Zeitschrift: IABSE reports of the working commissions = Rapports des commissions de travail AIPC = IVBH Berichte der Arbeitskommissionen

Band: 30 (1978)

Artikel: Behaviour of brick masonry buildings during earthquakes

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DOI: https://doi.org/10.5169/seals-24186

BEHAVIOUR OF BRICK MASONRY BUILDINGS DURING EARTHQUAKES

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SUMMARY

The characteristics and behaviour of brick masonry buildings in Turkey with reference to earthquakes, the measured dynamic properties of several masonry structures, and "Earthquake Resistant Design Code" provisions for brick masonry structures in Turkey are presented and the behaviour of several brick masonry buildings during Nov. 24, 1976 Çaldıran and March 25, 1977 Palu (eastern Turkey) earthquakes are compared with Code provisions. The importance of bearing wall length/floor area ratio and external wall opening ratio is studied and their importance for efficient earthquake resistant is stated.

1. INTRODUCTION

Brick masonry is very common and widely used construction system in Turkey. Approximately 70 % of all the new housing construction is in brick masonry. However the quality and strength of bricks available in Turkey prevents the construction of brick masonry houses higher than four stories. With the rapid growth of cities and the rise of land prices, the trend is to build high rise buildings, at least in large cities and they are all in reinforced concrete. Reinforced masonry is not used to construct high rise buildings since the same amount of steel is required for reinforced concrete construction and cement is readily available. In spite of that considerable number of brick masonry structures are still being built in smaller towns and even at the outskirts of large cities. Considering the high seismic activity of Turkey, the earthquake resistant design and construction of brick masonry structures is still a main topic of concern among Turkish civil engineering circles.

2. CHARACTERISTICS OF BRICK MASONRY STRUCTURES IN TURKEY

2.1 Bricks

In Turkey there are two obligatory standarts covering the production of clay bricks [1], [2]. The dimensions of standart bricks are 19x9x5 centimeters. The handmade bricks are produced by very primitive methods, dimensional, strength and other properties of hand made bricks are non-uniform. The temperature of burning is generally lower than factory made bricks which are stronger and dimensionally uniform. Hand made bricks are burned in simple kilns where control of temperature and rate of burning is impossible. Thus they show very inferior qualities. Even the quality and strength of factory made bricks are lower than corresponding bricks produced in Europe. Since the factory made bricks require considerable investment, they are relatively more expensive. In 1975, while factory made bricks costs 0.40 Turkish Liras (2.9 US cents), hand made brick costs 0.25 Turkish Liras (1.8 US cents). The usage of hand made bricks is very wide, perhaps 60 to 70 % of all the bricks used in Turkey are molded by hand and burned in simple kilns.

2.1.1 Compressive Strength of Turkish Bricks

Based on the brick compressive strength tests carried out at the Directorate of Building Materials of Ministry of Reconstruction and Resettlement the following brick compressive strengths are observed[3]:Table-1

TABLE-1
Compressive Strength of Bricks Tested

Brick type	Hand Made Solid	Factory Made Solid	Factory Made Hollow Load Bearing	Block Filler Brick
Average Compressive Strength	55 kg/cm2	236 kg/cm2	188 kg/cm2	44 kg/cm2
Variation of Strength	33 %	19 %	20 %	25 %

These values are very low in comparison with the brick strengths available in European countries and United States. These low values prevents the construction of high rise brick buildings even for purely vertical loads, because of the generally high safety factors used in brick masonry construction requires very thick walls in the lower floors of a high rise building.

2.1.2 Compressive Strength of Brick Masonry

Although there is a widespread usage of brick masonry in Turkey, the number of tests made on brick masonry walls to determine their mechanical properties are very few. In one of these tests carried out by Tolunay [4] the following results were obtained: Table-2

TABLE-2

Mechanical Properties of Brick Masonry In Turkey

	Factory Made Brick	Hand Made Brick
Brick Modulus of Elasticity	$E = 74\ f'_B$	$E = 112\ f'_B$
Brick Wall Mod. of Elasticity		
Lime Mortar 1:3	$E = 35\ f'_W$	$E = 45\ f'_W$
Cement-lime-sand Mortar 1:2:8	$E = 97\ f'_W$	$E = 97\ f'_W$
Brick Wall Compressive Strength		
Lime Mortar 1:3	$f'_W = 0.20\ f'_B$	$f'_W = 0.27\ f'_B$
Cement-Lime-sand Mortar 1:2:8	$f'_W = 0.27\ f'_B$	$f'_W = 0.28\ f'_B$

In this table f'_W is the brick wall ultimate compressive strength and f'_B is the brick ultimate compressive strength. These ratios are derived from a very limited number of test specimens and their usage is not very dependable, they can only be used if the brick compressive strength is known with sufficient accuracy.

