STRUCTURAL AND ARCHITECTURAL ASPECTS OF EARTHQUAKE RESISTANT DESIGN

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1. CHARACTERISTICS OF EARTHQUAKE GROUND MOTION

The characteristics of earthquake ground motion which are of most interest in earthquake engineering applications are:

1. Peak ground motions (acceleration, velocity and displacement) primarily influence the vibration amplitudes
2. Duration of strong motion has a pronounced effect on the severity of the shaking.
3. Frequency content spectral shapes relate to frequencies or periods of vibration of a structure (resonance conditions).

A ground motion with moderate peak acceleration and a long duration may be more damaging than a ground motion with a larger acceleration and a shorter duration. In a structure, ground motion is amplified the most when the frequencies that dominate the motion are close to the vibration frequencies of the structure.

2. EARTHQUAKE DESIGN SPECTRUM

A response spectrum is simply a plot of the peak response (displacement, velocity or acceleration) of a number of SDOF systems of varying natural period, that are forced into motion by the same base vibration. The resulting plot can then be used to find the response of any structure, knowing its natural period.

2.1 Advantages of Response Spectrum

Response spectrum has found vital importance in structural engineering since its inception Response spectrum method of analysis finds advantage due to following reasons:

- Unlike pseudo-static analysis it considers the frequency effects.

- Unlike thorough dynamic analysis, it provides a single suitable horizontal force for the design of structure.
- The idealization of treating the system as a single degree freedom system is acceptable in structural engineering problems where the complexities involved in terms of geometry, material property and boundary condition are relatively less.

2.2 Construction of Response Spectrum

- The response may be expressed in terms of acceleration, velocity or displacement.
- The maximum values of each of these parameters depend only on the natural period or frequency and damping ratio of the single degree of freedom system (SDOF).
- The maximum magnitudes of acceleration, velocity and displacement at different natural periods are referred to as the spectral acceleration (S_a), spectral velocity (S_v) and spectral displacement (S_d) respectively.
- A single degree of freedom system of zero natural period (infinite natural frequency) would be rigid, and its spectral acceleration would be equal to the peak ground acceleration.
- The maximum response motions and the spectral acceleration, velocity, and displacement can be approximately related to each other by the following simple expressions:

$$\textbf{Spectral Displacement} = S_d = |x|_{max}$$
$$\textbf{Spectral Velocity} = S_v = |\dot{x}|_{max}$$
$$\textbf{Spectral Acceleration} = S_a = |\ddot{x} + \ddot{x}_g|_{max} = \left|2\xi w_n \dot{x} + w_n^2 x\right|_{max}$$

$$\textbf{\textit{Pseudo}-spectral velocity} = PS_v = \omega_n \cdot S_d$$
$$\textbf{\textit{Pseudo}-spectral acceleration} = PS_a = \omega_n^2 \cdot S_d$$

- Since the peak ground acceleration, velocity and displacement for various earthquake records differ, the computed responses cannot be averaged on an absolute basis. Normalization is carried out by dividing the spectral ordinates by the peak ground acceleration, velocity and displacement for the corresponding region of the spectrum.

- Earthquake parameters such as soil condition, epi-central distance, and magnitude of earthquake, duration and source characteristics influence the shape and amplitude of response spectra. While the effects of some parameters may be studied independently, the influences of several factors are interrelated and it is difficult to consider individually.

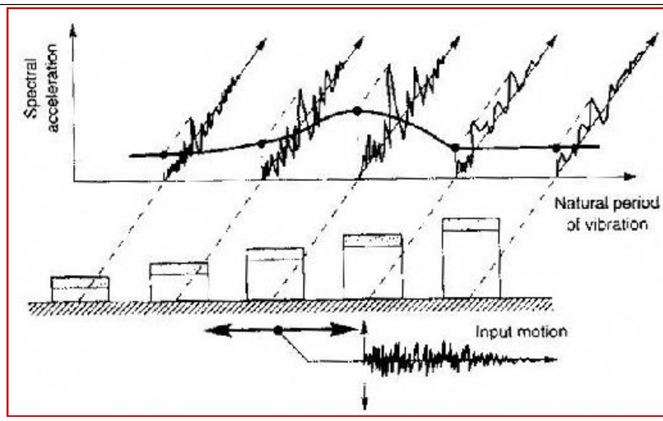

Fig. 2.1 : Construction of Response spectrum

2.3 Development of Response Spectrum Chart

- In order to explain the procedure for the development of the design spectrum chart, a typical time history of acceleration of with 2% damping shall be considered.
- For different natural periods T_n of the system, the peak displacements were obtained from the time history plots.
- The peak displacement so determined for each system provides one point on the deformation response spectrum.
- The complete deformation response spectrum plot for a damping of 2% is presented.
- Each of the Deformation, Pseudo Velocity and Pseudo acceleration Spectra for a given ground motion contain the same information.
- Deformation Spectrum provides peak deformation of the system.
- Pseudo Velocity spectrum is related to the peak strain energy stored in the system during Earthquake.
- Pseudo Acceleration Spectrum is related to peak value of the equivalent static force and base shear. Thus combined plot is useful.
- The three charts can be combined into a single chart with log scale called Tripartite

Chart The Vertical Scale for V and T are in log scale. The scales for D and A are sloping at +45 and -45 to the T axis.

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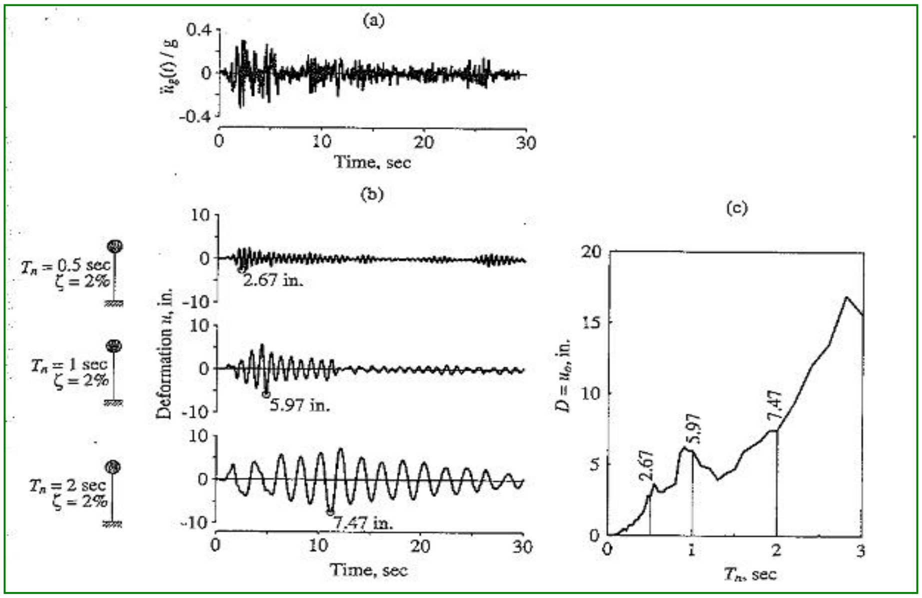

Fig.2.2: Deformation Spectrum of three SDOF systems with damping of 2%

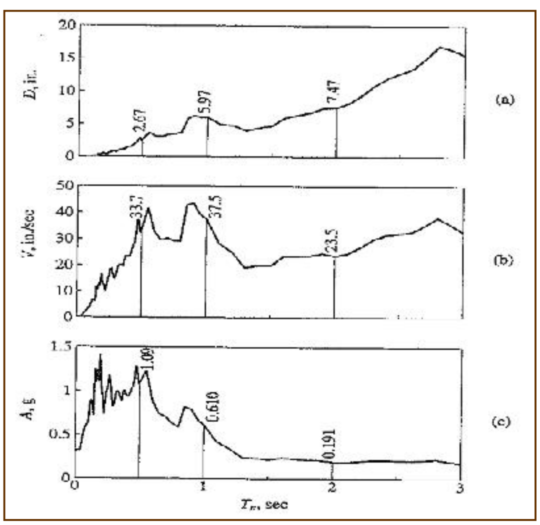

Fig.2.3 : Pseudo-Velocity and Pseudo–Acceleration Spectrum of three SDOF systems with damping of 2%

