# CHAPTER 1

# INTRODUCTION

## 1.1 EARTHQUAKES AND THEIR EFFECTS

Earthquakes have occurred in every part of the globe. It is one of the natural phenomena which has a long lasting and a devastating effect on the human society at large. Although some of the regions are identified as earthquake prone zones, the risk of earthquake has been a major cause of worry for the human race. It is generally felt that the occurrence of earthquakes in the recent times has increased. But the fact is that the awareness and instrumentation has increased throughout the world. This has led to the fact that if one just sees the USGS website which is one of the major online source of earthquake data occurring throughout the world in real time, one can see that there are more than 65 significant (M>4) earthquakes recorded up to October in 2010. The number of significant earthquakes is 74 for the year 2009.

Although almost all earthquakes are devastating some of the facts and figures tell us the specific reasons for caution against their effects. According to Asian Disaster Reduction Centre (ADRC), Japan, from 1991 to 2000 **38%** of world's disasters occurred in Asia and **5,88,000** people were killed which is **78%** of world's casualty. It also states that in the same period, **1.9** billion people were affected which is **90%** of people affected in the world. Economic losses amounted to **374** billion **US** dollars which accounts for **54%** of the world's total damages. ADRC data for the period of 25 years from 1975 to 2000 states that earthquakes affected only **1%** of the total people affected by natural disasters in Asia but accounted for about **50%** of the total economic damage.

It is a known fact that urbanization is an ongoing process and it cannot be altered or reversed. Hence, it is clear from the facts and figures presented earlier that the earthquake risk is going to be on the upward trend. To mitigate this trend, it is proposed by earthquake engineers that the seismic risk should be predetermined and as one plans the city, it should be divided into zones as per the seismic performance of the buildings.

In the event of an earthquake, it is generally seen that different buildings behave and respond differently. For example, one building which is properly designed and detailed to resist the seismic forces remains intact whereas, an adjoining building which may be designed to perform poorly in the event of an earthquake may be rigorously damaged or may even collapse. If such a thing happens, the building which is intact may not be approachable because of the debris of the adjoining building. Further usage of the intact building may be hampered because of the reconstruction or retrofitting of the damaged building.

In order to avoid such a scenario, it is desirable to go for performance based engineering and performance based design as far as seismic risk is concerned. Using the static pushover analysis, the structural and non-structural performance may be restricted to a predefined level say – Immediate Occupancy, Life Safety or Collapse Prevention. Hence, it is desirable to divide the newly planned city into zones having a specific seismic performance. Thus, a zone of the city may be reserved for all the buildings meeting the requirement of immediate occupancy as per push over analysis. Thus, in the event of an earthquake, all the buildings in that particular zone will be in a state of immediate occupancy. This will ensure that there is no disturbance from the adjoining buildings due to damage or collapse in the event of an earthquake. This will ensure that this particular zone will not experience any loss of man days and large corporate houses can opt for locating their offices in such zones.

Thus, the new technology and research may help in mitigating the earthquake risk to quite an extent. It is hoped that the concept of push over analysis for framed structures will become a common practice in future in order to identify the seismic performance of a building.

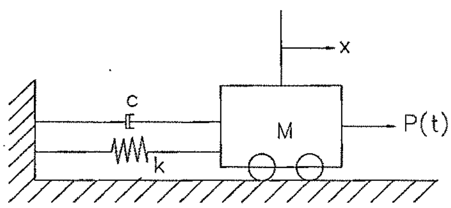
## 1.2 BASIC CONCEPTS OF STRUCTURAL DYNAMICS

It is a well known fact that when a building is subjected to time dependant force, it is said to be subjected to dynamic force. In order to analyze a structure which is subjected to dynamic forces, the structure may be assumed to be in a state of dynamic equilibrium. In such a state it will have it's mass M changing it's position as time changes. It is usual to assume the mass as lumped at a point in structural dynamics and if one is able to specify the location of the mass at various times with reference to a datum, one can say that the problem of dynamics is solved. In order to achieve this, the equation of motion may be considered for a Single Degree of Freedom (SDF) system with specific mass, stiffness and damping.