2.1.3 Shear Strength of Brick Masonry

During the earthquakes brick masonry structures are subjected to loads that develope shear and diagonal tension stresses in the walls. Thus these properties of brick masonry gain importance, sometimes it is more important than the brick or masonry wall compressive strength. The diagonal tensile strength of brick masonry is expressed in formulae of the following form:

$$\tau = \tau_o + \mu \sigma$$

In this formula τ is the diagonal tensile strength (shear) of the wall, τ_o is the shear strength without any vertical stress and can be accepted as the adherence between brick and mortar, σ is the vertical stress in the wall and μ is a coefficient of friction. According to tests made by Yorulmaz and Atan[5] in Turkey μ and τ_o values are dependent on brick and mortar type. They give the following values for μ and τ_o: Table-3

TABLE-3

τ_o and μ Coefficients For Shear Strength of Brick Masonry

Brick Type	Load Bearing Hollow Brick		Gas Beton (YTONG)		Filler Block Brick	
	Cement Mortar	Cement-lime Mortar	Cement Mortar	Cement-lime Mortar	Cement Mortar	Cement-Lime Mortar
μ	0.43	0.41	0.68	0.69	0.34	0.21
τ_o (kg/cm2)	5.14	4.02	1.52	1.53	3.64	5.28

One other important property of brick masonry is the adherence between mortar and brick. Tests carried out by Erdülek [6] show that this is also a property which depends on brick and mortar properties. Table-4

TABLE-4

Adherence Between Brick and Mortar

(kg/cm2)

Mortar Type / Brick Type	1:4 Cement:Sand	1:1:4 Cement:Lime:Sand	1:2:4 Cement:Lime:Sand
Hand Made	1.6-0.03	1.9-0.45-0.09	1.6-0.02-0.03
Factory Made Solid	1.5-1.06	1.8-0.64-0.31	3.32-0.82-0.03
Factory Made Hollow	2.[illegible]7-1.8	3.23-2.23-1.69	3.37-0.67-1.57

In these tests three different mortar types were used but their average tensile strength were in the order of 4 kg/cm2 (compressive strength of roughly 40 kg/cm2). These values correspond to values obtained from sample bricks which were water saturated, as it is, and oven dried. It seems that the values corresponding to bricks tested as they are should be taken as the case which represents the actual conditions. Although relatively scattered values for has been obtained in tests, it seems that a value not greater than 1 kg/cm2 for could be accepted as the probable value.

Considering the results of these two researches the shear strength of brick masonry walls in Turkey can be expressed as follows:

$$\tau = 1.0 + 0.45\,\mu$$

Taking into account the average dimensions of and loads on brick masonry the vertical stresses coming to ground floor walls of one to four stories high brick masonry structures are 1.40, 1.55, 2.50 and 3.60 kg/cm2; with these vertical stresses, the shear strength of brick masonry walls in

Turkey can vary between 1.63 and 3.62 kg/cm2.

2.2 Mortars

In Turkey the type of mortar which is commonly used is cement reinforced lime mortar. Mortar strengths are generally very low, in view of the low brick strengths, the use of relatively weak mortars is justifiable since the usage of high strength mortars do not bring a considerable rise in brick masonry strengths. The most widely used mortars contain lime plus some amount of cement. The usual lime sand ratio is 1 to 3 and if cement is added then the cement lime ratio is aproximately again 1 to 3. Again the number of tests on various mortar ratios are not very much in Turkey. The strength properties of the mortars used in various tests [4], [5], [6] are given in Table-5

TABLE-5

Mortar Strengths in Turkey

Mortar Ratio	[4]			[6]		[5]	
Lime:Cement:Sand	1:0:3	2:1:8	0:1:4	1:1:4	1:2:4	0:1:4	1.5:1:8
Comp. Strength (kg/cm2)	7.0	10.0	-	-	-	117-177	33-47
Tensile Strength (kg/cm2)	2.5	3.0	4.8	3.8	3.8	26-44	8-10

As seen from table above, the variation in mortar strengths is very high, the mortar strengths given in reference 5 are for mortars using sand with precisely determined gradation curves, while those taken from Reference [4] could be considered as being closer to the one which can be expected in actual construction conditions. In many cases low mortar strengths have been the cause of extensive earthquake damage.

