ACI STRUCTURAL JOURNAL TECHNICAL PAPER

Title no. 94-S4

Seismic Vulnerability Assessment of Low-Rise Buildings in Regions with Infrequent Earthquakes

by Ahmed F. Hassan and Mete A. Sozen

This paper presents a simplified method of ranking reinforced concrete, low-rise, monolithic buildings according to their vulnerability to seismic damage. The ranking process requires only the dimensions of the structure. The process is tested using a group of buildings that suffered various levels of damage during the Erzincan earthquake of 1992. The ranking procedure reflected the observed damage satisfactorily.

Keywords: buildings; earthquake-resistant structures; earthquakes; evaluation; failure; inspection; reinforced concrete; school buildings.

INTRODUCTION

The goal of conventional methods for evaluation of seismic vulnerability is to select buildings with a high probability of survival. This paper contains an alternative approach. A simple method is presented to help identify buildings with a high probability of severe damage.

In regions of frequent earthquake occurrence, it is proper and feasible to calibrate seismic safety assessment procedures conservatively in deference to extreme cases of damaged structures. Contradictions posed by buildings that survive earthquakes even though they would be rated hazardous by a ranking procedure calibrated exclusively on damaged structures are often ignored. As long as the number of buildings classified as hazardous is not overwhelming, this "upper-bound approach" does not stop the development of a policy for earthquake risk reduction.

In regions of infrequent earthquake occurrence where buildings with poorly delineated or weak structural systems are likely to represent a large portion of the building inventory, the upper-bound approach may actually be unconservative. If nearly all buildings are deemed hazardous, the likely policy is inaction.

In regions where earthquakes occur in intervals measured in centuries, there is a need for a simple evaluation method that focuses on selection of buildings with high vulnerability rather than those with a high probability of survival. Because seismic risk evaluation methods are based on concepts that are not all well understood, a procedure designed to identify buildings with a high probability of survival cannot be adapted conveniently to identify buildings with a high probability of failure simply by relaxing some of its requirements.

Undeniably, there is no better vehicle for identifying a vulnerable building than the considered judgment of an experienced professional. But this is an expensive vehicle, especially in regions of infrequent earthquakes. There is a need to provide reasonably objective criteria to be used for initial filtering of the building inventory. These criteria need to be at a very low level of sophistication in deference to the principle of proportionality. The required level of calculation has to be proportional to the quality of input.

The readily accessible data for an existing building are the dimensions and arrangement of its structural elements and the floor area. The challenge is to determine whether these properties alone may be used to determine the relative seismic vulnerability of a building inventory at a given location.

In a paper related to damage caused by the Tokachi-Oki earthquake of 1968, Shiga, Shibata, and Takahashi[1] presented a format (referred to as the SST Format in following text) for evaluating the seismic safety of low-rise monolithic construction in reinforced concrete. They defined the critical attribute for seismic vulnerability to be the weight of the structure divided by the sum of the cross-sectional areas of the walls and the columns.

The SST format is very attractive. The required data are easily acquired. The needed calculation is not time-consuming. The result is crisp. But the application of the SST Format in general is questionable because it was derived explicitly in relation to a group of buildings with well-reinforced walls dominating lateral resistance.

Recalibrating or testing the SST format on the basis of theory or experiment is not productive because the procedure needs to be tested on the basis of responses that defy calculation

---

ACI Structural Journal, V. 94, No. 1, January-February 1997.

Received June 26, 1995, and reviewed under Institute publication policies. Pertinent discussion will be published in the November-December 1997 *ACI Structural Journal* if received by July 1, 1997.

Ahmed F. Hassan *is an assistant professor of structural engineering at Cairo University, Egypt. He completed his doctoral dissertation on fatigue of structural steel at Purdue University, West Lafayette, Ind., in 1995.*

Mete A. Sozen *is the Kettelhut Distinguished Professor of Structural Engineering at Purdue University.*

and organized experiment. The procedure has to be tested against observed phenomena in a collection of buildings with dimensional and material properties based on random decisions in construction.

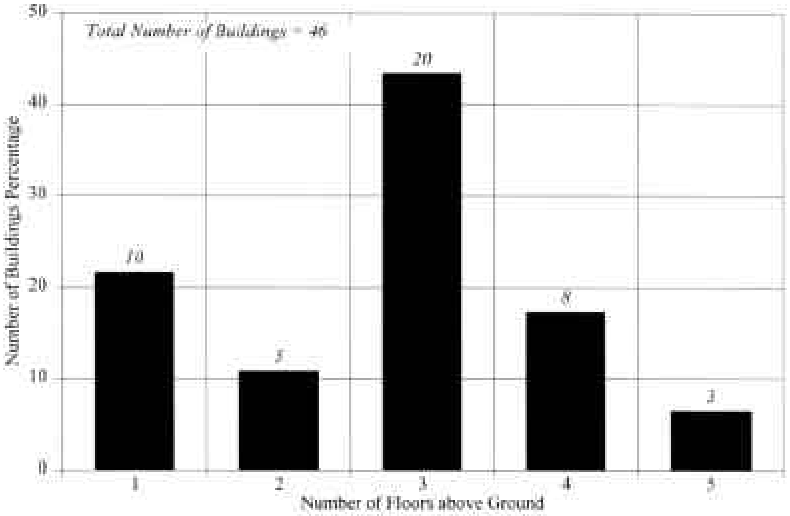
An opportunity for recalibrating the SST format was provided by the Erzincan earthquake of 1992. After the earthquake, the Ministry for Housing and Natural Disasters of the Turkish Republic sponsored the Middle East Technical University (METU[2]), Ankara, to document the damage to 46 institutional building units in Erzincan. The METU team also developed floor plans of the buildings inspected. The body of information assembled by engineers from METU will be referred to as the METU data.

