SEISMIC DESIGN OF CONCRETE BUILDING STRUCTURES

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Contents

UNESCO-EOLSS SAMPLE CHAPTERS

Summary

This chapter presents an overview of the salient aspects of earthquake behavior, analysis, design and detailing of reinforced concrete (RC) buildings. At the outset, salient observations of earthquake performance of RC buildings are outlined. Then the influences of these observations on the seismic design force provisions are discussed next. A series of steps are presented that ensure ductile earthquake performance of RC buildings. These include (a) choosing an acceptable seismic structural configuration, (b) undertaking capacity design of members to delay brittle modes of failure, (c) incorporating a hierarchy of relative strengths of members to force damage to chosen critical sections, and (d) performing ductile detailing of member geometry and of reinforcement bars in structural members. Some aspects of current buildings design practice need an urgent review. A few of these are presented at the end.

1. Introduction

Reinforced concrete (RC) structures have special features that are of interest to *designers*. Their behavior at ultimate loads can be achieved as desired by design – by providing different amounts of longitudinal and transverse reinforcing steel, the flexural and shear strength can be made almost independent of each other. This is not the case in structural steel structures, in which the ultimate strengths of sections in flexure and shear are pre-determined at the plant where the area and moments of inertia (about the two axes) are chosen before manufacturing the sections. It is this distinction, which makes the structural design of RC structures interesting, not to talk about *seismic* design which is even more exciting. This chapter provides an insight into this special nature of seismic design of RC buildings.

1.1. Performance of Concrete Buildings in Past Earthquakes

Observing and *studying* damages to buildings in past earthquakes and making efforts based on these to *improve* design have been features of progress in the seismic design of RC structures. Designers of structures and researchers undertook post-earthquake field investigations, understood mistakes made in the past, and have been trying to eliminate them in subsequent projects. Earthquakes are destructive tests on actual structures *in-situ*. They reveal that (a) damages occur only when there are deficiencies, and (b) they occur at locations where stresses and/or strains exceed bearing capacity. This exercise is valuable in the process of understanding the weaknesses of past structures and using this understanding in designing future structures to eliminate the deficiencies.

The damages to buildings can be divided broadly into three categories, namely (a) damages owing to deficiencies in building system as a whole, (b) damage owing to deficiencies in individual structural components, and (c) damages owing to deficiencies in construction aspects. The first two types can be eliminated or at least minimized by undertaking proper seismic design in the design office, while the latter by enforcing strict quality control and quality assurance measures at site. Deficiencies in building systems could include:

(i) *Heavy mass*: Heavy buildings develop stronger seismic forces in horizontal and vertical directions, and undergo heavy damage when inertia effects exceed their bearing capacity;

(ii) *Natural period*: Stiff buildings with short natural periods sustain more cycles of shaking and possibly more damage, if the duration of ground shaking is long. And, flexible buildings with long natural periods undergo large swinging action and possibly more damage, if the ground motion has long period waves. Damage in stiff buildings is due to large accelerations (i.e., force effects) and that in flexible buildings is due to large displacements;

(iii) *Lateral strength and deformation capacity*: Buildings sustain heavy damage when the inertia forces generated in them exceed their lateral strength, and when deformation demand exceeds deformation capacity;

(iv) *Vertical irregularity*: Buildings with irregularities in parts of the structural system or properties across the building (like mass, stiffness, strength, deformability and path of force flow) invite damage through discontinuity or abrupt change along their height;

(v) *Plan irregularity*: Buildings with irregularities in parts of the structural system or properties (like mass, stiffness, strength, deformability, and path of force flow) invite damage through torsion action in plan at each elevation of the building;

(vi) *Pounding* : Buildings or structurally independent parts of building, that are very close to each other, collide during earthquake shaking – this causes large localized impact on building components which is detrimental;

(vii) *Non-structural elements*: Building contents, that are massive and loosely affixed to the lateral load resisting system, like false ceiling and major equipment, collide with each other and with structural system of the building. On the other hand, building contents that are too rigidly affixed to the lateral load resisting

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system but do not have the capacity to deform with the lateral load resisting system (like sewer mains and electric cables) snap during lateral shaking of the building;

(viii) *Soil and foundation systems*: Usually, deficiencies in soil (like soil liquefaction, landslides, and differential settlement) cannot be corrected by foundation systems, and hence the whole building suffers damage or collapses. Also, it is difficult to protect buildings from large ground deformations associated with fault rupture under the building. Foundation inspection and strengthening are extremely difficult and expensive, and hence deficiencies in soil and foundation system need to be minimized to the extent possible.

