SEISMIC RESISTANT REINFORCED CONCRETE STRUCTURES-DESIGN PRINCIPLES

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SUMMARY: Earthquakes cause considerable economic losses. It is possible to minimize the economic loses by proper seismic design. In this paper basic principles for seismic design are summarized. There are three basic requirements to be satisfied; (a) strength, (b) ductility and (c) stiffness. In the paper these are briefly discussed.

In the second part of the paper the author summarizes his views on the damages observed in the past earthquakes. He concludes that most of the damages have been due to, (a) bad configuration, (b) inadequate detailing and (c) inadequate supervision. In the paper these are discussed, pointing out the common mistakes made and damages observed as a result of these mistakes.

In the last part of the paper some simple recommendations are made for producing seismic resistant reinforced concrete structures, emphasizing on detailing and proportioning.

Key Words: Seismic resistance, reinforced concrete.

1. INTRODUCTION

Every year more than 300 000 earthquakes occur on the earth. Many of these are of small intensity and do not cause any damage to our structures. However, earthquakes of larger intensity in the vicinity of populated areas cause considerable damage and loss of life. It is estimated that on the average 15000 people have been killed each year throughout the world because of earthquakes.

Since ancient times mankind has sought ways and means of minimizing the damage caused by earthquakes. The great masters of the art of building have been able to build structures which have withstood many severe earthquakes for centuries. Magnificent mosques and bridges in the Middle East built by our ancestors are still in service, These masters did not know seismic analysis, but were able to evaluate past experience with their excellent engineering intuition and judgement. Mosques, bridges and schools (Medrese) built by Sinan in Istanbul and Edirne are not only beautiful, but are also engineering masterpieces.

Today we have great advantages as compared to our ancestors. We have more experience, we have highly developed analytical tools and considerable experimental data. It should also be noted that computers enable us to consider more variables and several alternatives in the analysis.

The main objective of this paper is to lay down some basic principles for producing earthquake resistant reinforced concrete structures. These are simple principles and easy to apply. They have been developed in the light of analytical and experimental research done and on observations made from past earthquakes.

2. BASIC PHILOSOPHY AND REQUIREMENTS

Design principles cannot be laid down unless there is a well defined design philosophy. The design philosophy generally accepted is summarized below:

- Buildings should suffer no structural damage in

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minor, frequent earthquakes. Normally there should be no nonstructural damage either.

- Buildings should suffer none of minor structural damage (repairable) in occasional moderate earthquakes.

- Buildings should not collapse in rarely occurring major earthquakes. During such earthquakes structures are not expected to remain in the elastic range. Yielding of reinforcing stell weill lead to plastic hinges at critical sections.

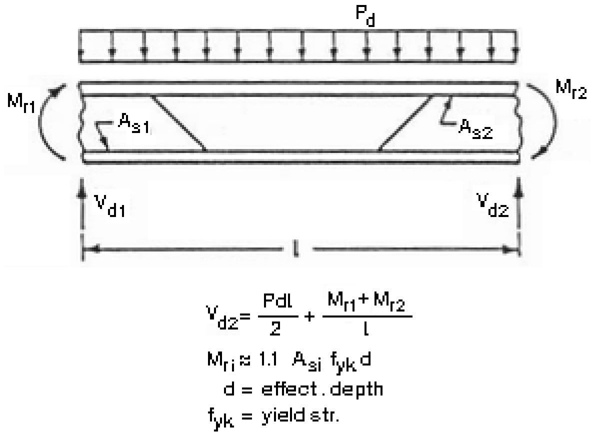


Figure 1.

The general design philosophy will not have much practical use unless design requirements are developed in parallel with this philosophy. The author believes that the design requirements can be summarized in three groups.

a. Strength requirements

b. Ductility requirements

c. Stiffness requirements (or drift control).

These three requirements will be briefly discussed in the following paragraphs.

2.1. Strength Requirements

Members in the structure should have adequate strength to carry the design loads safely. Since the designers are well acquainted with this requirement, it will not be discussed in detail. However, it should be pointed out that the designer should avoid brittle type of failure, by making a capacity design (1). The basic principles in capacity design are illustrated for a beam in Figure 1. If the design shear is computed by placing the ultimate moment capacities at each end of the beam, the designer can make sure that ductile flexural failure will take place prior to shear failure.