METU DATA

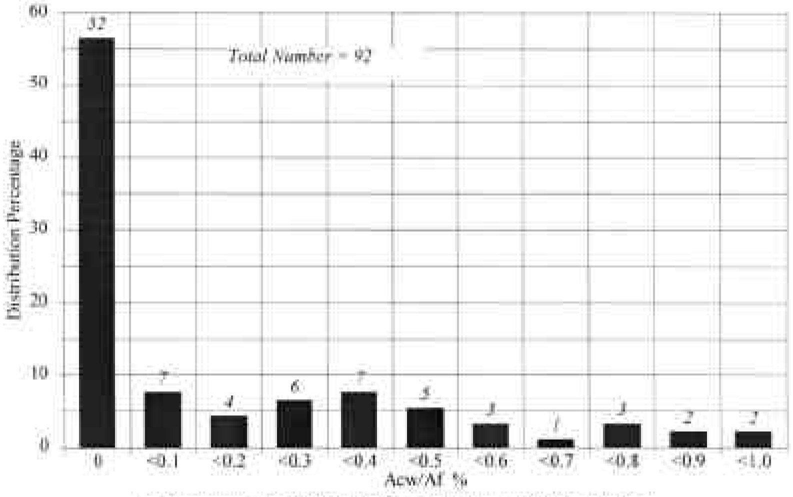
All buildings in the METU inventory were low-rise institutional buildings with one to five stories above ground. Fig. 1(a) shows the distribution of the number of stories for the METU data. Story heights ranged typically from 2.75 to 3.60 m although some had special areas with taller ceilings (up to 8.00 m). Some buildings had reinforced concrete walls. Most buildings had filler walls of stone, brick, or tile masonry. The tile wall was the predominant type. The ratio of reinforced concrete wall area at base to the total floor area above base ranged from 0 to 1 percent with more than one-half of the buildings without any reinforced concrete walls [Fig. 1(b)].

Core and Schmidt-Hammer tests implied the concrete strength to be typically 1.4 MPa. Plain bars with a yield

22



a) Distribution of Buildings According to Number of Stories.



b) Percentage of Reinforced Concrete Wall Area to Total Floor Area.

Fig. 1—Number of stories and percent of wall area distributions—METU building data: (a) distribution of buildings according to number of stories; (b) percentage of reinforced concrete wall area to total floor area

stress of 22 MPa were used for reinforcement. Representative reinforcement ratios were inferred from governing building codes to be 1 percent for frame elements and 0.15 percent for concrete walls.

Selected properties of the building units are listed in Table 1. Although the bays filled by walls were indicated, the wall thicknesses were not reported in the building plans. On the basis of information about local practice, infill walls were assumed to be 0.25 m thick. A perspective of the types of buildings may be obtained from the brief descriptions of three of the buildings in the METU inventory listed below.

Multipurpose assembly hall, Vocational School for Girls: The multipurpose assembly hall of the Vocational School for Girls (ID No. 6, Table 1) is a one-storey frame building with girder spans of 12 m spaced at 3.4 m. Cross-sectional dimensions are 0.4 x 0.85 m for the girders in both directions. Roof cover is provided by a reinforced concrete slab. The outside filler walls cover only part of the height to allow light. The plan of the building is given in Fig. 2.

Dormitory, Vocational School for Boys: The dormitory building for the Vocational School for Boys (ID No. 5b, Table 1) makes a very good analog for many buildings in Central United States because of the freedom exercised by the designer in locating elements and choosing sizes. Column locations are given in Fig. 3 and column sizes are summarized in Table 2.

Ulalar Elementary School: Because of the regularity of its plan (Fig. 4), the structure of the Ulalar Elementary School (No. 10, Table 1) is one of the unusual buildings in the inventory. A peremptory inspection of the floor plan will reveal that the critical direction is the longitudinal one. Total length of reinforced concrete walls in the short direction is three times that in the long direction. The observation that the damage in the short direction was considerably lighter than the damage in the long direction (inclined cracks in reinforced concrete walls, general cracking of filler walls) confirms, without the necessity of detailed analysis, the efficacy of walls for earthquake resistance in a low-rise building.