Deficiencies in structural components arise out of inconsistencies in design, detailing and construction, which lead to undesirable failure modes preceding desirable ones. Clearly, modes of failure of different elements (namely beams, columns, walls, slabs, footings and beam-column joints) of buildings result in different types of damage. The modes of failure in the beams, columns and walls are described below:

(i) *Failure of beams*: Long beams subjected to bending moment undergo the following predominant modes of failure. These are, flexural tension and compression failures, and flexural shear failure. When concrete is confined properly (*i.e.*, held in place without being allowed to dilate transverse to the direction of compression) by transverse reinforcement bars, long beams undergo bending tension failure causing reinforcing bars to yield in tension followed by crushing of concrete in compression. On the other hand, when spacing of transverse reinforcement is large and the transverse reinforcement is bent at 90°, they undergo shear failure and flexural compression failure. The former is manifested as a diagonal cracking followed by opening of the stirrups, buckling of longitudinal bars and transverse displacement across the diagonal crack along one of the diagonals, and the latter as sudden crushing failure of concrete in compression. Also, there is a third mode of failure. When there is insufficient anchorage of longitudinal bars, slip of longitudinal bars occurs when they are in tension; this manifests in the form of cracks oriented along the length of the longitudinal bars. But, flexural tensile failure is safer as the longitudinal bars yield in tension before any of the above modes of failure take place.

(ii) *Failure of columns*: Columns subjected to compression and bending moment also sustain the above first three types of failure – flexural compression failure, flexural shear failure and anchorage failure. But, the safest mode is again the flexural tensile failure, with the longitudinal bars yielding in tension at beam ends before the other three modes of failure occur.

(iii) *Failure of walls*: Structural walls also undergo flexural compression, flexural shear failures and anchorage failure. In addition, they undergo sliding failure, particularly at the construction joints. But, again, flexural tensile failure is the safest, with the vertical bars yielding in tension particularly along the outer edge of the structural walls.

When a few adjoining members together turn out to be too weak to meet the demand offered by the forces induced in that local region, unrestrained deformation occurs in that region and damage is localized in a small region. If the deformation capacity of a member is exceeded by this unrestrained deformation, strength loss occurs in these

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elements and the load carried by these elements is transferred away to the adjoining members; as a result the adjoining elements can be damaged. The situation becomes critical when the damage occurs in a critical column and it looses the capacity to carry vertical load. The other vertical members in the storey are now required to redistribute this load. But, sometimes this redistribution may result in damage to those other vertical elements also and/or to the interconnecting beams and can incapacitate the whole storey from carrying vertical load leading to its collapse. This, in turn, can even lead to a progressive collapse of the whole building.

Deficiencies in construction aspects arise when construction drawings are not correctly transferred into practice at the site. Some of the common errors include:

(i) *Transverse reinforcement bars*: When the ends of transverse ties in columns and beams are bent to form 90° hooks and not 135° hooks, the loops open up under compressive load generated by combined effects of axial compression and bending in columns and bending in beams.

(ii) *Lapping of longitudinal bars*: When the longitudinal bars are provided with insufficient lap lengths in columns and beams, the lapped bars are pulled apart under tension generated by combined action of axial tension and bending in columns and bending tension in beams.

(iii) *Cover to steel reinforcement*: Improper use or lack of cover blocks results in ingress of foreign elements (oxygen, chloride, etc.) to steel bars resulting in undue damage to reinforcing steel and concrete by corrosion, well before the design life of the building is reached.

(iv) *Concrete quality*: Mix-design of concrete with weigh batching is a requirement to ensure good quality of concrete. Controlling the correct amount of materials including water is a major responsibility of field engineers. Failing to ensure this results in poor concrete with high porosity or with honey-combing; such concretes deteriorate quickly and result in poor life of the reinforcement bars, and hence of the structure.

