minimum use of material for the most efficient seismic resistance. However, any irregularity results in a larger cross-section of structural members due to increased forces. This increased use of construction material, subsequently leads to higher construction costs. In this sense, engineers and architects should be aware of this conflict. Thus, the purpose of this study was to emphasize the need for their consciousness regarding the impact of building configuration on seismic design. Architects should be more involved in the field of seismic design to prepare efficient earthquake resistant buildings in collaboration with structural engineers. It is expected that this study will provide feedback information for architects who should be aware of irregular building configurations.

It would also be worthwhile conducting more exhaustive studies on larger numbers of buildings to provide findings that are more comprehensive. Those investigations may involve not only those aspects covered in this study, but also others of potential relevance. Such aspects might be configuration of structural elements, deflection caused by lateral earthquake forces, and irregularity among floors at various levels.

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