ERZINCAN EARTHQUAKE, MARCH 13, 1992

Erzincan is a town of 92,000 located in eastern Anatolia on a plateau (elevation 4000 ft) near the North Anatolian Fault. The March 13, 1992 event was rated to have a Richter surface magnitude of 6.8. Its epicenter was located at 39.7 deg latitude and 39.6 deg longitude. The estimated focal depth was 28 km. Components of the strong-motion record obtained in Erzincan are shown in Fig. 5. Maximum ground acceleration, recorded on alluvium with a depth of approximately 200 m, were 0.5G (E-W) and 0.4G (N-S). Maximum ground displacement, calculated in a direction parallel to the North Anatolian Fault (N 34 E) was 0.25 m (Kandilli Observatory and Earthquake Research Institute and Bogazici University[3]). Linear response spectra calculated for the two horizontal components are presented in Fig. 6. Damage intensity for the city was rated at MMI VIII (Ersoy et al.[4]). Over 2000 buildings, representing approximately 8 percent of the buildings in Erzincan, were destroyed or severely damaged.

DEFINITION OF DAMAGE STATES

Despite the strong ground motion, none of the buildings in the METU inventory suffered total collapse. Definitions of the damage state, listed in Table 1, are related to the entries in the METU data as follows:

Light: Reinforcement exposed but not buckled near joint faces. Fine flexural cracks in structural and nonstructural elements.

Moderate: Reinforcement buckled near joint faces and/or inclined cracks in structural walls.

Severe: Structural failure of individual elements.

PROPOSED PROCEDURE

Preliminary analyses of the METU data using the SST format immediately confirmed the obvious. It could not be used in its original form for the METU data. The SST format was developed from and was assumed to apply over a narrow range of building parameters limited essentially to those with well-built reinforced concrete walls. Therefore, a similar but different format was developed.

To rank the buildings with respect to the reported damage, various combinations of simple parameters were tried. The format shown in Fig. 7 was considered to be the most efficacious. In Fig. 7, each building is represented by a point in a two-coordinate representation.

The y-axis in Fig. 7 represents the "wall index," WI, which is defined as the ratio

$$WI = \frac{A_{wt}}{A_{ft}} \times 100 \qquad (1)$$

where

$A_{wt} = A_{cw} + \frac{A_{mw}}{10}$ = effective cross-sectional area of walls in a given horizontal direction

A_{cw} = total cross-sectional area of reinforced concrete walls in one horizontal direction at base

A_{mw} = cross-sectional area of nonreinforced masonry filler walls in one horizontal direction at base

A_{ft} = total floor area above base in a building

The x-axis represents the "column index," CI, which is the ratio

$$CI = \frac{A_{ce}}{A_{ft}} \times 100 \qquad (2)$$

where

$A_{ce} = \frac{A_{col}}{2}$ = effective cross-sectional area of columns at base

A_{col} = total cross-sectional area of columns above base

Plotting the values for the wall index (y-axis) against the column index (x-axis) resulted in a plausible ranking procedure that reflected the observed damage satisfactorily. It is very important at this point to emphasize that Fig. 7 is not meant to be a general graphical procedure for damage prediction. It is indifferent to many variables that affect building performance. It is simply an objective method to rank existing low-rise monolithic reinforced concrete buildings in a given region according to their seismic vulnerability. It is assumed that the earthquake demand is reasonably uniform as are the quality and type of construction.

Table 1—METU building data

Building name	ID no.	Dir.	No. of stories	Total floor area, m^2	Column area at base, m^2	RC wall area at base, m^2	Masonry wall length at base, m	Column index, percent	Wall index, percent	Damage state
Ezrincan High School gymnasium	1-1	T	1	501	4.32	0.00	0.00	0.43	0.00	None
		L				0.00	0.00		0.00	
Erzincan High School connecting building	1-2	T	1	256	2.16	0.00	0.00	0.42	0.00	None
		L				0.00	0.00		0.00	
Erzincan High School classroom building	1-3	T	2	1276	5.40	0.00	67.10	0.21	0.13	Moderate
		L				0.00	51.20		0.10	
Erzincan High School classroom building	1-4	T	2	872	4.85	0.00	50.90	0.28	0.15	Moderate
		L				0.00	24.80		0.07	
Erzincan High School cafeteria	1-5	T	1	383	3.46	0.00	0.00	0.45	0.00	Light
		L				0.00	0.00		0.00	
Imam Hatip High School	2	T	4	1717	3.29	0.37	42.36	0.10	0.08	Moderate
		L				4.40	20.60		0.29	
Erzincan Commerce High School assembly hall	3-1	T	1	603	6.97	0.00	0.00	0.58	0.00	None
		L				0.00	0.00		0.00	
Erzincan Commerce High School CRB	3-2	T	3	1884	6.86	0.00	59.80	0.18	0.08	Severe
		L				0.00	36.56		0.05	
Erzincan Commerce High School CRB	3-3	T	3	1299	3.81	0.00	52.90	0.15	0.10	Severe
		L				0.00	19.73		0.04	
Kazim Karabekir High School Bldg. 1	4a-1	T	2	390	2.33	0.00	16.55	0.30	0.11	Moderate
		L				0.00	17.25		0.11	
Kazim Karabekir High School Bldg. 2	4a-2	T	4	3479	4.03	9.50	56.40	0.06	0.31	Moderate
		L				5.14	47.60		0.18	
Vocational High School electrical shop	5a	T	2	830	3.96	0.00	31.58	0.24	0.10	Moderate
		L				0.00	20.27		0.06	
Vocational High School dormitory	5b	T	3	1698	1.12	7.11	36.30	0.03	0.47	Moderate
		L				0.23	58.45		0.10	
Vocational High School construction laboratory	5c-1	T	1	211	1.80	1.80	0.00	0.43	0.85	Light
		L				0.00	0.00		0.00	
Vocational High School construction laboratory	5c-2	T	1	328	4.08	1.20	0.00	0.62	0.37	Light
		L				0.00	0.00		0.00	
Vocational High School construction laboratory	5c-3	T	1	211	1.80	1.80	0.00	0.43	0.85	Light
		L				0.00	0.00		0.00	
Vocational School for Girls assembly hall	6	T	1	376	5.60	0.00	0.00	0.75	0.00	Light
		L				0.00	0.00		0.00	
Sumer Elementary School	7	T	3	1240	4.30	0.41	35.75	0.17	0.11	Light
		L				0.00	48.60		0.10	
Central Elementary School	8-1	T	3	1240	3.92	0.35	40.50	0.16	0.11	Moderate
		L				0.00	38.45		0.08	
Central Elementary School	8-2	T	3	1036	3.54	0.00	34.00	0.17	0.08	Moderate
		L				0.18	38.00		0.11	
Republic Middle School	9-1	T	3	374	1.50	0.00	12.00	0.20	0.08	None
		L				1.05	10.05		0.35	
Republic Middle School	9-2	T	3	1017	4.72	0.00	36.00	0.23	0.09	Light
		L				0.00	28.40		0.07	
Republic Middle School	9-3	T	3	855	4.20	0.00	30.00	0.25	0.09	Light
		L				0.00	38.00		0.11	
Ulalar Elementary School	10	T	3	1944	3.47	13.50	52.50	0.09	0.76	Moderate
		L				4.44	54.70		0.30	
Kemah High School	11-1	T	4	1511	4.68	3.60	30.00	0.15	0.29	None
		L				2.49	33.10		0.22	
Kemah High School	11-2	T	4	511	1.35	3.60	9.75	0.13	0.75	None
		L				2.70	0.00		0.53	