Training of field engineers and artisans is an important pre-requisite to ensuring good construction practices.

1.2. Historic Development of Seismic Design Provisions for RC Buildings

The changes in seismic design provisions for RC buildings can be reviewed from two points of view, namely, (a) seismic force demand, and (b) seismic capacity available. The following is a brief summary of the issues involved.

1.2.1. Seismic Force Demand

The first formal step to recognize seismic effects in the design was taken in the early 20^{th} century. The Japanese Building Law Enforcement Regulations in its 1924 edition recognized that the maximum ground acceleration was about 0.3g and introduced (for the first time in the world) a design seismic lateral force of 10% of building weight; the design was done by the *Allowable Stress Design* method with a factor of safety of 3 to prescribe the allowable stress. Subsequently, in 1927, the Uniform Building Code (UBC) of USA formally recognized that buildings on soft soil strata suffer more

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damage; the seismic force was varied between 7.5% and 10%. Also, concerned by the collapse of school buildings in the 1933 Long Beach earthquake, a minimum seismic design force of 2% was specified for all structures and of 10% for school buildings. The 1935 edition of UBC went a step further to recognize different seismic zones and specified different design seismic forces.

By 1943, the City of Los Angeles Building Code recognized that taller buildings sustain lesser effect of earthquakes than shorter ones. This concept was introduced in the 1949 edition of UBC for the whole of the USA; the number of storeys N came into the expression for design lateral force F_i at floor i:

$$F_i = Z \frac{0.15}{N+4.5} W_i, \qquad (1)$$

where Z is the seismic zone factor and W_i the dead plus live load on floor i. This requirement was better understood by a joint committee in USA of American Society of Civil Engineers (ASCE) and Structural Engineers Association of Northern California (SEAONC), when in 1951, it brought the natural period T (in place of the number of storeys N) into calculation of design seismic lateral forces; the design lateral force F_i was prescribed to be inversely proportional to natural period T, as

$$F_i = CW_i, \qquad (2)$$

where C is the base shear coefficient, given by $C = 0.015/T$ ($0.02 \le C \le 0.06$), and W the weight of the building. But, in Japan, this effect of natural period T was not introduced until 1981.

Research during the 1950s introduced a new concept of *ductility* into seismic design. It was recognized that the earthquake shaking is a displacement loading and not force loading. Hence, buildings with ductility were seen to sustain the earthquake shaking effects better than those without it (Figure 1); ductile RC buildings sustain larger maximum relative displacement even though the ground shaking below the two buildings is the same. The 1957 UBC reflected this through a horizontal force factor K as

$$F_i = KCW_i, \qquad (3)$$

where K takes value of 1.33, if the building has no or limited ductility, or 0.80, if it has ductility.

In the 1980s, seismic engineers in New Zealand explicitly introduced ductility of a building in the seismic design lateral force F, through ductility factor μ, as

$$F = CW = C_{\mathrm{h}}\left(T_1, \mu\right) S_{\mathrm{p}} RZL_{\mathrm{u}} W, \qquad (4)$$

UNESCO-EOLSS SAMPLE CHAPTERS

where C_h is basic seismic hazard acceleration coefficient, T_1 the fundamental translational period of vibration, S_p the structural performance factor, R the response reduction factor, Z the zone factor, and L_u the limit state factor for the ultimate limit state.

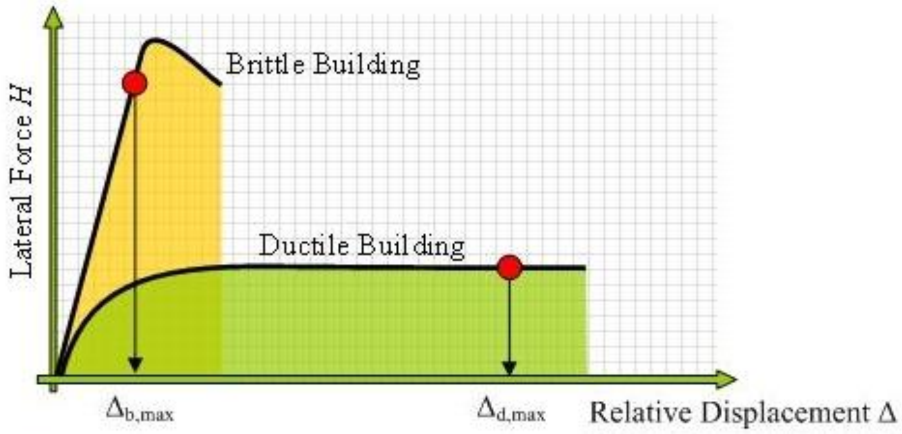

Figure 1. Same earthquake shaking pushes brittle and ductile RC structures to different levels of maximum displacement.