In general, a structure may have infinite number of degrees of freedom, but in order to simplify the problem, it is always worthwhile considering some finite number of degrees of freedom at the time of analysis. The analysis involves solution of a second order linear differential equation as per a SDF mass spring model shown in **Fig. 1.1** or a plane frame idealization shown in **Fig. 1.2**. The basic equation of motion considered in structural dynamics is as given below.

$$M\frac{\partial^2 x}{\partial t^2} + c\frac{\partial x}{\partial t} + kx = P \qquad \text{....(1.1)}$$

Where, M is the mass of the system, c is the damping coefficient, $\frac{\partial^2 x}{\partial t^2}$ is the acceleration , $\frac{\partial x}{\partial t}$ is the velocity , k is the stiffness of the system and x is the displacement of mass.



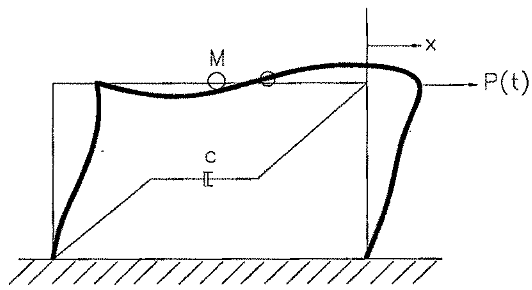




**Fig. 1.1 A SDF Mass Spring Model  Fig. 1.2 SDF Frame Model**

The solution of this equation involves finding out x, given some initial conditions on displacement and velocity at a certain time instant say at the beginning of the motion. For free vibrations with Multiple Degrees of Freedom (MDOF) system, **Eq. 1.1** may be written as

$$\mathbf{M}\frac{\partial^2 \mathbf{x}}{\partial t^2} + \mathbf{k_s x} = \mathbf{P} \qquad \text{....(1.2)}$$

Where **M** is the mass matrix of the order n x n consisting of masses $M_1$, $M_2$,.....,$M_n$ oriented along the principal diagonal, $\frac{\partial^2 \mathbf{x}}{\partial t^2}$ is the acceleration vector of the order n x 1 consisting of the accelerations of the n masses, $\mathbf{k_s}$ is the stiffness matrix of size n x n corresponding to the n displacements represented by the vector **X. P** is the dynamic force vector, the components of which are, in general, functions of the time t.

The solution of the MDOF system involves finding out the eigen values $\boldsymbol{\omega}^2$ and the corresponding eigen vectors $_1\mathbf{e}$ of the so called dynamic matrix $\mathbf{M^{-1}K_s}$. The eigen values corresponds to the natural frequencies of vibrations of the system and the eigen vectors represent the corresponding mode shapes. Thus, with the help of modern day computing tools, given the geometric parameters of a structure and the mass of the structure, the dynamic analysis can be carried out in the form of calculating the natural frequencies and the mode shapes of a structure. A typical MDOF shear frame model is shown in **Fig. 1.3**.

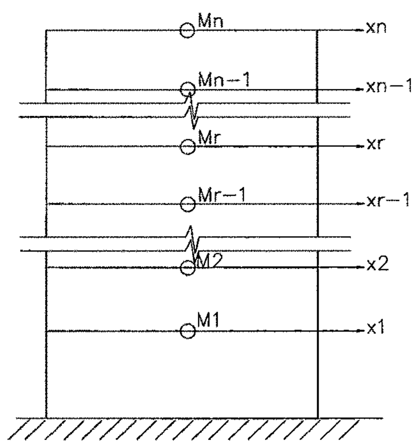



**Fig. 1.3 A typical MDOF shear frame model**

It may be noted here that for usual structures, a structural engineer is interested in finding only the first two or three normal modes because the frequencies of the higher normal modes are usually too high to be of consequence. Thus, in dynamic analysis, structures may be idealized as lumped-mass system. For example, a multi storey building frame may, as a first approximation, be idealized as a shear building. The mass of the frame, together with the mass of any dead or live load carried, shall be lumped at the floor levels.

## 1.3 INTRODUCTION TO SEISMIC ANALYSIS

Seismic analysis is a particular case of dynamic analysis. Here, instead of a uniform forcing function being applied, the ground motion generated by earthquakes is given as an acceleration in terms of g (gravitational acceleration) in the lateral direction to the building. The response of a building or a structure generated because of this dynamic force is studied and the internal forces and moments developed in the structure are evaluated.