Earthquake damage of buildings could be directly related to the amount of story drift that actually occurs during the earthquake (Algan[5]). The amount of drift is controlled by the overall building stiffness that depends on the stiffness of the individual structural and nonstructural components of the building. Unfortunately, determination of the overall structure stiffness would require considerable computation time and would be handicapped by the poor quality of information on the stiffness contributed by filler walls. On the other hand, computing the area of structural and nonstructural components that provide for the building stiffness is simple. To account for the difference in stiffness and strength, different weights were assigned to column, reinforced concrete wall, and nonreinforced infill wall areas [Eq. (1) and (2)]. These weights were initially based on strength and stiffness properties inferred from material behavior but later modified to produce the minimum number of apparent anomalies for the data studied.

The data in Fig. 7 identified as "moderate," "light," and "none" refer to the 46 buildings of the METU inventory. For each building, the attributes for the "weaker" direction were plotted ("weaker" determined as that resulting in the shorter radial distance from the origin). The line designated as "Boundary 1" and the two axes define a triangular region. If the two indices (the wall and the column indices) define a point within this triangle, the particular building is considered to be more vulnerable than a building for which the indices intersect at a position, say, outside Boundary 2. There

Table 1—METU building data (continued)

Building name	ID no.	Dir.	No. of stories	Total floor area, m^2	Column area at base, m^2	RC wall area at base, m^2	Masonry wall length at base, m	Column index, percent	Wall index, percent	Damage state
Kemah High School	11-3	T	4	996	2.04	3.60	0.00	0.10	0.36	None
		L				2.49	0.00		0.25	
Public Library	12	T	3	1350	5.60	0.00	31.40	0.21	0.06	Light
		L				0.00	12.00		0.02	
Vocational High School cafeteria	13	T	1	901	6.45	0.00	0.00	0.36	0.00	Moderate
		L				0.00	0.00		0.00	
Police College Administration Building	14a	T	3	917	3.18	9.21	33.80	0.17	1.10	Moderate
		L				0.00	31.40		0.09	
Police College gymnasium	14b	T	1	997	12.00	0.00	0.00	0.60	0.00	None
		L				0.00	0.00		0.00	
Police College classroom building	14c-1	T	3	479	1.50	1.68	11.90	0.16	0.41	Light
		L				4.77	10.00		1.05	
Police College classroom building	14c-2	T	3	1959	8.68	6.96	39.90	0.22	0.41	Moderate
		L				0.00	25.00		0.03	
Police College dormitory	14d-1	T	5	965	1.80	4.62	0.00	0.09	0.48	Light
		L				3.40	0.00		0.35	
Police College dormitory	14d-2	T	5	965	1.8	4.62	13.74	0.09	0.51	Moderate
		L				3.40	4.32		0.36	
Police College dormitory	14d-3	T	5	965	1.80	4.62	13.74	0.09	0.51	Moderate
		L				3.40	4.32		0.36	
Dept. of Agriculture Office Bldg. 1	15	T	3	1030	7.60	1.68	33.54	0.37	0.24	Moderate
		L				0.00	58.50		0.14	
Dept. of Agriculture Office Bldg. 2	16-1	T	4	649	3.36	0.00	34.65	0.26	0.13	Light
		L				0.00	16.08		0.06	
Dept. of Agriculture Office Bldg. 2	16-2	T	4	1193	4.92	6.53	52.70	0.21	0.66	Light
		L				0.63	24.12		0.10	
Adult Education Center	17	T	3	1533	7.54	1.66	30.76	0.25	0.16	Moderate
		L				0.60	46.71		0.12	
Police Headquarters Old Building	18	T	3	1243	5.20	0.00	36.35	0.21	0.07	Light
		L				0.00	47.60		0.10	
Yenisehir Police Station	19	T	2	506	3.13	0.00	42.85	0.31	0.21	Light
		L				0.00	53.22		0.26	
Boys' High School dormitory	20a	T	3	1009	3.80	8.06	46.20	0.19	0.91	Light
		L				4.68	0.00		0.46	
Boys' High School dormitory	20b	T	3	848	5.30	6.09	41.10	0.31	0.84	Light
		L				4.68	0.00		0.55	
Boys' High School dormitory	20c	T	3	507	3.90	0.00	11.55	0.38	0.06	Light
		L				0.00	0.00		0.00	
Kemah City Hall	21	T	4	1680	6.26	0.00	60.00	0.19	0.09	Light
		L				0.00	33.60		0.05	