2.2. Ductility Requirements

In general it is not economical to design R/C structures to remain elastic during a major earthquake. It has been demonstrated that structures designed for horizontal loads recommended in the codes can only survive strong earthquakes if they can have the ability to dissipate considerable amount of energy. The energy dissipation is provided mainly by large rotations at plastic hinges. The energy dissipation by inelastic deformations requires the members of the structure and their connections to possess adequate "ductility”. Ductility is the ability to dissipate a significant amount of energy through inelastic action under large amplitude deformations, without substantial reduction of strength.

Adequate ductility can be accomplished by specifying minimum requirements and by proper detailing (2).

2.3. Stiffness Requirements

In designing a building for gravity loads, the designer should consider serviceability in addition to ultimate strength. In seismic design, drift limitations imposed might be considered to be some kind of a serviceability requirement. However, the drift limitation in seismic design is more important than the serviceability requirement.

The limiting drift is usually expressed as the ratio of the relative storey displacement to the storey height (interstorey drift). Excessive interstorey drift leads to considerable damage in nonstructural elements. In many cases the cost of replacing or repairing of such elements is very high. Excessive interstorey drift can also lead to very large second order moments (P - effect) which can endanger the safety and stability of the structure. Therefore interstorey drift control is considered to be one of the most important requirements in seismic design. The recent Mexico and Chile earthquakes have demonstrated the importance of this requirement (1). In Turkish Code the interstorey drift is limited to 0.0025h, where h is the storey height.

3. LESSONS LEARNED FROM PAST EARTHQUAKES

Our knowledge in seismic design has developed has developed as a result of analytical and experimental research and experience gained from past earthquakes. The author believes that lessons learned from past earthquakes have been the most important source among all others, because earthquakes perform the most realistic laboratory tests on the buildings.

The author has reevaluated the damages observed in earthquakes during the past 30 years in Turkey. This reevaluation has revealed that more than 90% of the damages can be attributed to one of the following causes or combinations of these:

a. Mistakes made in choosing the building configuration (general configuration or the structural system chosen).

b. Inadequate detaling and proportioning or errors made in detailing.

c. Poor construction quality caused by inadequate supervision.

It is interesting to note that causes of damage grouped into the above three categories seem to apply to earthquake damages observed in other countries also. These three causes will be discussed briefly in the paragraphs to follow.

3.1. Building Configuration

Seismic resistance should be initiated at the architectural design stage. If the general configuration chosen by the architect is wrong, it is very difficult and expensive for the structural engineer to make the building seismic resistant. As a general principle the floor plan should be as symmetrical as possible. The length of wings (T, L,. cross shaped buildings) causing re-entrant corners should not be large. If the length of the wings is not short, then these should be separated from the main building by an expansion Joint. Symmetry about the elevational axis is not as significant as the plan symmetry. However, abrupt changes in building plan along the height of the building are not desirable from the seismic resistance point of view. Setbacks are common vertical irregularities in building geometry. Setbacks cause discontinuities and abrupt changes in strength and stiffness. The seriousness of the setback effect depends on the relative proportions and absolute size of separate parts of the building. In general the designer should try to make changes in strength and stiffness along the building height as small as possible.

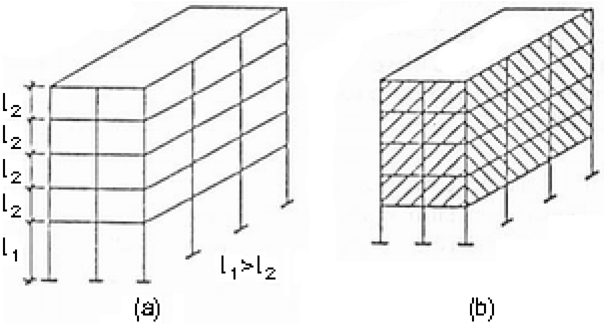


Figure 2.