Generally, seismic analysis involves the steps mentioned in the previous section wherein the natural frequencies are evaluated first and the mode shapes are also found out. The seismic code of practice specifies the method to be adopted in a particular country based on the past history of earthquakes and probable risk areas. The country is usually divided into various zones (e.g. in India, the entire country has been divided into 4 earthquake zones – II, III, IV and V ) based on the probability of an event occurring in that region. Some countries even go for microzonation of the major earthquake zones as the effect of an earthquake can be affected by local soil conditions and other factors.

Based on the occurrences of earthquakes, the various factors are specified by the seismic codes. The response of a structure to an earthquake force depends on variety of factors such as nature of foundation soil; materials, form, size and mode of construction of structures; and the duration and characteristics of ground motion. The codal provisions provide a general guideline for converting the complex phenomenon of earthquake ground motion into a simplified formula to convert the inertia force induced in the structure into a static force in the lateral direction which can be applied on the structure.

Usually, it is a policy adopted by all country codes to ensure that structures possess at least a minimum strength to withstand minor earthquakes, which occur frequently, without damage; resist moderate earthquakes without significant structural damage though some non structural damage may be expected and they ensure that structure is capable of withstanding a major earthquake likely to occur in that region without collapse.

It may be borne in mind that the seismic codes do not specify the amount of damage which is likely to be suffered by a structure under the effect of a real event. The actual forces that act on structures during a seismic event are much greater than the design forces specified in the seismic codes. The difference in the forces considered for design and the actual forces induced on the structures is assumed to be compensated by various factors like ductility due to inelastic material behavior and detailing and overstrength due to additional reserve strength in structures over and above the design strength.

Seismic analysis becomes even more important for Reinforced Concrete (RC) structures as the forces induced because of an earthquake are inertia forces which are directly proportional to the mass of the structure. The ductility of concrete structures is much less as compared to steel structures and the damping is also low. These factors make RC structures more vulnerable to earthquake forces. Moreover, it has been observed that the acceleration induced due to earthquakes is of the order of about 0.4 times gravitational acceleration g. Hence, in case of RC structures, although the seismic forces are induced in all possible orthogonal directions, it is usually considered to be critical when applied in the two lateral directions of a building. For RC structures, the loads considered in the gravity directions (dead and live loads) are multiplied by a load factor of 1.5 for design. This factor accounts for an additional load of 0.4g due to earthquake in the gravity direction over and above the force due to 1g acceleration applied to dead and live load masses. Hence, in the event of an earthquake the vertical component of force becomes 1g + 0.4g = 1.4g in case of ground motion in the upward direction and it becomes 1g – 0.4g = 0.6g in case of ground motion in the downward direction.

Hence, for RC structures, the lateral components of earthquake force are the ones which are to be accounted for and to be used in design. For high rise structures, this lateral load resisting system is designed and detailed separately but for low rise structures, the lateral force is transferred to the foundation of the structure through the beam column joint only. These types of frames have to be designed as moment resisting frames with proper rigidity to transfer the seismic forces. They are referred to as Ordinary Moment Resisting Frame (OMRF) if ductile detailing of reinforcement is not followed and Special Moment Resisting Frame (SMRF) if ductile detailing is followed.

As per the codal provisions, the seismic analysis of structures involves finding out equivalent static force which can be applied to the structure in order to find the internal forces in the members of the structure. This equivalent static force, in turn depends on the distribution of mass in the structure and the seismic acceleration experienced by the structure based on the natural period of vibration. Once, this force is evaluated, the analysis is done as per other load cases and load combinations specified for design of individual members.

In case of structures having special importance, site specific response spectra may be used to generate the equivalent static forces. It may be recommended to carry out time history analysis based on the past earthquake strong motion records. However, it may be noted here that it is a time consuming process and it's exact behavior in case of future earthquake can never be predicted.

Moreover, in actual buildings, exact symmetry of loading and geometry is rarely found. This fact indicates that there will be an eccentricity of seismic force by the distance between the centre of mass and the centre of rigidity. This eccentricity will induce torsional forces in a structure which also needs to be accounted for.

## 1.4 TYPES OF STRUCTURAL ANALYSIS

Analysis of framed structures depends on the type of structure and also the response developed by the structure under external forces acting on them (excitation). The excitations can be due to loads, vibrations, settlement and/or thermal changes. When a structure is subjected to these excitations, it undergoes some deformations and stresses known as response of the structure. The responses can be displacements, stresses, strains and/or stress resultants. The excitations can be either static or dynamic. The structure can be either elastic or inelastic and the response can be either linear or nonlinear. Thus, the analysis to be adopted and the equilibrium equations to be used can be broadly classified into following four different categories:

1. Linear Static Analysis (Elastic or Inelastic)

   The equilibrium equation for this type of analysis can be written as

   $$K\,D = A \qquad \text{.....(1.3)}$$

   Where, K = stiffness matrix, D = displacement vector and A = force vector.