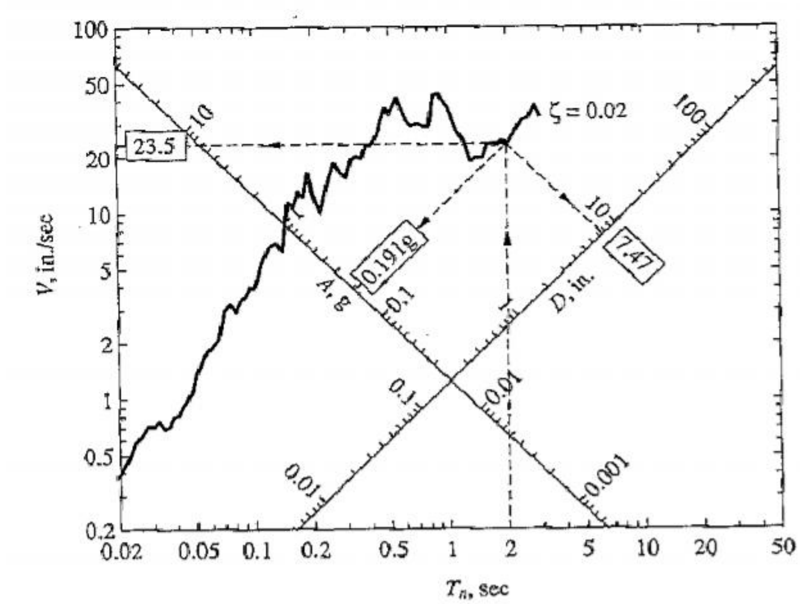

Fig. 2.4: Combined D-V-A spectrum with damping of 2% (Tripartite Chart)

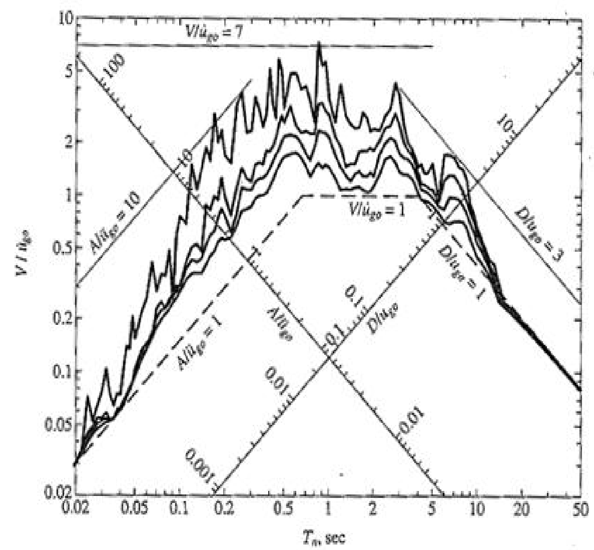

Fig.2.5: Combined D-V-A Spectrum with different damping normalised with ground acceleration, velocity and displacement

1. Elastic Design Response Spectrum (EDRS)

- The design spectrum should satisfy certain requirements as it is intended for the design of new structures.
- The response spectrum for a ground motion recorded during a past earthquake is

inappropriate.

- The RS for all different motions is also uneven or jagged.
- Thus the design spectrum should consist of smooth curves or series of straight lines with one curve for each damping.
- Generally as a compromise, different ground motions are considered and Rs is developed.
- The design RS is based on statistical analysis of the Response spectra for the ensemble of ground motions.
- Each ground motion is normalised (scaled up or down) so that all ground motions have the same peak ground acceleration.
- The Rs for each normalised ground motions is constructed.
- The mean values of the spectral ordinates for each period are obtained.
- Statistical analysis of these data provides the probability distribution for the spectral ordinates.
- Obtain the coefficient of variation = standard Deviation + Mean.
- Connecting all the points gives Mean RS and (Mean + SD) RS. These are smoother.
- The idealised series of straight lines leads to the EDRS.

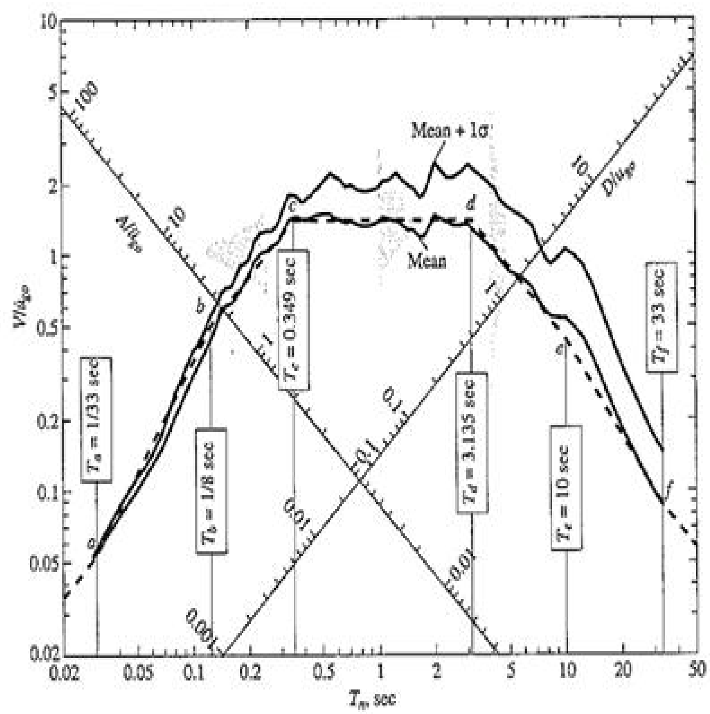

Fig. 2.6: Mean and (Mean + 1SD) spectra with dashed line showing an Idealised Design Spectrum

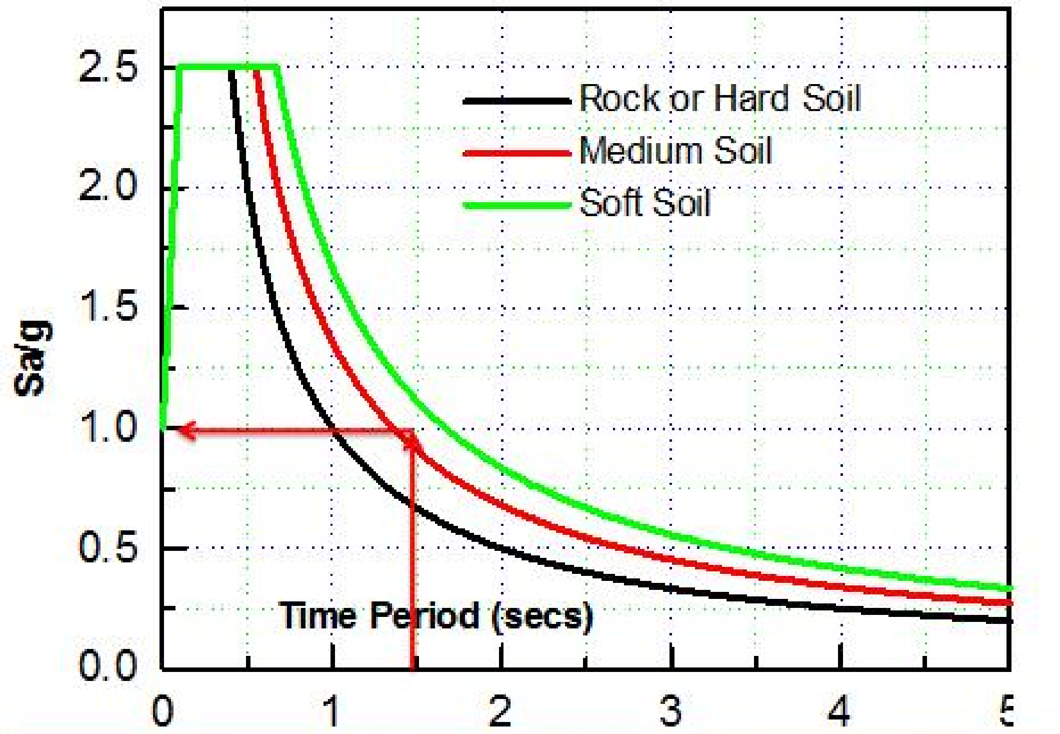

Fig. 2.7: The design response spectrum of IS : 1893 :2002

3. EARTHQUAKE EFFECTS

3.1 Direct effects.

The following are the direct seismic effects:

1. Damage due to surface faulting

The damage due to surface faulting varies widely. It may totally demolish houses, rupture the foundations, tilt the foundation slabs and walls or may cause minor damage to the houses.

2. Damage due to liquefaction

Liquefaction of soil may cause instability due to internal seismic waves and thereby may significantly damage in form of settlement, tilting and rupture of the structures. The extent of damage depends on properties of soils of different layers, depth of the water table and the intensity, magnitude and duration of the earthquake. Accordingly, there may be either large settlement or differential settlement of the ground surface. It is always desirable to avoid construction in such areas than to design the structures following codal provisions, which may be insufficient, though ensure effective design against vibration of structures due to shaking at the foundation level.

3. Damage due to ground shaking

As the state of the art of this subject is still developing, integrated field inspection of structures damaged by earthquakes and their analyses are useful in further adding/improving the expert knowledge in the seismic resistant design and construction. Earlier inspections and analyses established the types of foundation, configurations of structures, materials of construction and design and detailing of construction. Such data are being continuously updated.

4. Damage due to sliding of superstructure on its foundation

It is essential that the whole structure and the foundation should work as a unit especially for the seismic resistant design and construction of structures. For this the superstructures should be anchored properly to the foundation.