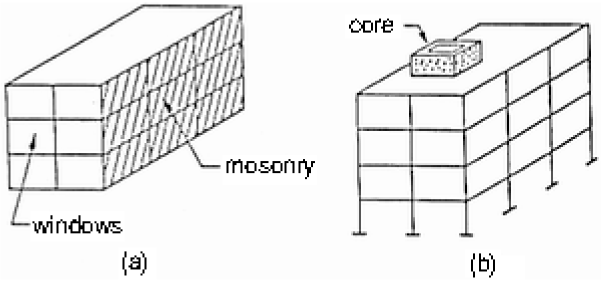


Figure 3.

As far as the structural system is concerned, one can set out some basic rules for better seismic resistance. Before setting out these rules, it would be appropriate to remind the engineers that nonstructural infill walls will influence the frame behaviour significantly unless separated from the frame.

Sudden changes in stiffness along the height of the building should be avoided. If the stiffness of one storey is significantly smaller than the others (soft storey), premature failure can occur due to excessive lateral displacement at this floor level. As shown in Figure 2, changes in the storey stiffness can be caused not only by structural elements, but also by nonstructural elements such as infill walls.

Two adjacent buildings should be separated from each other by an adequate distance in order to avoid the damage caused by pounding or reciprocal hammering of the buildings.

The vertical load carrying elements in a floor should be so proportioned and arranged that the center of mass and center of resistance should nearly coincide. If these two centers are away from each other, the resulting eccentricity can cause severe floor torsion, increasing the shear forces at the boundary elements considerably. Torsion is not only created by structural elements (Figure 3b) but can also be created by infill walls unless separated from the frame, Figure 3a.

The maximum shear force which be acting on a column can be found by adding the moment capacities (ultimate moments) at each end of the column and dividing by the column length Figure 4. This simply means that, if the length of the column is /5, then the column will cary five times as much shear. For this reason, short columns should be avoided whenever it is possible, because of the

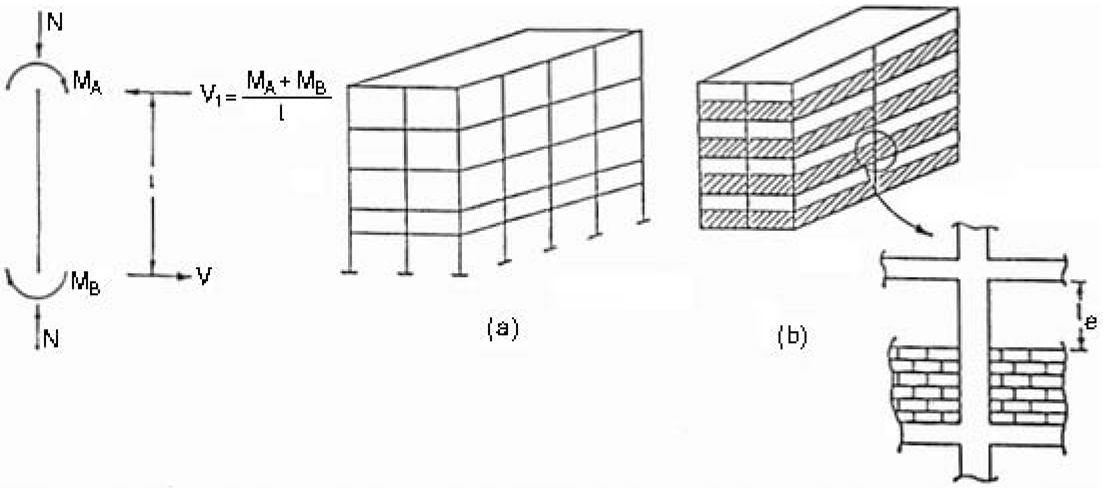


Figure 4.

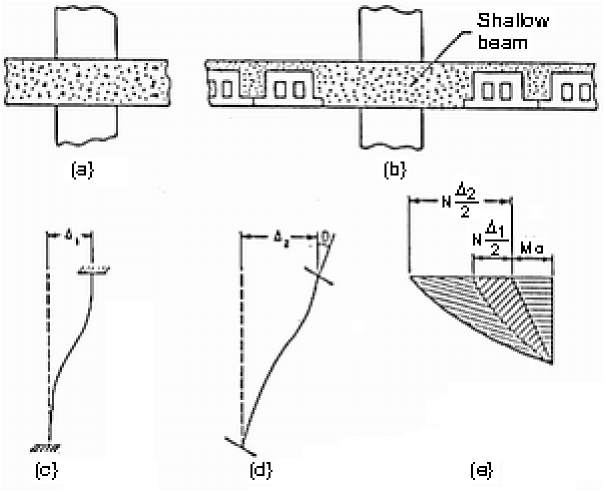


Figure 5.