1.2.2. Seismic Capacity Available

The early progress in the design of RC structures addressed strength capacity. The change from *Allowable Stress Design* to *Ultimate Load Design* was motivated by the need to better reflect nonlinear behavior of reinforced concrete. And then, the move from *Ultimate Load Design* to *Load & Resistance Factor (LRFD) Design* was inspired by the need to better reflect the uncertainties in the strengths realized in concrete and steel reinforcement bars. But, both changes recognized deformation capacity only indirectly in terms of specifying the limiting states of strain in the materials at cross-section of structural members. Often, it was not clarified if the specified strain states can be reached by the sections or not.

The main breakthrough in seismic design of RC structures came in the 1970s, when the concept of *Capacity Design* was proposed. It gave a formal quantitative method for sequencing the hierarchy of the various modes of failure through their ultimate strengths. In particular, it made it possible to delay undesirable shear failure in beams and columns before the occurrence of less undesirable flexural tensile modes of failure. But, these calculations only sequence the strengths of the member in the different modes of failure and not their ultimate deformability.

2. Earthquake Resistant Design

Methods of building design that worked to make buildings safely resist wind effects were found insufficient to make buildings safely resist strong earthquake ground shaking. Observations of RC buildings in the past earthquakes presented evidence of the undesirable modes of failure, which were systematically eliminated.

UNESCO – EOLSS SAMPLE CHAPTERS

2.1. The Philosophy

Design strategies for wind effects and for earthquake effects are distinctly different. The intuitive philosophy of structural design uses “force” as the basis, which is consistent in wind design wherein the building is subjected to a “pressure”-type loading on its exposed surface area. But, in earthquakes, the building is subjected to random movement of the ground at its base (Figure 2). This motion at its base induces inertia forces in the building that cause relative deformations in the structure, which in turn cause stresses.

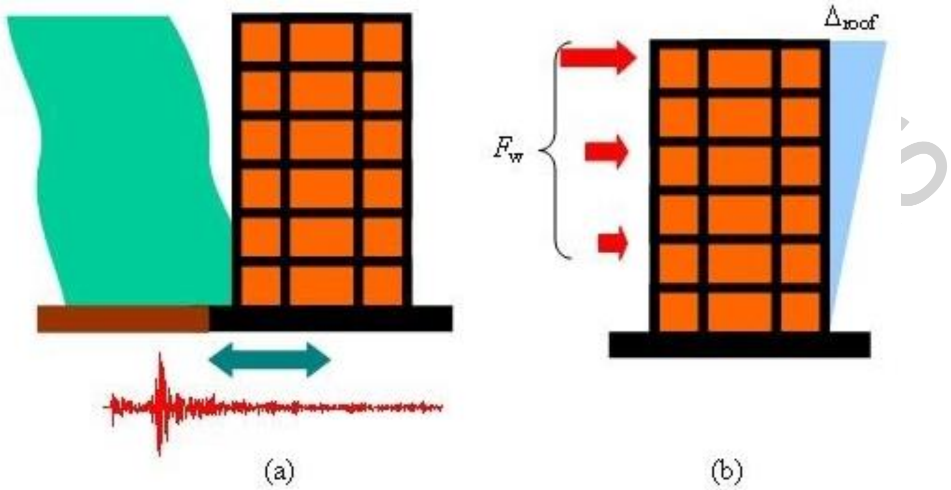

Figure 2. Difference in design effects on a building: (a) Earthquake ground motion at base, and (b) Wind pressure on exposed area.