5. Damage due to structural vibration

The extent of the damage due to structural vibration depends on the materials of construction. Wood, reinforced concrete and steel are widely used in civil engineering structures. It is well-known that inertia forces are developed as vibration response of a structure due to earthquake ground shaking. The intensity of such inertia forces is directly proportional to the product of mass and acceleration. Hence, reduction of mass is very effective to minimise the inertia forces. In this respect, timber has the maximum advantage as a potential construction material due to its low mass. Concrete, though a heavy material when reinforced with steel bars, has good strengths both in compression and in tension. Accordingly, reinforced concrete can be used effectively by providing proper amount of reinforcement and correct detailing of them as they play significant roles in the seismic resistant design of reinforced concrete structures. Steel has the additional advantages of ductility, strength and toughness per unit weight than concrete.

3.2 Indirect effects

Tsunamis, seiches, landslides, floods and fires are the indirect effects of earthquakes. These may occur either alone or in combinations to add to the damages during an earthquake

4. SEISMIC EFFECTS ON STRUCTURE

4.1 Inertia Forces in Structures

Earthquake causes shaking of the ground. So a building resting on it will experience motion at its base. From Newton's First Law of Motion, even though the base of the building moves with the ground, the roof has a tendency to stay in its original position. But since the walls and columns are connected to it, they drag the roof along with them. This is much like the situation that you are faced with when the bus you are standing in suddenly starts; your feet move with the bus, but your upper body tends to stay back making you fall backwards!! This tendency to continue to remain in the previous position is known as inertia. In the building, since the walls or columns are flexible, the motion of the roof is different from that of the ground. Consider a building whose roof is supported on columns (Fig. 4.1). Coming back to the analogy of yourself on the bus: when the bus suddenly starts, you are thrown backwards as if someone has applied a force on the upper body. Similarly, when the ground moves, even the building is thrown backwards, and the roof experiences a force, called inertia force. If the roof has a mass M and experiences an acceleration a, then from Newton's Second Law of Motion, the inertia force F_I is mass M times acceleration a, and its direction is opposite to that of the acceleration. Clearly, more mass means higher inertia force. Therefore, lighter buildings sustain the earthquake shaking better.

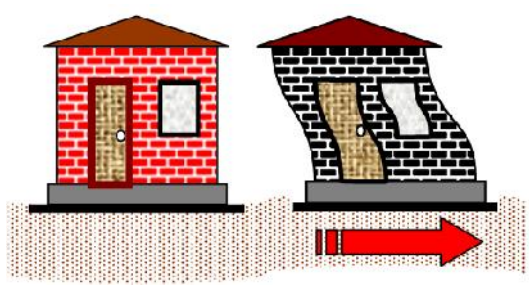

Fig. 4.1: Effect of Inertia in a Building when shaken at its base

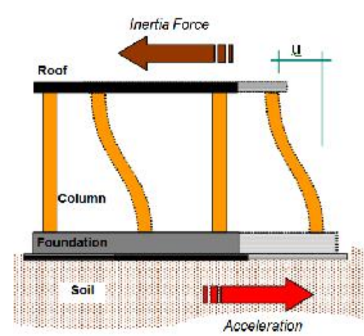

Fig. 4.2: Inertia force and relative motion within a building.

4.2 Effect of Deformations in Structures

The inertia force experienced by the roof is transferred to the ground thro the columns, causing forces in columns. During earthquake shaking, the columns undergo relative movement between their ends. In Fig. 4.2, this movement is shown as quantity u between the roof and the ground. But, given a free option, columns would like to come back to the straight vertical position, i.e., columns resist deformations. In the straight vertical position, the columns carry no horizontal earthquake force through them. But, when forced to bend, they develop internal forces. The larger is the relative horizontal displacement u between the top and bottom of the column, the larger this internal force in columns. Also, the stiffer the columns are (i.e., bigger is the column size), larger is this force. For this reason, these internal forces in the columns are called stiffness forces. In fact, the stiffness force in a column is the column stiffness times the relative displacement between its ends.

4.3 Horizontal and Vertical Shaking

Earthquake causes shaking of the ground in all three directions – along the two horizontal directions (*X and Y, say*), and the vertical direction (*Z, say).* Also, during the earthquake, the ground shakes randomly *back and forth* (- and +) along each of these X, Y and Z directions (Fig. 4.3). All structures are primarily designed to carry the gravity loads, *i.e.*, they are designed for a force equal to the mass *M* (this includes mass due to own weight and imposed loads) times the acceleration due to gravity *g* acting in the vertical downward direction (-Z). The downward force *Mg* is called the *gravity load*. The vertical acceleration during ground shaking either adds to or subtracts from the acceleration due to gravity. Since factors of safety are used in the design of structures to resist the gravity loads, usually most structures tend to be adequate against vertical shaking. However, horizontal shaking along X and Y directions (both + and – directions of each) remains a concern. Structures designed for gravity loads, in general, may not be able to safely sustain the effects of horizontal earthquake shaking. Hence, it is necessary to ensure adequacy of the structures against horizontal earthquake effects.

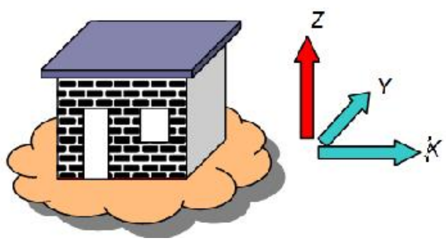

Fig. 4.3: Principal directions of Shaking

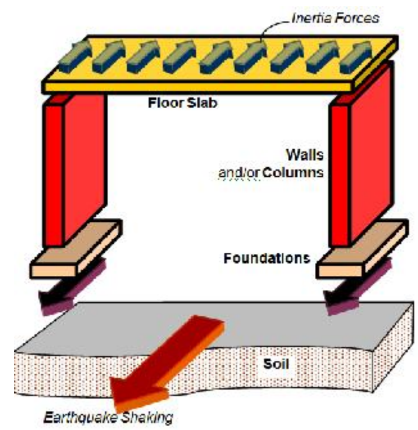

Fig. 4.4: Flow of seismic Inertia forces through all structural components.

4.4 Flow of Inertia Forces to Foundations

Under horizontal shaking of the ground, horizontal inertia forces are generated at level of the mass of the structure (usually situated at the floor levels). These lateral inertia forces are transferred by the floor slab to the walls or columns, to the foundations, and finally to the soil system underneath (Fig. 4.4). So, each of these structural elements (floor slabs, walls, columns, and foundations) and the connections between them must be designed to safely transfer these inertia forces through them. Walls or columns are the most critical elements in transferring the inertia forces. But, in traditional construction, floor slabs and beams receive more care and attention during design and construction, than walls and columns. Walls are relatively thin and often made of brittle material like masonry. They are poor in carrying horizontal earthquake inertia forces along the direction of their thickness. Failures of masonry walls. The failure of the ground storey columns resulted in numerous building collapses during previous earthquakes.

5. RESPONSE OF STRUCTURES

When the response to earthquake induced forces is of concern, the aspects of structural configuration, symmetry, mass distribution and vertical regularity must be considered and the importance of strength, stiffness and ductility in relation to acceptable response appreciated. Irregularities, often unavoidable, contribute to the structural complexity of structural behaviour. When not recognized they may result in unexpected damage and even collapse. There are many sources of structural irregularities. Drastic changes in geometry, interruptions in load paths, discontinuities in strength and stiffness, disruptions in critical regions by openings, unusual proportions of members, reentrant corners, lack of redundancy and interference with induced or assumed structural deformations are only a few of the possibilities. The recognition of many of these irregularities and of conceptions for remedial measures for the avoidance or mitigation of their undesired effects relies on sound understanding of structural behaviour. So, the structural response characteristics and gross seismic response of the buildings are important to understand the basic structural behaviour.

The important response characteristics are;

1. Stiffness
2. Strength
3. Ductility
4. Damping

5.1 Stiffness

Stiffness defines the relationship between actions and deformations of a structure and its components.

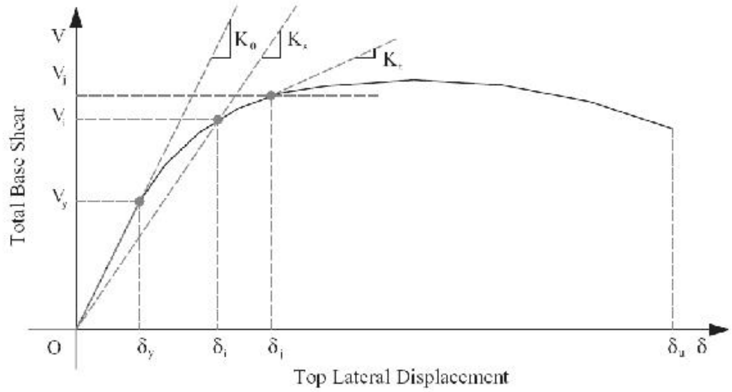

Fig. 5.1: Definition of Initial and Secant Structural Stiffness

Fig. 5.1 shows a plot of the structural response of a system subjected to lateral loads; the response curve is represented by base shear V versus top horizontal displacement δ. The initial slope K_0 is the elastic stiffness of the structure, while the secant stiffness is the slope K_s of the line corresponding to a given level of load. For reinforced concrete (RC) and masonry structures, the stiffness can be taken as the secant to the yield point or to any other selected point on the response curve. Variations in stiffness in the inelastic range are often expressed by the tangent stiffness K_t, which is the slope of the tangent to the response curve for a given V - δ pair. A decrease in the values of K_t indicates that softening of the structure is taking place. In analysis of inelastic structures, use is often made of secant stiffness to avoid dealing with negative tangent stiffness beyond the peak action resistance.