2.3 Brick Masonry Design Code

It is sad fact that there is not a specific design code with regard to brick masonry in Turkey. Lately there has been an attempt to formulate a standart for the design of brick masonry construction but it is not published as yet. There are some guidelines as to the allowable compressive stresses which can be used in masonry walls with respect to their being stone or clay brick and the kind of mortar used as lime, cement reinforced lime and cement mortar. Table-6. In case of stone masonry these va-

TABLE-6

Allowable Compressive Strengths for Masonry

Wall Type	Brick Wall Lime Mortar	Brick Wall Lime and Cement	Brick Wall Cement Mortar
Allowable Compressive Stress kg/cm2	5 kg/cm2	8 kg/cm2	10 kg/cm2

lues are decreased by 20 percent.

2.5 Earthquake Resistant Design Code Provisions for Brick Masonry Buildings

In the absence of any brick masonry design and construction regulations in Turkey, it had been felt to incorporate many provisions concerning brick masonry into the earthquake resistant design code of Turkey [7]. In the following parts some of the important provisions of the code with respect to earthquake behaviour will be given.

2.5.1 Building Height Limitations

According to the earthquake zoning map of Turkey, the country is divided into 5 seismic danger regions. In zones I and II brick masonry houses can be only two stories high (ground floor and 1st floors), in zone III brick masonry buildings can be three stories high (ground, 1st and 2nd floors) and in zone IV brick masonry houses can be four stories high (ground, 1st, 2nd and 3rd floors). In zone V which is taken as seismically inactive, there is no height limitation for brick masonry houses. However as already explained above the quality of bricks available in Turkey prevents construction of brick masonry houses higher than four stories. The code besides limiting the height of brick masonry construction, also specifies the minimum brick wall thickness of each story.

For two story brick masonry houses the ground floor wall thickness must be 1.5 brick size (29 centimeters), while the upper floor must at least be 1 brick thick (19 cm.). For three story high brick masonry construction, the ground floor wall thickness must be at least 1.5 brick size (29 cm.), while the upper two stories must be at least of 1 brick thickness (19 cm.). For four story high brick masonry houses, the ground and first story walls must have a thickness of 1.5 bricks (29 cm.) and the rest would have a thickness of 1 brick. For single story high brick construction the minimum wall thickness is one brick (19 cm.). If these construction have basements, the basement walls should be at least 50 centimeters thick stone masonry.

2.5.2 Openings in Walls

This is the most detailed part of the code [7]. It is based on the assumption that solid walls between openings are the lateral load carrying elements and their size effects the safety of brick masonry construction during earthquakes.

In the code the total length of the openings in an external wall should not be greater than 40 % of the length of that wall.

The maximum size of window or door openings should not be greater than 3.00 meters.

The solid wall between the corner of the building and the first window or door opening on that wall should at least be 1.50 meters in I and II degree earthquake zones and 1.00 meters in III and IV degree earthquake zones. If the building is less than 7.50 meters high, these solid wall lengths could be reduced to 1.00 meters and 0.80 meters in the respective earthquake zones.

The solid wall length between two openings (door or window) while being not less than 1/4 of the length of larger opening, should also be at least 0.80 meters in I and II earthquake zones and 0.60 meters in III and IV degree earthquake zones.

2.5.3 Lintel Beams

While the parts of lintel beams resting on the walls should extend at least 0.20 meters beyond on each side of the opening, these parts should also be greater than 15 % of the span of the lintel beam. This provision of the code in practice enforces the placing of a continous lintel beam at the top level of the door and window openings all around the building.