Wind pressure acting on buildings has a non-zero mean component superposed on a relatively small oscillating component (Figure 3). Thus, under wind pressure, building members may experience small fluctuations in the stress field, but reversal of stresses occurs only when the direction of wind reverses, which happens only over a large duration of time. On the other hand, the motion of the ground during the earthquake is cyclic about the neutral position of buildings. The stresses in buildings due to seismic actions undergo many complete reversals and that too over the small duration of earthquake.

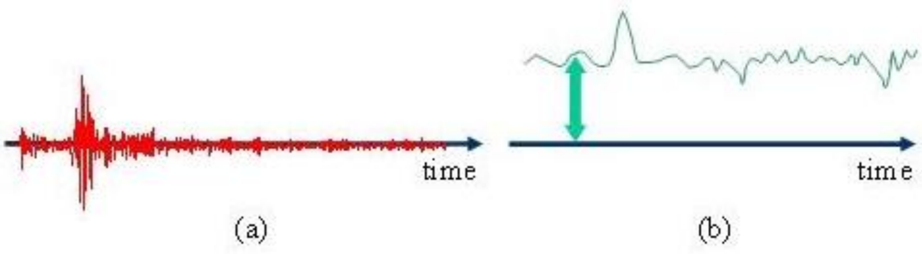

Figure 3. Temporal variations of design actions: (a) Earthquake ground motion: zero mean, cyclic (b) Wind pressure: non-zero mean, oscillatory.

Since earthquakes induce inertia forces, the mass of the building being designed enters seismic design calculations. Normal buildings tend to be very massive, and designing them to behave elastically during earthquakes without damage may render the project economically unviable. On the contrary, it may be necessary for the building to undergo damage and thereby dissipate the energy input to it during the earthquake. Therefore, as per the seismic design philosophy, (a) under strong shaking, structural damage is acceptable, but collapse is not, (b) under moderate shaking, *repairable* structural (and non-structural) damage is acceptable, and (c) under minor shaking, structural damage is not acceptable. Consequently, buildings are designed only for a fraction of the force that they would experience if they were designed to remain elastic during the expected strong ground shaking (Figure 4), and thereby permitting damage (Figure 5). But, sufficient initial stiffness must be ensured to avoid structural damage under minor shaking. Thus, seismic design balances reduced cost and acceptable level of damage, thereby making the project viable. This careful balance is arrived at based on extensive research and detailed post-earthquake damage assessment studies. A wealth of this information is translated into precise seismic design provisions. In contrast, structural damage is not acceptable under design wind forces.

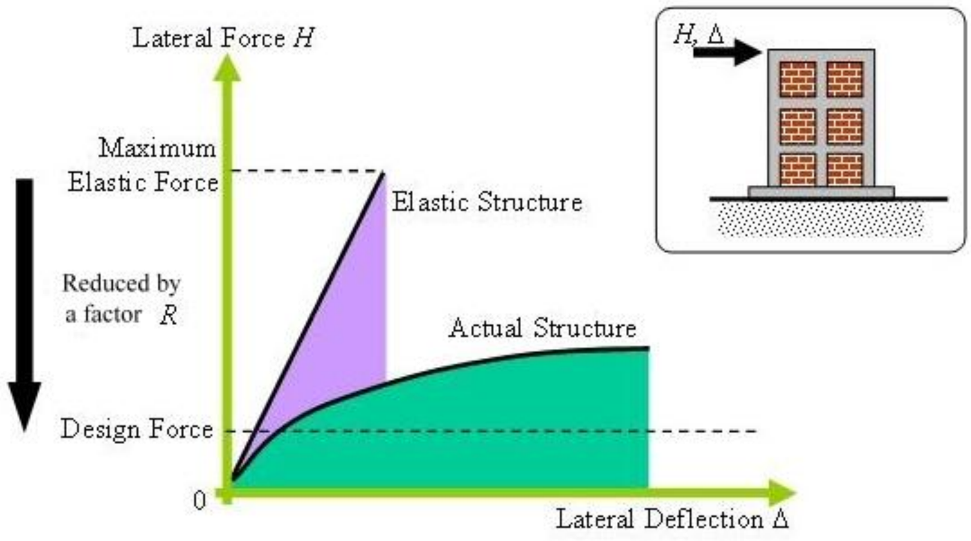

Figure 4. Basic strategy of earthquake design: Maximum elastic forces are reduced by a factor to obtain design forces.