5.2 Strength

Strength defines the capacity of a member or an assembly of members to resist actions. This capacity is related to a limit state expressed by the stakeholder. It is therefore not a single number and varies as a function of the use of the structure. For example, if the interested party decides that the limit of use of a structural member corresponds to a target sectional strain, then the strength of the member is defined as its load resistance at the attainment of the target strain. This may be higher or lower than the peak of the load – displacement curve, which is the conventional definition of strength. Target strains may assume different values depending on the use of structural systems. For instance, strains utilized in multi - storey frames for power plants may be lower than those employed in residential or commercial buildings. Target strains can be correlated to the risk of failure, which in turn depends on the use of the structure.

5.3 Ductility

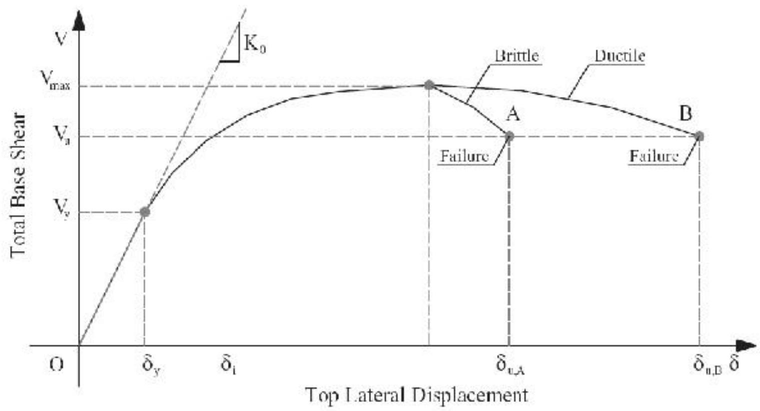

Fig. 5.2: Definition of Structural Ductility

Ductility is defined as the ability of a material, component, connection or structure to undergo inelastic deformations with acceptable stiffness and strength reduction. Fig. 5.2 compares the structural response of brittle and ductile systems. Curves A and B express force – displacement relationships for systems with the same stiffness and strength but distinct post - peak (inelastic) behaviour. Brittle systems fail after reaching their strength limit at very low inelastic deformations in a manner similar to curve A. The collapse of brittle systems occurs suddenly beyond the maximum resistance, denoted as V_{max}, because of lack of ductility. Conversely, curve B corresponds to large inelastic deformations, which are typical of ductile systems. Whereas the two response curves are identical up to the maximum resistance V_{max}, they should be treated differently under seismic loads. The ultimate deformations δ_u corresponding to load level V_u are higher in curve B with respect to curve A, i.e. $\delta_{u,B} >> \delta_{u,A}$. Most structures are designed to behave inelastically under strong earthquakes for reasons of economy. The response amplitudes of earthquake - induced vibrations are dependent on the level of energy dissipation of structures, which is a function of their ability to absorb and dissipate energy by ductile deformations. For low energy dissipation, structural systems may develop stresses that correspond to relatively large lateral loads. Consequently, such structures should be designed to withstand lateral forces of the same proportion of their weight to remain in the elastic range. This is uneconomical in all practical applications with the exception of nuclear power plants, offshore platforms and water - and fluid - retaining structures, alongside other safety - critical structures.

The general analytical definition of displacement ductility is given below:

$$\mu = \Delta_u / \Delta_y$$

where Δ_u and Δ_y are displacements at ultimate and yield points, respectively. The displacements Δ may be replaced by curvatures, rotations or any deformational quantity. The ratio μ in equation is referred to as 'ductility factor'.

In seismic design, high available ductility is essential to ensure plastic redistribution of actions among components of lateral resisting systems, and to allow for large absorption and dissipation of earthquake input energy. Ductile systems may withstand extensive structural damage without collapsing or endangering life safety; this corresponds to the 'collapse prevention' limit state.

5.4 Damping

Damping is utilized to characterize the ability of structures to dissipate energy during dynamic response. Unlike the mass and stiffness of a structure, damping does not relate to a unique physical process but rather to a number of possible processes. Damping values depend on several factors; among these are vibration amplitude, material of construction, fundamental periods of vibration, mode shapes and structural configurations.

Seismic energy transmitted to structures can be dissipated through different damping mechanisms. Primary sources of damping are, however, as follows:

i. **Structural damping:** due to energy dissipation in materials of construction, structural components and their connections;

ii. **Supplemental damping:** due to energy dissipation of devices added to structural systems to increase their damping;

iii. **Foundation damping:** due to the transfer of energy from the vibrating structure to the soil, through the foundations;

iv. **Radiation damping:** due to radiation of seismic waves away from foundations.

External damping may be aerodynamic and hydrodynamic caused by interaction between structure and surrounding air and water, respectively. The latter mechanisms are generally negligible compared to other types of damping in earthquake response of structures. Inelastic deformations of the ground in the vicinity of foundations, caused by soil hysteresis, and seismic wave propagation or radiation result in two fundamentally different damping mechanisms associated with soils, namely foundation and radiation damping. Soil - structure interaction may significantly contribute towards the overall damping. This depends on several site and structural characteristics. When the soil is infinitely rigid, then the foundation damping may be neglected. Supplemental damping can be added to structures to enhance their dissipation capacity and hence reduce actions and deformations.

Structural damping is a measure of energy dissipation in a vibrating system that results in bringing the structure back to a quiescent state. It is associated with absorption of seismic energy in structural components. It also accounts for material viscosity and friction at connections and supports. In structural components, the energy imparted by earthquakes is dissipated mainly through hysteretic damping characterized by action – deformation loops. Such loops express action – deformation relationships of materials, sections, members, connections or systems under alternating loads. For hysteretic damping, the dissipation varies with the level of displacement, but it is constant with the velocity. The amount and mechanisms of material hysteretic damping vary significantly depending on whether the material is brittle, such as concrete and masonry, or ductile, e.g. metals. For reinforced concrete (RC), energy dissipation is due to opening and closing of cracks but the material remains held together by the steel. In masonry, there is also sliding along the cracks; hence the hysteretic damping of masonry is lower than that of reinforced concrete (RC). Whereas hysteretic damping is complex and cannot be expressed in simple forms, it is almost always represented in dynamic analysis as equivalent viscous damping, which is proportional to the velocity. This form of damping conveniently allocates a parameter to the velocity term in the dynamic equilibrium equations that matches the mass and stiffness terms associated with acceleration and displacement, respectively.

Friction or Coulomb damping results from interfacial mechanisms between members and connections of a structural system, and between structural and non - structural components such as infills and partitions. It is independent of velocity and displacement; its values significantly depend on the material and type of construction. For example, in steel structures, the contribution of friction damping in bolted connections is higher than welded connections. In infilled masonry walls, friction damping is generated when cracks open and close. In other materials, e.g. for concrete and masonry, this type of damping cannot be relied upon because of the degradation of stiffness and strength under cyclic load reversals.

IS: 1893 – 2002 suggests that the value of damping for buildings may be taken as 2 and 5 percent of the critical for the purposes of dynamic analysis of steel and reinforced concrete (RC) buildings, respectively.

6. STRUCTURAL MODELLING

Structural models are idealizations of the prototype and are intended to simulate the response characteristics of systems. Three levels of modelling are generally used for earthquake response analysis. These are summarized below in the order of complexity and accuracy:

6.1 Substitute (or equivalent SDOF) Models

The structure is idealized as an equivalent single – degree of freedom (SDOF) system or 'substitute system'. Four parameters are needed to define the substitute system: effective mass M_{eff}, effective height H_{eff}, effective stiffness k_{eff} and effective damping ξ_{eff}. The height H_{eff} defines the location of the equivalent or effective mass M_{eff} of the substitute system. The equivalence used to estimate k_{eff} and ξ_{eff} assumes that the displacement of the original structure is the same as that of the substitute model. For inelastic systems, the effective stiffness k_{eff} may be assumed as the secant stiffness at some given displacement, while ξ_{eff}, which is utilized to quantify the energy dissipation, is assumed as the equivalent viscous damping. Substitute models are inadequate to assess local response of structures, although they are effective for global analyses.