3. DYNAMICAL CHARACTERISTICS AND EARTHQUAKE BEHAVIOUR

3.1 Dynamic Characteristics

Brick masonry structures because of their large sized walls are stiff structures and their periods of vibration are usually low. Period measurements made at the Earthquake Research Institute show that their period of vibration lie usually in between 0.05-0.15 seconds depending on the height of the building. Table-7

TABLE-7

Periods of Vibration of Brick Masonry Buildings

Building Description	Height H (m)	Length L (m)	Width W (m)	Period (sec.)	H/W	Period (sec.)	H/L
One story Brick masonry	2.50	7.80	6.30	0.093	0.40	-	0.32
One story Brick masonry	2.50	9.76	4.55	0.054	0.55	-	0.26
One story Brick masonry	2.50	8.00	6.80	0.045	0.37	-	0.31
One Story Stone masonry	2.50	10.97	9.90	-	0.25	0.042	0.23
Three story Brick masonry	-	-	-	0.073	-	0.049	-
Four story Brick Masonry	11.00	17.25	15.00	0.16	0.67	-	0.64
Two story Brick masonry with basement	9.00	21.00	14.25	-	0.63	0.065	0.43
Two story Brick masonry w/o basement	6.50	21.00	14.25	0.036	0.45	0.045	0.31
Four story Brick masonry with basement	12.00	26.00	24.00	0.164	0.50	0.156	0.46
Three story Brick masonry	7.80	19.70	9.75	0.126	0.80	0.156	0.40

Same as above Heavily damaged in earthquake, with fewer wall opening	7.80	19.70	9.75	0.096	0.80	0.390	0.40

Based on these relatively limited number of brick masonry buildings, the following relation between the period of vibration (T) and the building story number (N) may be suggested:

$$T = 0.05\ N$$

However this relationship needs further investigation. In this form the T value is slightly greater than the actual value of period of vibration. Brick masonry structures due to their rigidity will exhibit very low damping values, probably, never more than 2 %. But in case of earthquake damage the damping may go up as much as 10 %. Comparison of the last two data on Table-7 indicates that very large changes in the period of vibration of damaged masonry structures should be expected.

Significance of low periods of vibration of brick masonry buildings points out that these buildings will be subjected to spectral accelerations almost equal to the maximum ground acceleration. Considering the shear strength of brick masonry, the lateral force which will cause the cracking of brick walls could be established. Once the brick wall cracks its resistance to shear stresses is provided by the friction along the cracks and thus its shear strength after cracking is highly dependent on the vertical loads. Tests must be carried out to determine the shear strength of brick masonry in the cracked state.

3.2 Earthquake Behaviour

Brick masonry is a highly brittle material and under earthquake loads it breaks very easily and even an earthquake of intensity V MSK would be sufficient to have cracking in the walls. Higher intensities of earthquake motion will increase the level of damage. In this part of the paper an attempt will be made to explain the behaviour of brick buildings during earthquakes.

Under the action of lateral forces (wind and earthquake) the longitudonal walls will transfer the lateral loads to the roof or floor slab (if there is one) or to the roof truss and this element will in turn transfer the loads to end walls. Figure-1. Thus the end walls will be subjected to shear forces and when the shear stress exceeds the shear strength of the wall, failure in the form of diagonal tension cracks occurs. These cracks will make an angle of 45 degrees with the horizontal.

Since the earthquake forces will act in the two principal directions of the building, the corners of the building will be very critical. Figure-2