2. Linear – Dynamic (Elastic) Analysis

   The equilibrium equation for this type of analysis can be written as

$$M\frac{\partial^2 x}{\partial t^2}(t) + c\frac{\partial x}{\partial t}(t) + kx(t) = P(t) \quad .....(1.4)$$

Where the various terms are as explained in **Eq. 1.1** and they are all time dependent.

3. Nonlinear – Static (Elastic or Inelastic) Analysis

   The equilibrium equation for this type of analysis can be written as

$$K\,D + A_{NL} = A \quad .....(1.5)$$

   Where $A_{NL}$ = nonlinear force vector.

4. Nonlinear – Dynamic (Elastic or Inelastic) Analysis

   The equilibrium equation for this type of analysis is written as

$$M\frac{\partial^2 x}{\partial t^2}(t) + c\frac{\partial x}{\partial t}(t) + kx(t) + P(t)_{NL} = P(t) \quad .....(1.6)$$

   Where, $P(t)_{NL}$ represents nonlinear time dependent force.

Thus, the type of analysis which can be carried out depends on the following three basic factors:

1. Type of excitation (Loads)
2. Type of structure (Material and Geometry)
3. Type of response

It may be worthwhile here to mention the difference between static and dynamic excitations, with the following points:

- **Static Excitation**
  - When the excitation (load) does not vary rapidly with time.
  - When the load can be assumed to be applied "Slowly".
- **Dynamic Excitation**
  - When the excitation varies rapidly with time.
  - When the "Inertial Force" becomes significant.

*Most of the excitations are dynamic in nature but they are considered as "Quasi Static". Also, most dynamic excitations can be converted to "Equivalent Static Loads".*

The difference between elastic and inelastic structures is as follows:

- **Elastic Material**

  Follows the same path during loading and unloading and returns to initial state of deformation, stress, strain etc. after removal of load / excitation.

- **Inelastic Material**

  Does not follow the same path during loading and unloading and may not return to initial state of deformation, stress, strain etc. after removal of load / excitation.

*Most materials exhibit both, elastic and inelastic behavior depending upon level of loading.* Similarly, the difference between linear and nonlinear response can be clarified as follows:

- **Linearity**

– The response is directly proportional to excitation.
– Deflection doubles if load is doubled.

- **Non-Linearity**

– The response is not directly proportional to excitation.
– Deflection may become 4 times if load is doubled.

Non-linear response may be produced by:

– Geometric Effects (Geometric non-linearity)
– Material Effects (Material non-linearity)
– Both Geometric and Material Effects (Hybrid non-linearity)

The **Fig. 1.4** clarify further all the concepts discussed above.

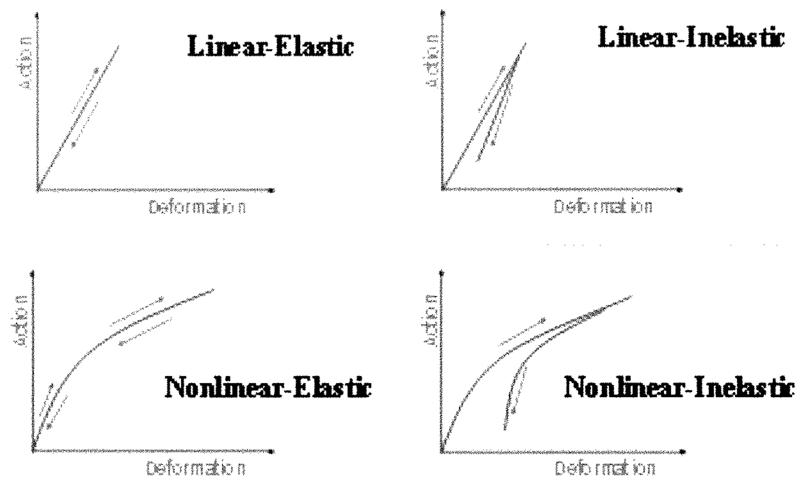



**Fig. 1.4 Elasticity and Linearity**

The various types of analysis which can be carried out based on the three factors viz. Excitation, Structure and Response, is shown in **Table 1.1**.