6.2 Stick Models

These consist of multi - degree of freedom (MDOF) systems in which each element idealizes a number of members of the prototype structure. In multi - storey building frames, each storey is modelled by a single line of finite elements (FE) representing the deformational characteristics of all columns and their interaction with beams. For three - dimensional models, the stick element relates the shear forces along two horizontal orthogonal directions and the storey torque to the corresponding inter - storey translations and rotations, respectively. The lateral stiffness of each equivalent stick element is the stiffness of the frame comprising columns connected to beams. For dynamic analysis, the mass of each floor is concentrated at the nodes representing the centroid of the slab. Lumping both mass and stiffness at a limited number of nodes and pairs of nodes leads to a significant reduction in the size of the problem to be solved. Distributed masses are seldom employed for stick models. They are used, for example, to simulate the response of structural walls. Shear beam elements are also utilized as stick elements for multi - storey frames employing members where shear deformation cannot be ignored. Stick models are suitable for sensitivity analyses to assess the effects of various design parameters, such as beam - to - column strength ratio and the degree of irregularity along the height. Conversely, they cannot be used to evaluate the distribution of ductility demands and damage among the individual structural members.

6.3 Detailed Models

These include general FE idealizations in which structures are discretized into a large number of elements with section analysis or spatial elements in 2D or 3D. Such a modeling approach allows representation of details of the geometry of the members, and enables the description of the history of stresses and strains at fibers along the length or across the section dimensions. Provided that the problem size remains manageable, detailed models also provide global response quantities and the relationships between local and global response. In the detailed modelling approach, beams and columns of frames are represented by flexural elements, braces by truss elements, and shear and core walls by 2D elements, such as plates and shells. For accurate evaluation of deformations and member forces, three - dimensional modelling may be required. Its use is essential to study stress concentrations, local damage patterns or interface behaviour between different materials. However, spatial FE models are often cumbersome for large structures, especially when inelastic dynamic analysis with large displacements is required.

Substitute and detailed models used to discretize structural systems may be described as macro and micro models. Stick models constitute an intermediate group and employ member level representations. Hybrid models, e.g. combining detailed and stick elements, can also be used especially for the seismic analysis of large structures. For example, the upper deck of multi-span bridges, which is expected to remain elastic, is often discretized using beam elements, while fine FE meshes are utilized for the piers, where inelasticity is expected. For buildings, detailed models are often used to idealize the frame of the superstructure, while stick models are used for foundations. Where walls and cores exist, there are possibilities of modelling them using 2D or even 3D continuum elements to detect the spread of inelasticity.

In 3D Modelling the displacement at each node and can simulate any type of behavior. 3D frame models which are especially useful to simulate the responses of three dimensional effects Buildings with irregular geometric configuration Torsional response in the structures with eccentric distributions of stiffness/mass. Earthquake motion in two directions or in skew direction etc. 2 D Modelling. is used for buildings having symmetric plan and where torsional responses are expected to be small. The model connects all the plane frames in one principal direction by assuming the identical horizontal displacement in a floor. In 2D plane frame modelling, the number of degrees of freedom can be reduced to about one-fourth as compared to the 3D frame models.

7. CODE BASED SEISMIC DESIGN METHODS

There are four methods of seismic Design based on Indian Standards:

1) Lateral strength based design
2) Displacement and ductility based design
3) Capacity based design
4) Energy based design

7.1 Lateral Strength Based Design

This is the most common seismic design approach. It is based on providing the structure with minimum lateral strength to resist seismic loads assuming that the structure will behave adequately in the non-linear range. Simple Constructional details are to be satisfied – IS :13920-1993

7.2 Displacement And Ductility Based Design

It is very well recognized that because of economic reasons, the structure is not designed to have sufficient strength to remain elastic in severe earthquakes. The structure is designed to possess adequate ductility so that it can dissipate the energy by yielding and survive the shocks. This method operates directly with deformation quantities and gives better insight on the performance of the structure rather than simply providing strength. Many country adopts this method of design

7.3 Capacity Based Design

It is a design approach in which the structures are designed in such a way that hinges can only be formed in pre-determined positions and sequences. The strength and ductilities are allocated and analysis are independent. This method stipulates the margin of strength that is necessary for elements to ensure that their behavior remains elastic. The capacity based design method is that in the yielding condition, the strength developed in the weaker member is related to the capacity of the stronger member.

Example:

Steel chain with one Ductile link and remaining Brittle links. Strength (or Ductility) of a chain is the strength (or Ductility) of its weakest link !. For ductile behavior, weakest link MUST be ductile.

7.4 Energy Based Design

One of the promising approaches for earthquake resistant design in future. In this approach, the total energy input E_I can be resisted by the sum of the Kinetic energy E_K, Elastic strain energy E_{ES}, Energy dissipated through plastic deformations E_H and Equivalent viscous damping $E_{\text{خ}}$.

8. LATERAL LOAD RESISTING SYSTEMS

Many buildings consist of mixtures of the basic types of the lateral resistive systems. Walls existing with a frame structure, although possibly not used for gravity loads, can still be used to brace the frame for lateral loads. Shear walls may be used to brace a building in one direction whereas a braced frame or rigid frame is used in the perpendicular direction. Multistory buildings occasionally have one type of system, such as rigid frame, for the upper stories and a different system, such as a box system or braced frame, for the lower stories to reduce deformation and take the greater loads in the lower portion of the structure. In many cases it is neither necessary nor desirable to use every wall as a shear wall or to brace every bay of the building frame. This procedure does require that there be some load-distributing elements, such as the roof and floor diaphragms, horizontal struts, and so on, that serve to tie the unstabilized portions of the building to the lateral resistive elements.

There is a possibility that some of the elements of the building construction that are not intended to function as bracing elements may actually end up taking some of the lateral load. In frame construction, surfacing materials, plaster, dry wall, wood paneling, masonry veneer, and so on may take some lateral load even though the frame is braced by other means. This is essentially a matter of relative stiffness, although connection for load transfer is also a consideration. The choice of the type of lateral resistive system must be related to the loading conditions and to the behavior characteristics required. It must also, however, be coordinated with the design for gravity loads and with the architectural planning considerations. Many design situations allow for alternatives, although the choice may be limited by the size of the building, by code restrictions, by the magnitude of lateral loads, by the desire for limited deformation, and so on. Different types of lateral load resisting systems are shown in Fig. 8.1.

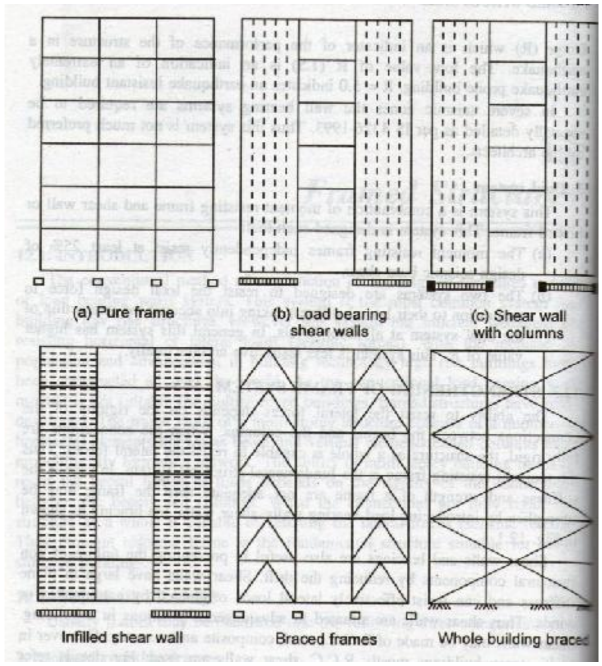

Fig. 8.1: Types of lateral resistive systems

8.1 Moment-resistive frames

There is some confusion over the name to be used in referring to frames in which interactions between members of the frame include the transfer of moments through the connections. In years past the term most frequently used was rigid frame. This term primarily from the classification of the connections or joints of the frame as fixed (or rigid) versus pinned, the latter term implying a lack of capability to transfer moment through the joint. As a general descriptive term, however, the name was badly conceived, since the frames of this type were generally the most deformable under lateral loading when compared to trussed frames or those braced by vertical diaphragms. In rigid frames with moment-resistive connections, both gravity and lateral loads produce interactive moments between the members. In most cases rigid frames are actually the most flexible of the basic types of lateral resistive systems. This deformation character, together with the required ductility, makes the rigid frame a structure that absorbs energy loading through deformation as well as through its sheer brute strength. The net effect is that the structure actually works less hard in force resistance because its deformation tends to soften the loading. Most moment-resistive frames consist of either steel or concrete. Steel frames have either welded or bolted connections between the linear members to develop the necessary moment transfers. Frames of concrete achieve moment connections through the monolithic concrete and the continuity and anchorage of the steel reinforcing. Because concrete is basically brittle and not ductile, the ductile character is essentially produced by the density of the reinforcing. The type and amount of reinforcing and the details of its placing become critical to the proper behavior of rigid frames of reinforcing concrete. For lateral loads in general, the rigid frame offers the advantage of a high degree of freedom in architectural terms. Walls and interior spaces are freed of the necessity for solid diaphragms or diagonal members. For building planning as a whole, this is a principle asset. Walls, even where otherwise required to be solid, need not be of a construction qualifying them as shear walls.