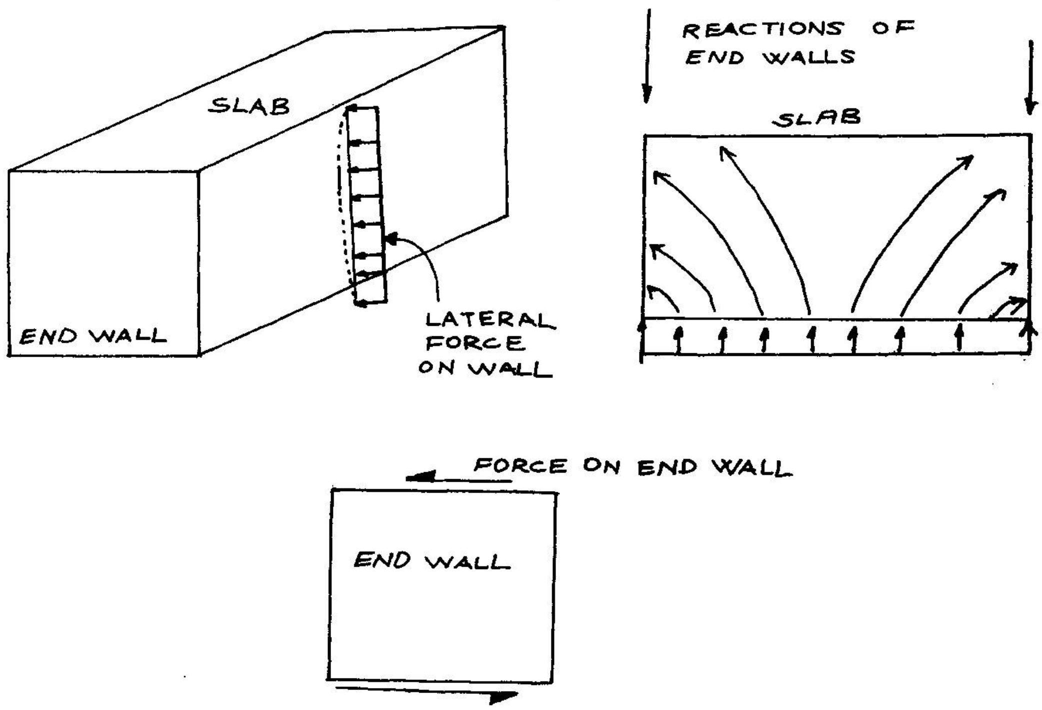

Figure-1 State of Loading on Brick
Walls Due to Lateral Forces

In fact such kinds of corner failures have been observed many times in Turkey. Figure-3. In case when there are no slabs of reinforced concrete or the roof truss is not rigid enough to hold the two cross walls together this form of damage should be expected.

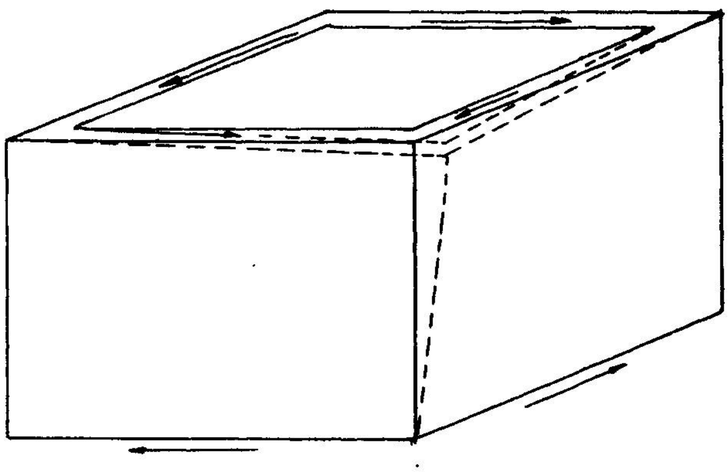

Figure-2 Corner Behaviour of Masonry Buildings.

Figure-3 Corner Damage due to Earthquake

Due to action of shearing forces on the walls of brick masonry, various forms of diagonal tension failures occur. However the walls are also subject to compressive stresses due to the weight of the wall and weight of upper stories. Thus the diagonal tension cracks will deviate from 45^o and the angle between the cracks and vertical direction will be smaller than 45^o degrees. Apart from the angle of cracks, the extension of the