is no absolute basis for locating the boundaries or for the number of boundary lines. The graphical scheme is simply to evaluate the relative vulnerability of buildings in a given region. If decisions are to be made for renewal or strengthening of the building inventory, attention must first be paid to those buildings related to data within the first boundary. The first boundary may be placed close to or far away from the origin depending on the risk that can be tolerated and the resources available for seismic risk reduction.

The priority for remedial action, be it removal or strengthening, of the structure may be expressed by a "Priority Index," PI, expressed as follows

$$PI = WI + CI \tag{3}$$

In evaluating a group of buildings, those with the lowest values of PI would be candidates for the earliest action. No additional factors are included to reflect seismic risk because the procedure is designed to rank buildings in the same region. Summing WI and CI reduces the process to a judgment based on a single variable that reflects the weighted areas of the columns, reinforced walls, and unreinforced walls. This is convenient but may be counterproductive for improving the method on the basis of experience. The distinctions between the relative effects of the walls and the columns must be recognized explicitly. The weights used for determining effective areas are open to further development.

The METU data set does not include buildings that suffered structural failure. Spot checks of the proposed procedure were made by examining data from other sources. Three severely damaged low-rise reinforced concrete buildings in Erzincan are reported by the Joint Reconnaissance Team of AIJ et al.[6] Two other low-rise buildings are included in the spot-check procedure from other regions: one from Skopje (Sozen[7]) and one from San Fernando (Murphy[8]). The results are shown in Fig. 7 by solid squares. These two

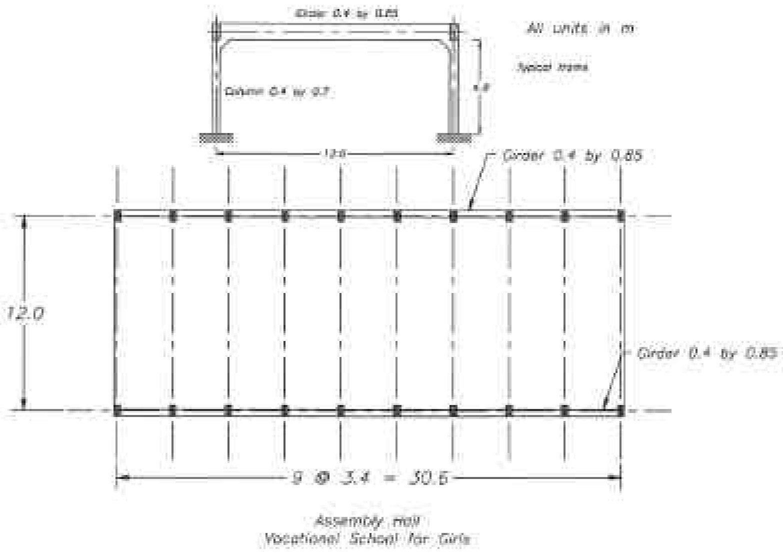


Fig. 2—Plan, Vocational School for Girls

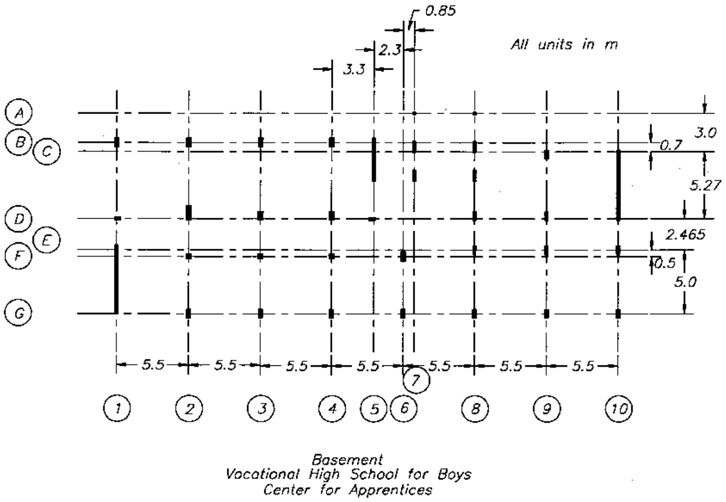


Fig. 3—Plan, Vocational School for Boys

buildings, which had severe damage, would also be identified as having relatively high risk. The five buildings are identified in Fig. 7 by solid squares, according to their column and wall indices. It can be seen that the proposed method would rate these buildings as having relatively high risk.