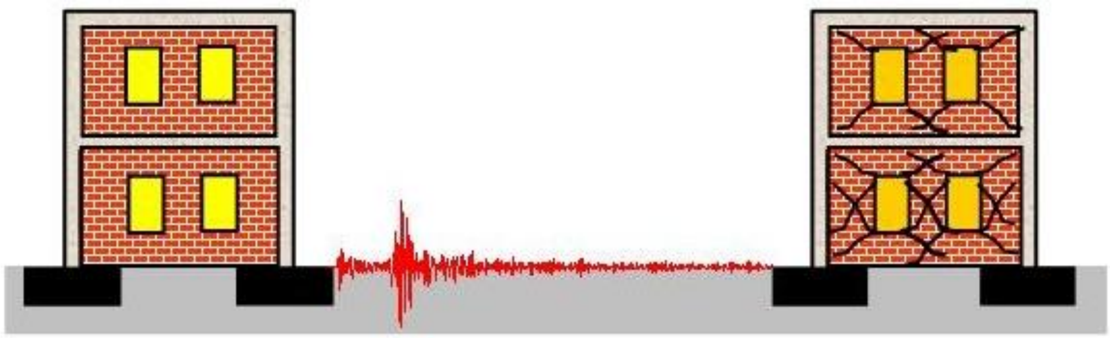

Figure 5. Damage during earthquakes: In normal structures, damage is acceptable, but location and type of damage need to be carefully tuned through Capacity Design Concept.

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Biographical Sketches

C.V.R. Murty was born at Shahdol, State of Madhya Pradesh, India, on 5 July 1963. He received the Bachelor of Technology degree in Civil Engineering from Indian Institute of Technology Madras (India) in 1984, and then Master of Technology degree from the same institute in 1986. After completing doctoral studies at California Institute of Technology at Pasadena (USA), he earned Ph.D. degree in 1992. His major field of study is structural engineering with focus on earthquake engineering. He is a Professor of structural engineering in the Department of Civil Engineering at the Indian Institute of Technology Kanpur (India) and assumed the position of Director of Indian Institute of Technology, Jodhpur (India), since September 2013. He is also currently the Editor-in-Chief of the World Housing Encyclopedia. He has authored/co-authored three books, noted amongst them is the "*IITK-BMTPC Earthquake Tips – Learning Earthquake Design and Construction*" published by the National Information Center of Earthquake Engineering, IIT Kanpur, India, 2005. He is one of the editors of the Special Issue on *2001 Bhuj Earthquake of Earthquake Spectra*, Vol.18, a Professional Journal of the Earthquake Engineering Research Institute (EERI), Oakland (CA, USA), 2002, and one of the authors of the "*Earthquake Rebuilding in Gujarat India*", an EERI Recovery Reconnaissance Report, 2005,. His research interests include nonlinear behavior of reinforced concrete and steel buildings and bridges, and limit state design of reinforced concrete, relevant to earthquake-resistant structures. Professor Murty is a member of the Earthquake Engineering Committee of the Bureau of Indian Standards and was a member of the Indian Roads Congress Committee on bridge substructures. He is a life member of Indian Society of Earthquake Technology, Indian Concrete Institute and Institute for Steel Development and Growth, India. He is an Associate Member of EERI (USA). He is Fellow of the Indian National Academy of Engineering.

Rupen Goswami was born at Calcutta, India, on 14 August 1976. He received his Bachelor of Civil Engineering degree from Jadavpur University (India) in 1999 and Master of Technology degree from Indian Institute of Technology Kanpur (India) in 2002. He is a doctoral candidate at Indian Institute of Technology Kanpur (India). His major field of study is structural engineering with focus on earthquake engineering. He worked as Trainee Engineer (Civil) at *M/s* Development Consultants Private Limited, a member of DC Group, at its headquarters at Calcutta, India, and was responsible for analysis and design of reinforced concrete and steel structures for high-voltage power stations in India. His research interests include seismic performance assessment and deign of reinforced concrete and steel buildings, and reinforced concrete bridge substructures. Mr. Goswami is a life member of Indian Society of Earthquake Technology and Indian Roads Congress.

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