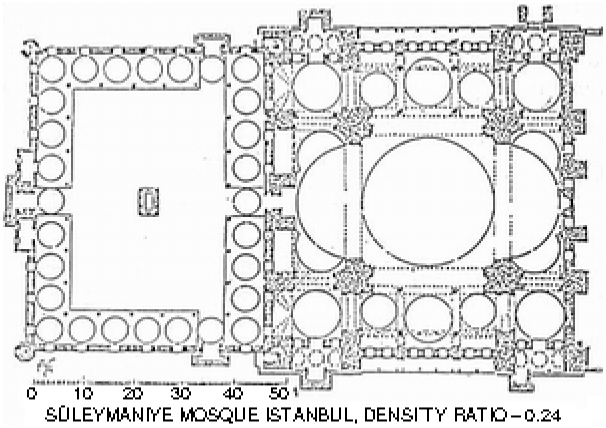


Figure 6.

danger of shear failure. As illustrated in Figure 4, short columns are created by either structural or nonstructural (infill) elements.

Structures with flexible floor members (flat plates or joist system with shallow beams) should either have rigid columns or shear walls (or cross - bracing) to prevent excessive drift. If the vertical load carrying members are not rigid enough, very high second order moments can result as shown in Figure 5. In 1967 Adapazari and 1985 Mexico earthquakes numerous failures have been observed in buildings with flexible floors and selender columns.

For a more detail discussion on configuration, the reader is directed to Reference 2.

3.2. Proportioning and Detailing

The dimensions of structural members not only influence the strength, but also the overall stiffnes of the structure. In the light of experience gained from the past earthquakes, the author believes that the ratio of the sum of the cross - sectional areas of vertical load carrying members to the floor area is an important parameter in seismic resistance. This ratio will be called the "Density Ratio". The author has studied the variation of this ratio in the monumental historical buildings in Istanbul, which have with - stood several severe earthquakes during the past centuries. It was found out that this ratio varied between 0.2 and 0.28. As an example, the floor plan of the Süleymaniye Mosque is shown in Figure 6. The author would like to point out the symmetry in the arrangement of load carrying members. In Süleymaniye the density ratio was about 0.24.

Another investigation made on modern reinforced concrete buildings built in seismic areas in Turkey reveal that the average density ratio is less than 0.01. The author finds the ratio rather low and suggests that it should be about 0.015-0.0020.

In the city of Vina del Mar, Chile the average density ratio in reinforced concrete buildings (4 to 23 stories) is quite high, 0.06 (3). This seems to be one of the reasons why relatively small damage occurred during the 1985 Chile earthquake, which created quite a severe ground motion.

It should be pointed out that although density ratio is a very important parameter for lateral stiffness, the relative stiffness of floor members have also a significant influence on the stiffness.

Ductility required for energy dissipation during an earthquake is closely related to detailing. A well designed R/C structure can suffer considerable damage if it is not properly detailed.

Detailing is an art which cannot be realized unless the seismic behaviour of reinforced concrete is well understood. The basic principle in detailing is to provide the necessary strength and ductility at critical sections and joints. In cutting the bars and in making lapped splices, adequate anchorage length should be provided. The critical regions where plastic hinging is expected to occur should be well confined by closely spaced hoops. Our experience in Turkey shows that inadequate detailing played a very important role in the earthquake damage observed during the past 30 years. Most of the damages attributed to detailing were due to inadequate anchorage or splice length and inadequate confinement.

Basic rules for detailing of beams, columns and structural walls are summarized in Figures 7, 8 and 9.

3.3. Construction

The earthquake will be resisted by the structure which is actually built and not by the structure shown on the design drawings. No matter how good the design methods used are, it is not possible to produce a seismic resistant building unless the structure is constructed in accordance with the design project under proper supervision. In most of the developing countries emphasis is on the design stage; quality control and supervision are usually looked down upon and ignored by the engineer.