8.2 Braced frames

Bracings are the lateral resistive system used for reduction of responses and earthquake induced torsion in the building. Although there are actually several ways to brace a frame against lateral loads, the term braced frame is used to refer to frames that utilize trussing as the primary bracing technique. In buildings, trussing is mostly used for the vertical bracing system in combination with the usual horizontal diaphragms. It is also possible, however, to use a trussed frame for a horizontal system, or to combine vertical and horizontal trussing in a truly three-dimensional trussed framework. The latter is more common for open tower structures, such as those used for electrical transmission lines and radio and television transmitters.

8.3 Shear walls based frames

Shear walls are the lateral resistive system used for reduction of responses and earthquake induced torsion in the building. Shear walls are the walls constructed in structures to resist lateral load or forces developed due to wind or earthquake. Shear walls have a very large in plane stiffness and thus resist lateral loads and control deflection very efficiently. Shear wall being flexible in the perpendicular plane, they can transfer the lateral forces in their own plane by developing movement and shear resistance. Regarding the shapes of shear wall Rectangular-type, C-type and L-type cross section are used, out of which rectangular type is common. In the present study, the main focus is on the reduction of seismic induced torsion by providing shear walls.

9. BUILDING CHARACTERISTICS

- The seismic forces exerted on a building are not externally developed forces like wind instead they are the response of cyclic motions at the base of a building causing accelerations and hence inertia force.
- The response is therefore essentially dynamic in nature.
- The dynamic properties of the structure such as natural period, damping and mode shape play a crucial role in determining the response of the building.
- Besides other characteristics of the building system also affect the seismic response such as ductility, building foundation, response of non-structural elements etc.

9.1 Mode Shapes and Fundamental Period

- The elastic properties and mass of building cause to develop a vibratory motion when they are subjected to dynamic action.
- This vibration is similar to vibration of a violin string, which consists of a fundamental tone and the additional contribution of various harmonics.
- The vibration of a building likewise consists of a fundamental mode of vibration and the additional contribution of various modes, which vibrates at higher frequencies.
- Fundamental period of vibration can be determined by the code-based empirical for the fundamental modes of the building may be determined by any one of several methods developed for the dynamic analysis of structures.
- On the basis of time period, building may be classified as rigid ($T < 0.3$ sec), semi – rigid (0.3 sec $< T < 1.0$ sec) and flexible structure ($T > 1.0$ sec).
- Buildings with higher natural frequencies, and a short natural period, tend to suffer higher accelerations but smaller displacement.
- In the case of buildings with lower natural frequencies, and a long natural period, this is reversed: the buildings will experience lower accelerations but larger displacements.

9.2 Building Frequency and Ground Period

- Inertial forces generated in the building depend upon the frequencies of the ground on which the building is standing and the building's natural frequency.
- When these are near or equal to one another, the building's response reaches a peak level.
- Past studies show that the predominant period at a firm ground site 0.2 – 0.4 sec rigid

structure (0-0.3) will have more unfavourable seismic response than flexible structures, while period on soft ground can reach 2.0 sec or more.

- Seismic response of flexible structures (t>1.0) on soft foundation sites will be less favourable than that of rigid structure.
- Building fundamental periods of approximately 0.1N (where, N is the number of storey).

9.3 Damping

- The degree of structural amplification of the ground motion at the base of the building is limited by structural damping.
- Damping is the ability of the structural system to dissipate the energy of the earthquake ground shaking.
- Since the building response in inversely proportional to damping, the more damping in a building possesses, the sooner it will stop vibrating--which of course is highly desirable from the standpoint of earthquake performance.
- In a structure, damping is due to internal friction and the absorption of energy by the building's structural and non-structural elements.
- There is no numerical method available for determining the damping. It is only obtained by experiments.

9.4 Ductility

- Ductility is defined as the capacity of the building materials, systems, or structures to absorb energy by deforming in the inelastic range.
- The safety of building from collapse is on the basis of energy, which must be imparted to the structure in order to make it fail. In such instance, consideration must be given to structure’s capacity to absorb energy rather than to its resistance.
- Therefore ductility of a structure in fact is one of the most important factors affecting its earthquake performance.
- The primary task of an engineer designing a building to be earthquake resistant is to ensure that the building will possess enough ductility
- The ductility of a structure depends on the type of material used and also the structural characteristics of the assembly.
- It is possible to build ductile structures with reinforced concrete if care is taken in the design to provide the joints with sufficient abutments that can adequately confine the

concrete, thus permitting it to deform plastically without breaking.

9.5 Seismic Weight

- Seismic forces are proportional to the building weight and increases along the height of building.
- Weight reduction can be obtained by using lighter materials or by reducing the filling and other heavy equipments not essential for building construction.

9.6 Hyperstaticity / Redundancy

- Hyper static (statically indeterminate) structures have advantage because if primary system yields or fails, the lateral force can be redistributed to secondary elements or system to prevent progressive failure (alternate load path).
- Moreover, Hyperstaticity of the structure causes the formation of plastic hinges that can absorb considerable energy without depriving the structure of its stability.

9.7 Quality of Construction and Materials

- Grade of concrete not achieved in site – reasons.
- Poor execution of the concrete joint/ discontinuity- quality of concrete
- Reinforcement detailing not taken care of appropriately.
- Accumulation of sawdust, dust and loose materials at the surface of joint.
- Result: A defective concrete joint, which contributed significantly to causing of failure of many building in past earthquakes.

10. GENERAL PRINCIPLES OF EARTHQUAKE RESISTANT DESIGN

As earthquakes cannot be predicted accurately, magnitude, intensity and duration of earthquake must be estimated on the basis of available seismic history and geological information. Assuming successful prediction, even if all the population are evacuated safely, the structures cannot be saved from earthquakes. Therefore, earthquake resistant design of a structure is the only answer in minimizing the damaging effects of earthquakes on structures. For ordinary structures it is not feasible to undertake a special development of earthquake criteria. For each structure, instead, general design criteria are presented in the code which is applicable to regular structures of more or less uniform configurations. The design philosophy is developed on the basis of lessons learnt from the past earthquakes and analytical studies. For static analysis, elastic modulus of materials shall be taken unless otherwise mentioned

The following are the assumptions in the earthquake resistant design of structures:

1. Impulsive ground motions of earthquake are complex, irregular in character, changing in period and time and of short duration. They, therefore, may not cause resonance , except in tall structures founded on deep soft soils.
2. Wind, maximum flood or maximum will not occur simultaneously with the earthquake.

10.1 Objectives of Earthquake Resistant Design of Structures

Basically, the earthquake resistant design and construction is based on

(i) The philosophy of estimation of earthquake loading on a structure and

(ii) The philosophy for earthquake resistant design.

a. Estimation of Earthquake Loading

Earthquake cases random ground motion which can be resolved in any three mutually perpendicular directions. When such a motion strikes a structure resting on ground causes it to vibrate in horizontal and vertical directions. Earthquake forces in a structure are generated depending upon the intensity of the vibratory ground motion, and the mass and stiffness distribution, damping property of structure, and the manner in which it is supported on foundation. The random oscillatory earthquake load is in many ways different because of the uncertainty involved in estimating the earthquake intensity parameters.

b. Earthquake Resistant Design

The basic philosophy of earthquake resistant design is the provision of adequate strength and ductility against future expected severe earthquake. It is based on design for two levels of earthquake. One is Design Basis Earthquake (DBE) and other is Maximum Credible Earthquake (MCE).

õ Structures are designed to remain elastic during more frequent moderate size earthquake (DBE) by permitting the increase in permissible stresses, then check.

õ Structures are designed to resist infrequent most severe earthquake (MCE) allowing limited damage without collapse which may occur once in its useful life time.

It is uneconomical to design structures to withstand major earthquakes elastically. Therefore, the trend of the design is that the structure should have sufficient strength and ductility to withstand large tremors elastically. For this the interconnections of the members must be designed particularly to ensure sufficient ductility. Accordingly, the design approach adopted in IS 1893 (Part 1): 2002 is stated in cl 6.1.3 of the standard which is as follows:

The design approach is to ensure the following:

(a) that structures possess at least a minimum strength to withstand minor earthquakes ((DBE), which occur frequently, without damage;

(b) that structures resist moderate earthquakes (DBE) without significant structural damage though some non-structural damage may occur; and

(c) that structures withstand major earthquakes (MCE) without collapse.

11. METHODS OF EARTHQUAKE RESISTANT DESIGN CONSTRUCTION

The principles of earthquake resistance design are to evolve safe and economical design of structures to withstand possible future earthquakes. This can be achieved by (a) reducing the earthquake forces and (b) withstanding it by increasing the resistance of the structure. c) Planning consideration.