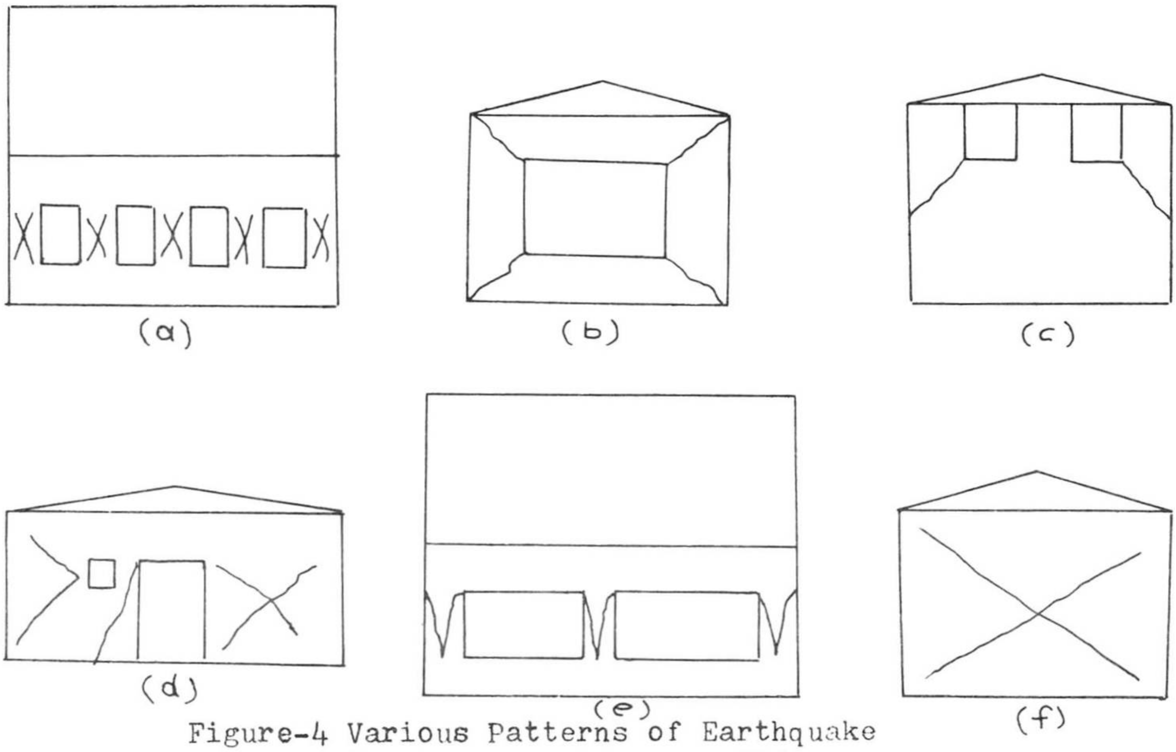

Figure-4 Various Patterns of Earthquake Cracking in Masonry Buildings of the cracks will be influenced by the height to width ratio of the wall and location and size of the window and door openings. Figure-4.

This initial diagonal cracking of the wall, if the earthquake continues at a high intensity, will result in the decrease of vertical load carrying capacity of the wall and vertical cracks due to vertical loads will begin to appear in addition to the existing cracks due to diagonal tensile stresses in the wall. This process will eventually lead to the complete collapse of the wall. Figures-5,6,7 show this kind of heavily damaged brick masonry walls

Figure-5 Typical Failure of Brick Masonry

Figure-6 Typical Failure of Brick Masonry

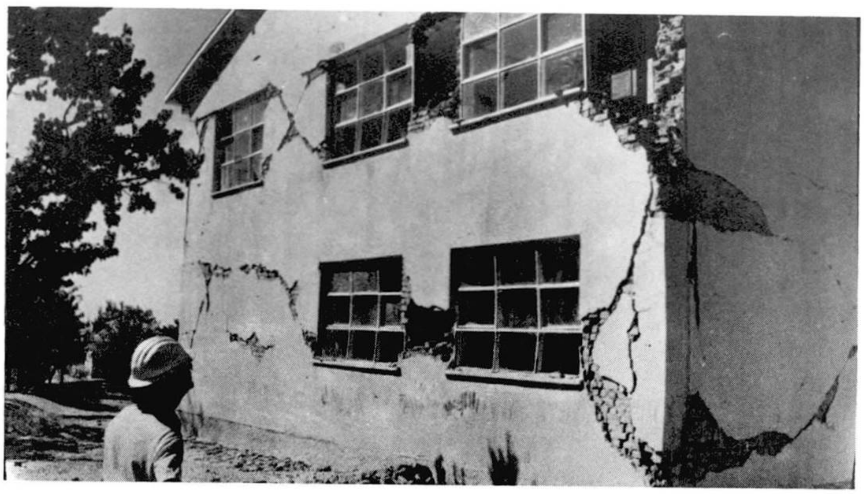

Figure-7 Typical Failure of Brick Masonry

4. COMPARISON OF CODE PROVISIONS AND EARTHQUAKE BEHAVIOUR

The earthquake resistant design code provisions for brick masonry buildings generally is composed of certain rules for wall openings with respect to the total external walls, placement of lintel beams, the foundations and certain restrictions on the height of brick masonry buildings. Although earlier editions of the earthquake resistant design code of Turkey had also stressed on the importance of wall opening ratios, there had been no systematic emprical research on the effectiveness of wall opening ratio as an earthquake resistant feature for brick masonry buildings, using data from buildings damaged in actual earthquakes.

After November 24, 1976 Çaldıran and March 25, 1977 Palu earthquakes [8] [9] a number of masonry buildings were investigated and the effectiveness of wall opening ratio as an earthquake resistant design feature for brick masonry buildings were tested. The results of the analysis of five buildings are given in reference [10]. Here, only a brief summary of the result will be presented.