The engineer should realize that the important requirements for seismic resistance, i.e. the strength, ductility and stiffness depend on the actual dimensions, material qualities and reinforcement details accomplished on the site. Poor supervision results in poor material quality and errors in the placement of the reinforcing steel. Our experience in Turkey shows that inadequate supervision has been the most important cause of structure damage during past earthquakes.

In the light of these discussions one can conclude that, for better seismic resistance, the first step should be in the direction of correcting the mistakes made in the past. If configuration, detailing and construction supervision cannot be improved, well written codes and sophisticated methods of analyses will not be able to prevent damage and failures in future earthquakes.

4. RECOMMENDATIONS FOR DESIGN

The main objective of this section is to specify some simple rules for the design of ordinary reinforced concrete structures. By ordinary, the author means regular structures up to say ten stories.

4.1. Summary of Facts

Before stating the design rules, it would be useful to state some basic facts about the seismic action and seismic resistance of reinforced concrete structures.

- The characteristics of the ground motion expected cannot be fully defined.
- The structure cannot remain elastic when subjected to a strong ground motion. Yielding will occur at different locations and most of the energy will be dissipated at these sections.
- Response of the structure depends not only on the ground motion, but also on the dynamic characteristics of the structure, such as mass, stiffness and damping. For reinforced concrete structures it is very difficult to estimate the stiffness and damping, because of cracking and time dependent deformations which have taken place prior to the earthquake.
- Nonstructural elements influence the behaivour.
- In order to analyze a building, first a simple physical model is created by making many simplifying assumptions. The analysis made is for this model and not for the real building. The assumptions made in creating this model introduce errors.
-Important dynamic characteristic such as mass, stiffness and damping depend on the actual dimensions and material strengths obtained during construction. These can be quite different from the ones assumed at the design stage.

In the light of these facts, one can easily see that there are many uncertainties involved in the seismic design of reinforced concrete buildings. The engineer should be well aware of these facts and should not rely entirely on the numbers he has obtained from analyses. More sophisticated and more complicated methods of analyses can easily carry the engineer away from the actual behaviour and make him a slave of numbers. Usually simple methods supported by sound judgement based on behaviour will result in as satisfactory seismic design.

4.2. A simple Approach

Seismic resistance can be accomplished by following the basic steps given below:

a. Choosing a good configuration

b. Making a satisfactory analysis (Static or dynamic)

c. Proportioning and detailing the members properly.

d. Constructing the building in accordance with the design project, under good supervision.

The author believes that for ordinary residential or office buildings up to say ten stories, seismic resistance can be obtained to a great extent by following some simple rules. The rules given below are being used by a municipality in Turkey as a guide to designers and for checking the designs submitted to this municipality.

The first rule concerns the density ratio mentioned previously. For residential and office buildings up to ten stories, the summation of the cross-sectional areas of vertical load carrying members (structural walls and columns) should satisfy the following equation.

$$A_v\ 0.020A_p \qquad (1)$$

A_v - summation cross-sectional areas of all vertical structural members at the floor (m^2)

A^p- plan area at that floor (m^2)

In addition to this rule, the cross-sectional area of each individual column should satisfy the following condition:

$$A_c\ 0.0015A_t\ (n) \qquad (2)$$

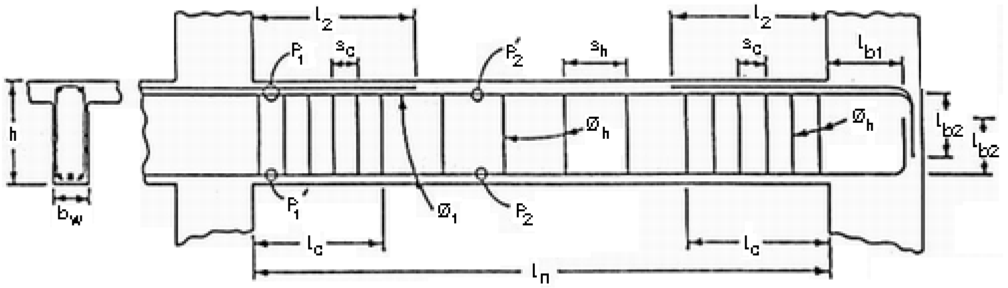
However the minimum column dimensions cannot be less than 25x25 cm.