11.1 Reducing the earthquake forces

The structures can be safe guarded from damaging earthquake forces acting on a structure either by reducing earthquake forces or partially deflecting the earthquake energy from the structure by adopting any or a combination of the following procedures.

i) Use of light weight construction: Since, the earthquake force generated is proportional to the mass, a decrease in the mass of the structure by using the light weight materials, reduces the magnitude of seismic forces and hence increase the seismic safety of structures.

ii) Avoid quasi-resonance: Earthquake forces generated can be reduced by keeping the fundamental time period of the structure away from the predominant ground motion time period range.

iii) Diverting or absorbing the earthquake energy: Non-conventional design methods have been evolved to either deflect part of the earthquake force from the structure or to absorb a part of the earthquake energy in specially designed devices introduced in the structure so as the remaining earthquake force can be withstood by the structure without any damage. These are achieved by

- Base isolation technique, or
- Introducing energy dissipating devices in a structure or
- Introducing a combined isolation and energy absorbing devices.

iv) Neutralizing the earthquake forces: In this the building itself respond actively against earthquakes and tries to control the vibrations. Such buildings are also known as Dynamic Intelligent Building (DIB). This is achieved by Active Control System which consists of sensors to measure structural response, computer hardware and software to compute control forces n the basis of observed response and actuators to provide the necessary control forces.

11.2 Increasing the capacity of structure to resist earthquake

A structure can be safe guarded from earthquakes by increasing its resistance capacity by introducing earthquake resistant features.

11.3 Planning Considerations

In the very early stage of planning, the type of structure, the configuration, basic materials, and the framing of the structure have to be carefully chosen. The selections result in greatly improved and economical design of a structure and increase the seismic safety. The general building configuration problems are depicted in Fig. 4. following should be taken care as far as possible at the planning stage of structure

1. Proper selection of site: Considerable advantage can be gained by choosing the best site from the earthquake hazard point of view or the best type of structure for that site.
2. Use of proper material properties: The earthquake force is proportional to mass and therefore the building should be as light as possible. The material selected should have high strength to weight ratio, high deformability, high strength in compression, tension and shear.
3. Configuration of structure: Irregular configured buildings usually develop torsion due to seismic forces. Hence, the structural configuration should be as simple as possible

and symmetrical with respect to mass and rigidity so that the centers of mass and center of rigidity of the structure coincide with each other. If functional requirements dictate adoption of un-symmetry in the plan, then adjust the moments of inertia of shear walls so that the center of mass and center of stiffness of building coincides. Irregular shaped buildings may designed as a combination of regular shaped blocks.

4. Stiffness distribution: arbitrary position of infill walls, arbitrary introduction of bracings and stepped elevation cause sudden change in stiffness. Short columns attract lot of forces due to its high stiffness and liable to undergo damages and there fore be avoided.
5. Continuity of construction: All the elements of the building should be suitably tied so that all the resisting elements counter the earthquake forces as one unit without separating from each other.
6. Projecting parts: Projecting parts such as parapets, balconies, canopies be avoided as for as possible.
7. Ductile Provision: To avoid sudden collapse of the structure during earthquake and enable them to absorb energy beyond yield point, the main structural elements and their connections should be so designed such that the failure is of ductile nature. Ductile enables them to absorb energy by deformation.

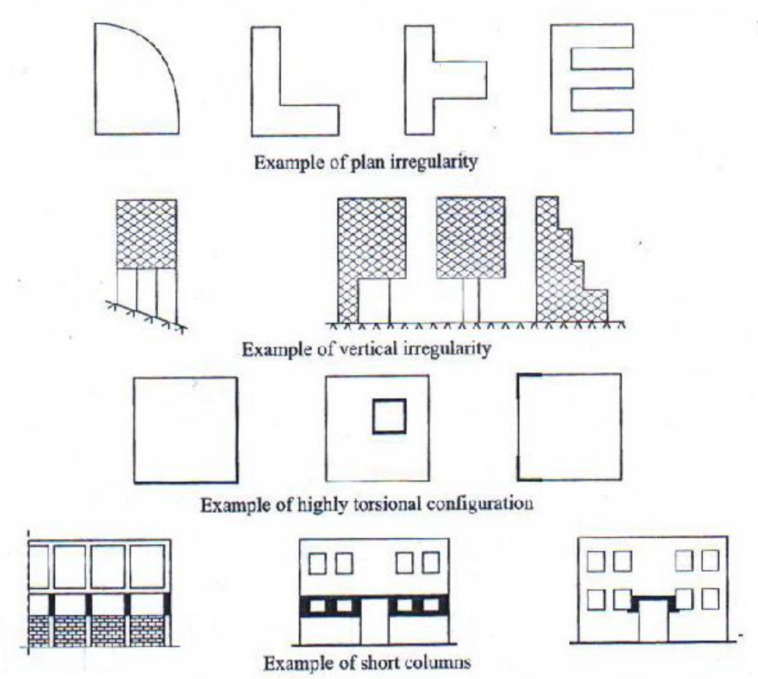

Fig. 11.1: The general building configuration problems

12. SEISMIC INDUCED TORSION

When the centre of mass and centre of rigidity does not coincide, torsional shear force will be induced on the structure in addition to the direct shear force. The horizontal load P_X (i.e. seismic force) will be acting at the centre of mass along X-direction, thus a torsional moment M_t is induced, that is equal to $P_X \times e_y$ (Fig. 12.1). The term 'e_y' equals, the distance between line of seismic force P_X (i.e. centre of mass, CM) and the line of resistive force V (i.e. centre of rigidity, CR) in Y-direction.

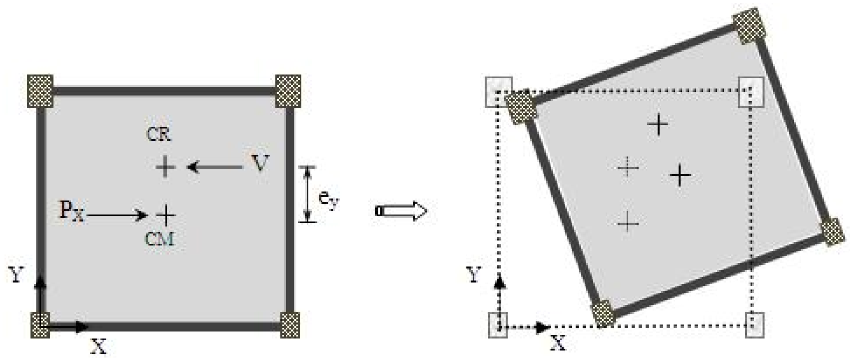

Fig. 12.1: Seismic response of plan-asymmetric building

Even in symmetrical structure, where the eccentricity (e) between mass centre and stiffness centre is zero, a minimum eccentricity amounting to 5% of the building dimension is assumed which is called 'accidental eccentricity' (e_a). The accidental eccentricity accounts for factors such as rotational component of ground motion about the vertical axis, the difference between computed and actual values of the mass, stiffness or yield strength and an unfavourable distribution of live load mass. When lateral forces are applied concurrently in two orthogonal directions, the accidental torsion should be applied only in the direction producing the greater effect.

Whenever there is significant torsion in a building, the concern is for additional seismic demands and lateral drifts imposed on the vertical elements by rotation of the diaphragm. Buildings can be designed to meet codal forces including torsion, but buildings with severe torsion are less likely to perform well in earthquakes. It is best to provide a balanced system at the start rather than design torsion into the system. As a consequence, two important concepts must be defined. These will enable the effects of building configuration on the response of structural systems to lateral forces to be better appreciated. In order to have a clear understanding about the seismic induced torsion, it is necessary to have a clear understanding of the following terms.

Centre of Mass (CM)

Centre of mass (CM) is a point through which the resultant of the masses of a system acts. This point corresponds to the centre of gravity of masses of the system. Hence the location of a force at a particular level will be determined by the centre of the accelerated mass at that level. During an earthquake, acceleration-induced inertia forces will be generated at each floor level and it will act at a point, where the mass of an entire story may be assumed to be concentrated. In buildings having symmetrical distribution of mass, the positions of the centres of floor masses will not differ from floor to floor. However, irregular mass distribution over the height of a building may result in variations in centres of masses at various floors. Depending on the direction of an earthquake-induced acceleration at any instant, the resultant force passing through centre of mass may act in any direction.

12.1 Centre of Rigidity (CR)

Centre of rigidity (CR) is the point through which the resultant of the restoring forces of a system acts. In regular buildings having uniform distribution of structural components, the position of centre of rigidity is constant for all floors. However, for buildings having asymmetrical distribution of structural members or irregular plan configurations like L, C, T, and Y- shape etc. the variation of centre of rigidity is significant over the height of the building.

13. INFLUENCE OF BUILDING CONFIGURATION ON SEISMIC RESPONSE

An aspect of seismic design of equal if not greater importance than structural analysis is the choice of building configuration. By observing the following fundamental principles, relevant to seismic response, more suitable structural systems may be adopted.