The window and door opening ratios of two principal axes of these buildings, along with the wall length (cm)/floor area (m2) ratio is as given in Table-8. On this table x-axis of the building corresponds to the lon-

TABLE-8

Opening and Wall Ratios of Earthquake Damaged Buildings

Building	External Wall Opening Ratio %	Wall/Floor Area Ratio cm/m2	Damage	Remarks
Çaldıran Staff Housing				
x-axis	41-37	26	No damage	I = IX
y-axis	0	31	No damage	(Figure-8)
Muradiye Staff Housing				
x-axis	54-53	17	Heavy damage	I = VII
y-axis	0	26	No damage	(Figure-9)
Muradiye Junior High School				
x-axis	15	20	Slight damage	I = VII
y-axis	53-37	12	Heavy damage	(Figure-10)
Palu Monopoly Office				
x-axis	42-35	21	Damage	
y-axis	0-16	24	No damage	I = VI
Palu Local Administration Building				
x-axis	55	25	Heavy Damage	I = VI
y-axis	29	30	No damage	(Figure-11)

Figure-8 Çaldıran Staff Housing

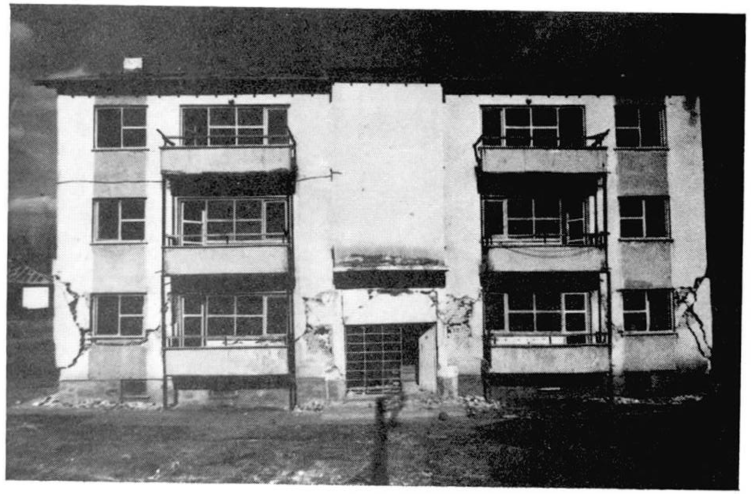

Figure-9 Muradiye Staff Housing

Figure-10 Muradiye Junior High School

Figure-11 Palu Local Administration Building ger plan dimension of the building, while y-axis coincides with the shorter dimension of the building. Wall length/floor area ratio is currently advocated as an earthquake resistant design feature in Japan[11].

From these observed damage and properties of buildings, it can be seen that an external wall opening ratio more than 40 % causes damage in the walls.

On the other hand, buildings with wall/floor ratio less than 25 cm/m2 are also damaged heavily. This points out the fact that large sized rooms in masonry houses could lead to damage in case of earthquakes.

The number of observed cases is few thus the impressions should be taken with caution. However, they could still be taken as useful parameters in the design of earthquake resistant brick masonry houses.

5. SUGGESTIONS AND CONCLUSION

As it is known brick masonry is not a construction system desired and used for earthquake resistant construction however certain economical conditions enforce its usage, specially for one to two stories high houses which are being built in considerable numbers in Turkey. The brittle nature of the brick masonry walls and rapid cracking of walls during earthquakes necessitates certain counter measures. Since the rapid shear cracking weakens the vertical load carrying capacity of walls thus increasing the possibility of collapse, measures are required to prevent extensive cracking and crack propagation. This is usually achieved by providing lintel beams of more ductile nature and of higher strength such as reinforced concrete at certain levels of the walls.

Another critical condition occurs at the corners of external walls,. under the action of earthquake forces, the cross walls tend to displace each other outwards at the corners. This could be prevented by providing vertical reinforced concrete columns at the corners. This detail is widely followed and commonly executed in Turkey even in one story high houses. Presence of reinforced concrete slabs at floor and roof levels will prevent outward displacement of corners by exerting a vertical restraint.

External wall opening and wall length/floor area ratios seem to be two important amprical parameters which could be used to improve earthquake behaviour of brick masonry structures. Research work, both analytical and experimental, could be carried out to provide more rational basis to these parameters.

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