Undoubtedly, the method leaves out more variables than it includes. It is insensitive to changes in material quality, storey height, girder properties, framing in upper storeys, and detail. It lacks proof by theory or experiment. It cannot make absolute judgments about structural safety. Nevertheless, it offers a pragmatic method for identifying the most vulnerable in a regional inventory of low-rise buildings with monolithic reinforced concrete framing. Granted that an engineer's judgment is the most important criterion for determining seismic vulnerability, the proposed method conserves the most expensive ingredient: time of the experienced professional.

Table 2—Column dimensions, Vocational High School for Boys

		1	2	3	4	5	6	7	8	9	10
A	3rd storey							23*23	23*23		
	2nd storey							23*23	23*23		
	1st storey							23*23	23*23		
	Basement							23*23	23*23		
B	3rd storey	23*35	23*35	23*35	23*35			23*90	23*90		
	2nd storey	23*50	23*50	23*50	23*50			23*90	23*90		
	1st storey	23*70	23*70	23*70	23*70			23*90	23*90		
	Basement	35*70	35*70	35*70	35*70			23*90	23*90		
C	3rd storey									23*35	
	2nd storey									23*50	
	1st storey									23*50	
	Basement									23*50	
C-D	3rd storey							23*90	23*90		
	2nd storey							23*90	23*90		
	1st storey							23*90	23*90		
	Basement							23*90	23*90		
D	3rd storey	23*35	23*45	23*35	23*35	23*23			23*35		
	2nd storey	23*50	23*70	23*70	23*50	23*50			23*50		
	1st storey	23*50	23*110	30*70	30*70	23*50			23*70		
	Basement	23*50	40*110	40*70	40*70	23*50			23*70		
E	3rd storey								23*35	23*35	23*35
	2nd storey								23*50	23*50	23*50
	1st storey								23*70	23*70	23*70
	Basement								23*70	23*70	23*70
F	3rd storey		23*35	23*35	23*35						
	2nd storey		23*50	23*50	23*50						
	1st storey		35*35	35*35	35*35						
	Basement		40*40	40*40	40*40						
G	3rd storey		23*35	23*35	23*35		23*35		23*35	23*35	23*35
	2nd storey		23*50	23*50	23*50		23*50		23*50	23*50	23*50
	1st storey		23*70	23*70	23*70		23*70		23*70	23*70	23*70
	Basement		30*70	30*70	30*70		30*70		30*70	30*70	30*70

Note: All dimensions in cm.
Walls on 1 (G-F), 5 (C-), and 10 (D-C).