**Table 1.1 Types of Analysis for General Structures**

| Excitation | Structure | Response | Basic Analysis Type |
|---|---|---|---|
| Static | Elastic | Linear | Linear-Elastic-Static Analysis |
| Static | Elastic | Nonlinear | Nonlinear-Elastic-Static Analysis |
| Static | Inelastic | Linear | Linear-Inelastic-Static Analysis |
| Static | Inelastic | Nonlinear | Nonlinear-Inelastic-Static Analysis |
| Dynamic | Elastic | Linear | Linear-Elastic-Dynamic Analysis |
| Dynamic | Elastic | Nonlinear | Nonlinear-Elastic-Dynamic Analysis |
| Dynamic | Inelastic | Linear | Linear-Inelastic-Dynamic Analysis |
| Dynamic | Inelastic | Nonlinear | Nonlinear-Inelastic-Dynamic Analysis |

Nonlinear and dynamic analysis can be further classified as

- **Non-linear Analysis**

– P-Delta Analysis

- Buckling Analysis
- Static Pushover Analysis
- Fast Non-Linear Analysis (FNA)
- Large Displacement Analysis

• **Dynamic Analysis**

- Free Vibration and Modal Analysis
- Response Spectrum Analysis
- Steady State Dynamic Analysis

## 1.5 SCOPE AND OBJECTIVES OF THE PRESENT WORK

Out of the various parameters affecting the response of a structure, the soft storey and weak storey effects arise out of a poor structural framing and hence it is presumed that a responsible engineer following the codal provisions would be well aware to avoid such effects. Also, the earthquake codes give very specific guidelines on such effects. The provision of providing tie beams in both the lateral directions is a case of good engineering practice and hence it need not be stressed any further. The location of mass at certain locations so as to avoid large torsional effects on the building can also be addressed by using proper analysis tools.

The present work specifically aims at giving guidelines to a structural engineer who is not very sure about the effects of column orientation or shape on the overall seismic response. Furthermore, when a structural engineer is detailing the beam-column joints, this work aims to give some specific guidelines on the effect of joint rigidity on the seismic performance of the structure. Thus the objective is to provide clear guidelines to a structural engineer in terms of care to be taken to enhance the seismic performance of RC buildings.

From the literature review it is found that lot of work has been done on seismic response of the beam-column joint in RC framed structure. However, researchers have not paid enough attention to the rigidity of the joint. It was thus thought fit to explore the possibility of varying the stiffness of the beam column joint and consider it as semi rigid instead of the usual fully rigid. Even the modern trend of fast construction involving precast members forming a beam-column joint further enhances the possibility of a semi rigid joint which is explored in detail in the present study. The basic aim is to evaluate the seismic response of RC framed structures with semi rigid joints under various parameters and to compare the performance of the structure under lateral force application.

Push over analysis is one of the most powerful tools for seismic evaluation of 2D and 3D frames. Therefore, it is decided to study the response of RC frames under push over analysis as per Indian conditions and to report the effects of change in various parameters like shape of the columns, rigidity of the joints, location of the semi rigid joint in the frame. It is also proposed to report the response of the structure, considering brick infill walls as diagonal strut and to compare it's performance to that without the same.

The various parameters considered during push over analysis are base shear, roof displacement, effective damping, time period, number and stress level of plastic hinges developed at the performance point. It is proposed to use commercially available software ETABS for developing a mathematical model of 3D RC frame. An open source software OPENSEES is also used to correlate the results obtained from the ETABS software to get more confidence in the accuracy of the results obtained.

One more construction technology which is gaining popularity now-a-days is the post tension technology wherein the columns are normal reinforced concrete and the slabs and beams are casted with post tension cables placed in it. These cables are tensioned to give a prestressing force to concrete which helps in balancing about 60 to 90 percent of the gravity loads. The seismic resistance capability of such post tensioned slabs has always been questioned as it replaces the normal beams with so called "fat" beams which are having very less depth. In the present study, a mathematical model of such types of buildings is also analyzed under push over analysis.

It is also proposed to study the roof displacement and base shear of RC framed structures under time history analysis. The models are subjected to time history load along with response spectrum loads due to Bhuj earthquake as well as that specified by IS 1893 **[24]** to critically examine the results. This will give an insight into the actual behavior of the structure under random vibrations generated by actual events which has occurred in the past. Thus, another important objective of the current work is to report the base shear and roof level displacements for RC framed structures by applying various methods of dynamic loads.