A_c- cross- sectional area of the column (m^2)

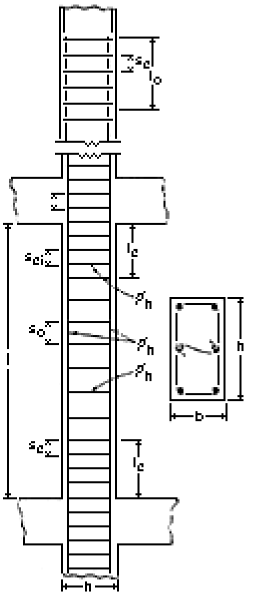
A_t-tributory area of the column (m^2)

n-number of stories above

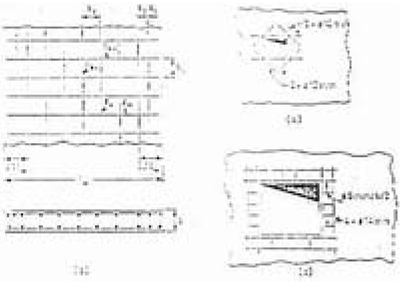
The second set of rules are about minimum requirements and detailing. These are summarized in Figures 7, 8 and 9 for beams, columns and structural walls.



Descriptions	Requirements	Remarks
min. $A_c=b_wh$	100 V_d	V_d= ton, A_c= cm^2
max. b_w	column with + 2h	
min.h	ln/15, 30cm	
min.p_2	0.005 (BÇ-ýl)	
or p_1	0,003 (bç-III)	
max. p	0,02 (BÇ-I)	
	0,015 (BÇ-III)	
l_c	2h	confined region
$Ø_h$	(min.) 8 mm	
S_h	(max.) h/2, 30 cm	
S_c	(max.) h/4, 15 cm	
min.p_1	1/3 p_1	
min.p_2	1/3 p_2	
min.l_2	l_n/4	at least 1/3 of the total
min.l_{b2}	15Øl	
min.l_{b1} + l_{b2}	40Øl	



COLUMNS		
Descriptions	Requirements	Remarks
min. A_c= (cm^2)	20 A_p (n) or 15 N_d	A_p= trib. area (m^2)
		n= no. of stories
		Nd= design axial force (ton)
max. l/b	20	-
min. b	25 cm	-
max. h/b	3,0	-
min. l_u	50 Ø l	If away from the joint, 40Ø
l_c	l/6 or 45 cm	confined region
p_t	min. = 0,01	min. 4- Ø14
	max. = 0,04	
max. S_o	20 cm	-
max. S_c	10 cm	-
max. S_{cj}	10 cm	If confined by beams on all four sides, 15 cm
min. hoop diameter	8 mm	-



STRUCTURAL WALLS		
Rescriptions	Requirements	Remarks
min. l_w / b	5	-
min. b	15 cm, l_w/20, h_w/20	-
min. p_V or p_H	0,0025	p_V= A_{sV}/bl_w, p_H=A_{sH}/bl_w
max. S_H or S_V	1,5 b, 30 cm	-
min. $Ø_H$ or $Ø_V$	8 mm	-
min. A_c	20 N_d, 80 ,V_d	A_c= cm^2
		N_d ve V_d = ton

Note: (b) small, (c) large openings.

In addition to these two sets of rules, the designer should choose a reasonable configuration and proper supervision should be provided at the construction stage. If these simple rules are followed and if the requirements are satisfied, most probably adequate seismic resistance will be obtained for the building classes specified, even if a lateral load analysis is not performed.

5. CONCLUSIONS

The response of reinforced concrete buildings under seismic action depends not only on the nature of the ground motion, but also on the dynamic characteristics of the structure. Due to uncrtainties involved in estimating the nature of the ground motion and the structural characteristics, only approximate results can be expected from analyses. The numbers obtained from analyses should be filtered by making use of past experience and judgement. Sound judgement can only be based on a firm knowledge about the seismic behaivour of structures.

A re-evaluation of damage observed during past earthquakes has revealed that seismic resistance can significantly be improved by following some simple rules. Such simple rules have been summarized in this paper.

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