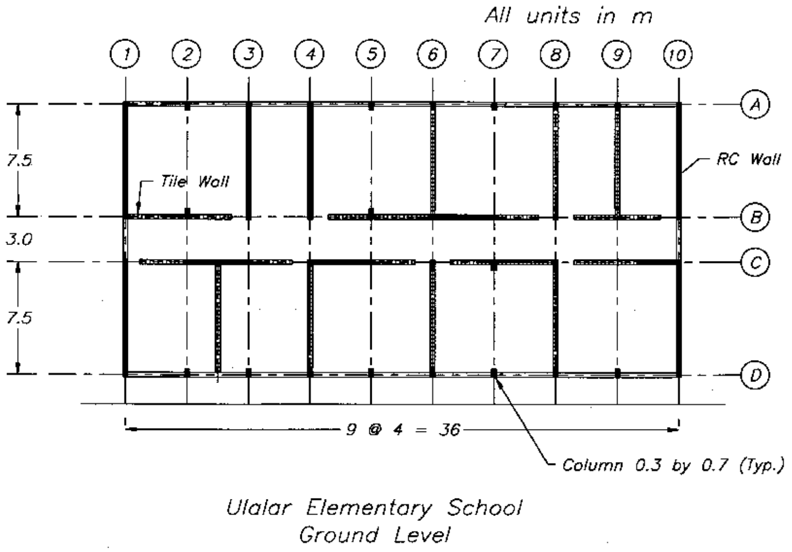


Fig. 4—Plan, Ulalar Elementary School

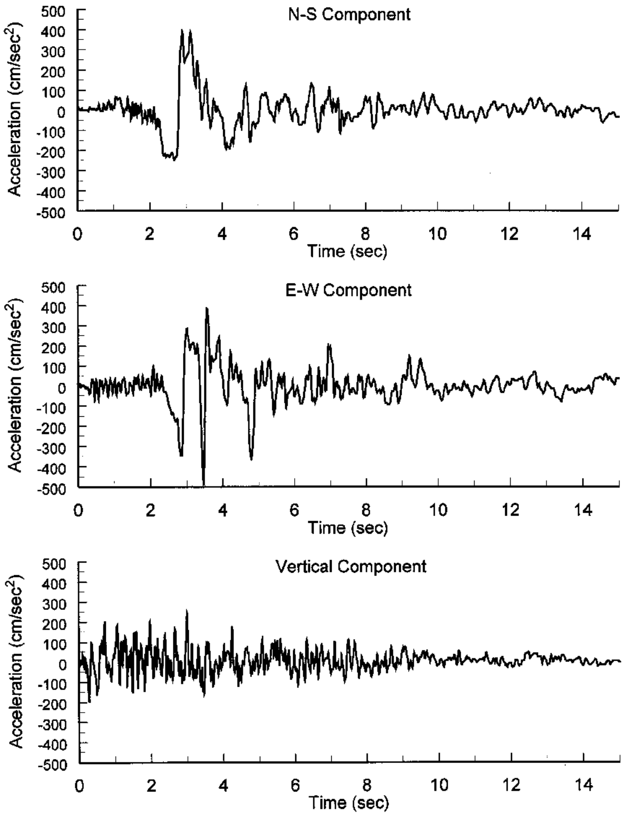


Fig. 5—Components of Erzincan earthquake, March 13, 1992

SUMMARY

A method is proposed to help select the buildings with higher seismic vulnerability in an inventory of low-rise monolithic reinforced concrete buildings located in the same region. The method requires only the dimensions of the structure as input and is based on defining the position of a building on a two-dimensional plot using the wall and column indices. The wall index is the ratio of the effective wall area at the base of the building to the total floor area above base. The column index is the ratio of the effective column area at base to the total floor area above base. In the computation of the effective areas, 100 percent of reinforced concrete walls, 10 percent of nonreinforced infill walls, and 50 percent of column area are considered effective. As indicated in Fig. 7, the closer is the point located by the two indices to the origin, the more vulnerable is the building.

The function of the proposed method is to rank a group of buildings with respect to the expected amount of earthquake damage. In the rehabilitation process, the ranking may be modified by the importance of the building and other knowledge about building properties.

The salient attribute of the method is that it requires a minimum of information and computation for filtering a large inventory of low-rise monolithic reinforced concrete buildings to identify the fraction that should have priority for remedial action.

ACKNOWLEDGMENTS

This work, which has been undertaken to reduce engineering labor, has consumed more labor by many engineers than implied by the simplicity of the paper. Two members of the METU faculty, Dr. Ugur Ersoy and Dr. Polat Gülkan, helped the project throughout its two-year duration by making data available, by suggesting solutions, and by their critical discussions. Adolfo

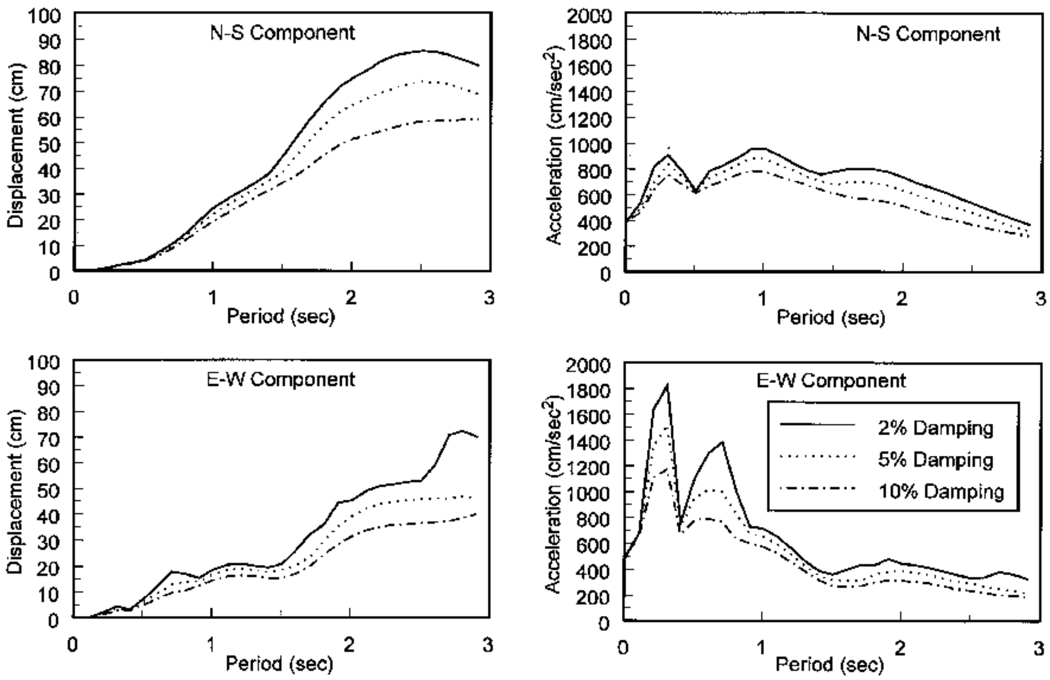


Fig. 6—Linear response spectra, Erzincan earthquake, March 1992

Matamoros, a graduate student at the University of Illinois, Urbana, Siddika Demir, a graduate student at Purdue University, W. Lafayette, and Colleen Konwinski and Kai Kraut, undergraduate students at the University of Illinois, were instrumental in interpreting the archives to express the data in reliable and manageable form. Mr. Matamoros is also thanked for his contributions to the discussions, which helped reduce the procedure from one with many to one with few variables.