Another factor which influences the behavior of a structure is the use of floating columns to support the structure above. This concept is being used almost in all Indian cities and towns because of the local building permitted byelaws. However, use of floating columns has resulted in wide spread damages observed in the city of Ahemdabad during the 2001 Bhuj earthquake. Hence, it is proposed to subject some of the low rise structures, having floating columns, to push over analysis to critically examine their effect on the seismic performance of RC framed structures.

## 1.6 ORGANIZATION OF THE THESIS

**Chapter 1**, after mentioning some facts about the earthquakes, deals with the general concepts of structural dynamics and the various seismic analysis tools. The chapter further describes the types of analysis as per the excitation, model and response types exhibited by framed structures followed by the scope and objectives of the present work and the overall flow of the thesis.

**Chapter 2** deals in brief with the various methods available to evaluate the response of the structure. The time history analysis which is considered to be more accurate but time consuming is explained followed by the non-linear static analysis. The non-linear dynamic analysis is also briefly explained followed by the steady state dynamic analysis.

The literature available on the subject of dynamic and seismic evaluation of structures has been split up into sub topics in **Chapter 3** and presented so that the current trend can be clearly understood.

**Chapter 4** explains the key features required to be understood for push over analysis and provides a theoretical background for seismic evaluation process. It explains how the capacity and demand curves are developed in ADRS format and superimposed to get a performance point. The properties of hinges that develop at pre determined locations are also defined in this chapter.

The mathematical model is generated for analysis under seismic forces and the performance is studied and reported in **Chapter 5**. The mathematical models for G+6 structures are developed using SAP2000 software and are subjected to pushover analysis for rectangular and square shaped columns. The results obtained are presented with the critical observations and discussions on the same.

**Chapter 6** is devoted to evaluating the same models with infill masonry walls modeled as struts in one incidence and as finite elements in another incidence. The various models are subjected to push over analysis and the results obtained for performance point are noted. The effect of infill walls on the overall performance of the structure is studied in this chapter. Further, to demonstrate the effect of column shape on the performance of RC framed structures, T-shaped columns are selected for the same models in **Chapter 7**. It also compares the performance point obtained when the space frames are having T-shaped columns with those considered with square and rectangular shaped columns.

**Chapter 8** is dedicated to the study of rigidity of the beam-column joints. In order to study the effect of change in rigidity of a beam-column joint, a plane frame is studied under beam column joints having varying stiffness from 0% (pinned) to a very high stiffness i.e. 100% (fixed). Results obtained for beam end moments for varying rigidity are evaluated and reported. Similarly, in **Chapter 9**, the effect of semi rigidity of joint on seismic performance of space frames is studied in detail.

**Chapter 10** deals with a new concept of hybrid frame which involves considering joints of the external frames as fully rigid and all the internal joints as semi rigid. The comparison of performance point for such a hybrid frame is made with the conventional frame with all joints as fully rigid followed by the discussion of results.The hybrid frame concept is extended further in **Chapter 11** to some bigger sized frames in plan to establish their effectiveness.

**Chapter 12** is devoted to one of the recent concepts of post tensioned (PT) beams in RC structures. This chapter involves modeling the structure with three variations in it's framing. The performance of regular frame with all RC beams is compared with that of frame consisting of peripheral RC beams and internal PT beams and one having all beams as PT. The models are subjected to pushover analysis and the performance point parameters evaluated for each of the models are compared.

In **Chapter 13**, a verification of push over analysis results obtained by ETABS software is done by using an open source software OpenSEES. Whereas, **Chapter 14** is specifically devoted to the study of the effects of floating columns on the seismic performance of an RC framed building. The aim is to quantify the seismic resistance of a structure having a floating column vis-a-vis one having firm columns.

In **Chapter 15**, Bhuj earthquake time history is applied as load to the mathematical models of the RC frames considered in the previous chapters. The model is also analyzed using linear static, non linear static, response spectrum as per Indian code and response spectrum for Bhuj earthquake. A comparison of base shear, roof displacement and storey drift by above mentioned methods is presented for models with square and rectangular columns.

Finally, the **Chapter 16** highlights the important conclusions and contributions of the current work followed by mention of the direction to be taken up for future research in this field.