The project was sponsored by the National Science Foundation (Program Director, Dr. S. C. Liu) under Grant No. 9496280-CMS at the University of Illinois and Purdue University. The work at METU was sponsored by the Ministry of Housing and Natural Disasters of the Turkish Republic (Dr. Oktay Ergunay, director). Data were processed at the R. G. Smith Computational Facility at Kettelhut Laboratory, Purdue University.

REFERENCES

1. Shiga, T.; Shibata, A.; and Takahashi, T., “Earthquake Damage and Wall Index of Reinforced Concrete Buildings,” *Proceedings*, Tohuku District Symposium, Architectural Institute of Japan, No. 12, Dec. 1968, pp. 29-32. (in Japanese)

2. Personal communications, Middle East Technical University, Ankara, Turkey, 1993.

3. “March 13, 1992 (Ms = 6.8), Erzincan Earthquake: A Preliminary Reconnaissance Report,” Kandilli Observatory and Earthquake Research Institute and Faculty of Engineering, Department of Civil Engineering, Bogazici University, May 1992, 119 p.

4. Ersoy, U.; Gülkan, P.; Karaesmen, E.; Özkan, M.; Sucuoglu, H; Tokyay, M.; and Çobanoglu, M., “March 13, 1992, Erzincan Earthquake Engineering Report,” Chamber of Engineering, Ankara, Bizim Buro Printers, June 1992, 102 p. (in Turkish)

5. Algan, B. B., “Drift and Damage Considerations in Earthquake-Resistant Design of Reinforced Concrete Buildings,” PhD thesis, University of Illinois, Urbana-Champaign, 1982.

6. “Damage Report on 1992 Erzincan Earthquake, Turkey,” Joint Reconnaissance Team of Architectural Institute of Japan, Japan Society of Civil Engineering, and Bogazici University, Istanbul, Turkey, 1993.

7. Sozen, M. A., “Structural Damage Caused by the Skopje Earthquake of 1963,” report to the Committee on Masonry and Reinforced Concrete of the American Society of Civil Engineers and the American Concrete Institute, University of Illinois, Urbana, Jan. 1964.

8. Murphy, L. M., “San Fernando, California, Earthquake of February 9, 1971,” United States Department of Commerce, National Oceanic and Atmospheric Administration, Washington, D.C., V. I, Part A, 1973.

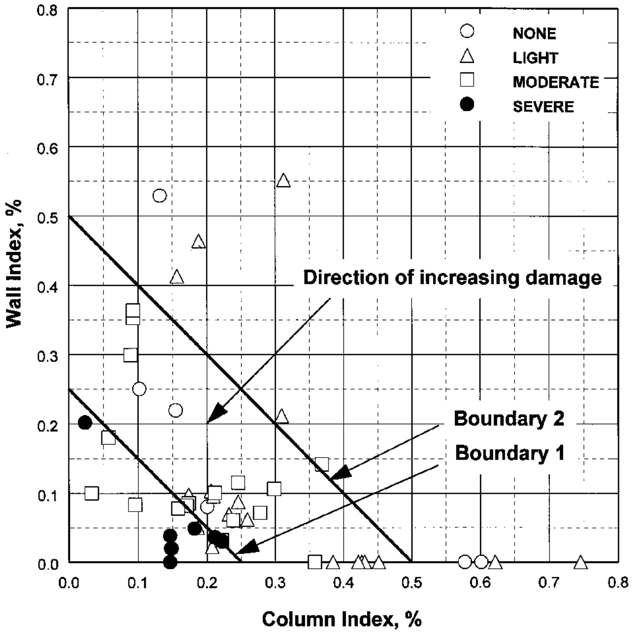


Fig. 7—Proposed evaluation method, all data

Table 3—Additional building data

Building name	Dir.	No. of stories	Total floor area, m^2	Column area at base, m^2	RC wall area at base, m^2	Masonry wall length at base, m	Column index, percent	Wall index, percent	Damage state
Faith District Apartment Buildings[*]	T	4	517	2.30	0.00	56.0	0.22	0.27	Severe
	L				0.00	7.80		0.04	
Hotel[*]	T	6	2646	7.84	0.00	21.00	0.15	0.02	Severe
	L				0.00	36.80		0.03	
Clinic[*]	T	4	1023	4.32	0.00	14.70	0.21	0.04	Severe
	L				0.00	50.00		0.12	
Transformer Building[†]	T	3	1564	4.58	0.00	11.70	0.15	0.02	Severe
	L				0.00	0.00		0.00	
Museum for Antique Cars[‡]	T	5	4900	2.33	9.90	0.00	0.02	0.20	Severe
	L				12.60	0.00		0.26	

[*] Erzincan earthquake of 1992 (Joint Reconnaissance Team of AIJ, JSCE, and BU, 1993).

[†] Skopje earthquake of 1963 (Sozen, 1964).

[‡] San Fernando Earthquake, 1971 (Murphy, 1973).