1. Simple, regular plans are preferable. Building with articulated plans such as T and L shapes should be avoided or be subdivided into simpler forms (Fig. 13.1).
2. Symmetry in plan should be provided where possible. Gross lack of symmetry may lead to significant torsional response, the reliable prediction of which is often difficult. Much greater damage due to earthquakes has been observed in buildings situated at street corners, where structural symmetry is more difficult to achieve, than in those along streets, where a more simple rectangular and often symmetrical structural plan could be utilized.
3. An integrated foundation system should tie together all vertical structural elements in

both principal directions. Foundations resting partly on rock and partly on soils should preferably be avoided.

4. Lateral-force-resisting systems within one building, with significantly different stiffnesses such as structural walls and frames, should be arranged in such a way that at every level symmetry in lateral stiffness is not grossly violated. Thereby undesirable torsional effects will be minimized.
5. Regularity should prevail in elevation, in both the geometry and the variation of storey stiffnesses.

The principles described above are examined in more detail in the following sections.

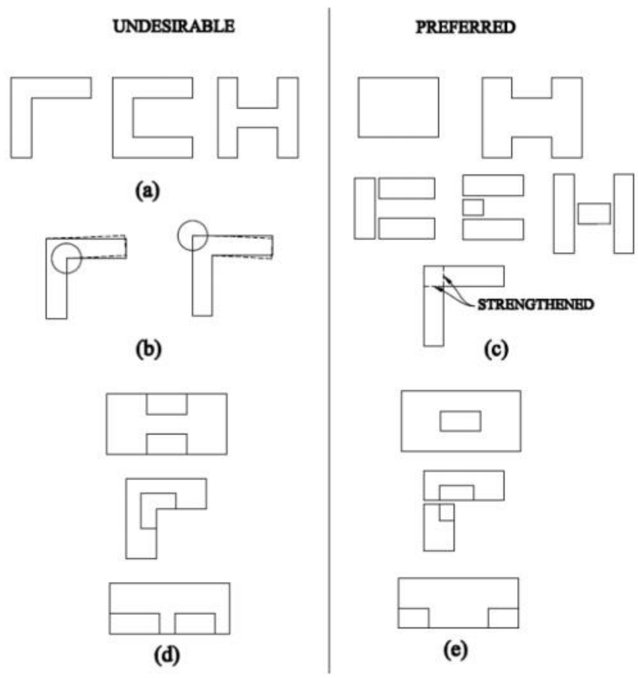

Fig. 13.1: Plan Configurations in Buildings

13.1 Torsion irregularities

Torsion irregularity shall be considered when floor diaphragms are rigid in their own plan in relation to the vertical structural elements that resist the lateral forces. Torsion irregularity is considered to exist when the maximum storey drift, computed with design eccentricity, at one end of the structure transverse to an axis is more than 1.2 times of the average storey at the two ends of the structures (Fig. 13.2).

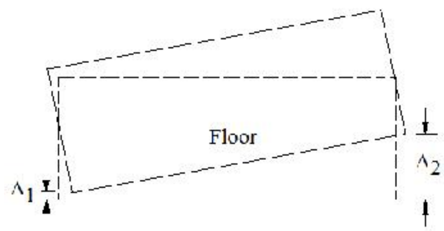

Fig. 13.2: Torsion irregularities with stiff diaphragm

The lateral force resisting elements should be well-balanced system that is not subjected to significant torsion. Significant torsion will be taken as the condition where the distance between the storey's center of rigidity and storey's center of mass is greater than 20% of the width of the structure in either major plan dimension. Torsion or excessive lateral deflection is generated in asymmetrical buildings, or eccentric and asymmetrical layout of the bracing system that may result in permanent set or even partial collapse. Torsion is most effectively resisted at point farthest away from the center of twist, such as at the corners and perimeter of the buildings.

13.2 Re-entrant corners

The re-entrant, lack of continuity or "inside" corner is the common characteristic of overall building configurations of an L, T, H, + due to lack of tensile capacity and force concentration. According to the code, plan configurations of a structure and its lateral force resisting system contains re-entrant corners, where both projections of the structure beyond the re-entrant corner are greater than 15% of its plan dimension in the given direction. The re-entrant corners of the buildings are subjected to two types of problems. The first is that they tend to produce variations of rigidity, and hence differential motions between different parts of the building, resulting in a local stress concentration at the notch of the re-entrant corner. The second problem is torsion. To avoid this type of damage, either provide a separation joint between two wings of buildings or tie the building together strongly in the system of stress concentration and locate resistance elements to increase the tensile capacity at re-entrant corner. In an L-shaped building shown in Fig. 13.3, when subjected to a ground motion, building attempt to move differently at their corner, pulling and pushing each other. So the stress concentration is high at the re-entrant corners.

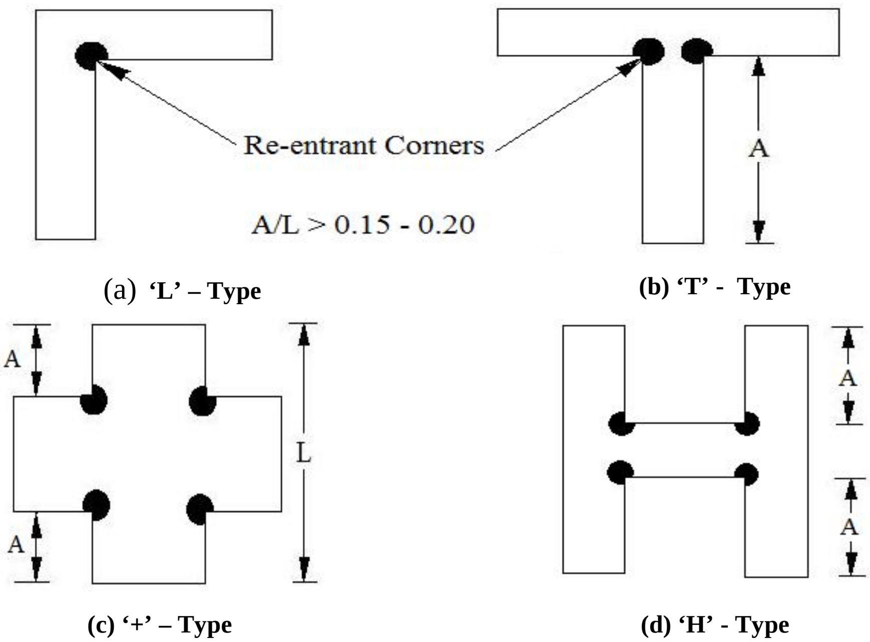

Fig. 13.3: Buildings with re-entrant corners

13.3 Non-parallel Systems

In some cases, vertical load resisting elements are not parallel or symmetrical about the major orthogonal axis of the lateral force resisting system of the building (Fig. 13.4). These situations are often faced by architects. This condition results in a high probability of torsional forces under a ground motion, because the centre of mass and centre of rigidity does not coincide.

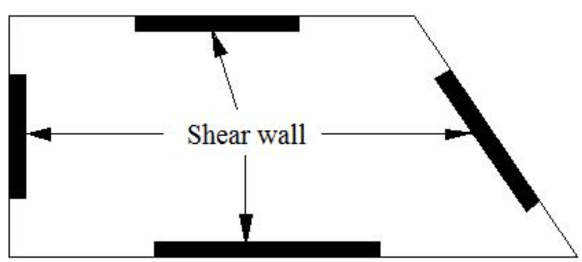

Fig. 13.4: Non-parallel systems

This problem is often exaggerated in the triangular or wedge shaped buildings resulting from street inter-sections at an acute angle. The narrower portion of the building will tend to be more flexible than the wider ones, which will increase the tendency of torsion.

13.4 Diaphragm Discontinuity

The diaphragm is a horizontal resistance element that transfers forces between vertical resistance elements. The diaphragm discontinuity may occur with abrupt variations in stiffness, including those having cut-off or open areas greater than 50% of the gross enclosed diaphragm area, or change in effective diaphragm stiffness of more than 50% from one storey to the next (Fig. 13.5). The diaphragm acts as a horizontal beam, and its edge acts as flanges. It is obvious that opening cut in tension flange of a beam will seriously weaken its load carrying capacity.

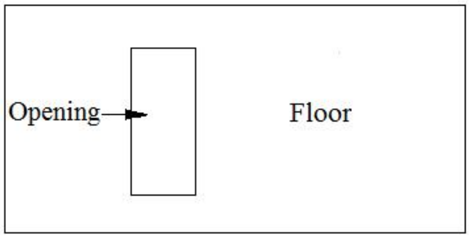

Fig. 3.13: (a) Diaphragm discontinuity

13.5 Vertical Configurations

A selection of undesirable and preferred configurations is illustrated in Fig. 13.14. Tall and slender buildings may require large foundations to enable large overturning moments to be transmitted in a stable manner. When subjected to seismic accelerations, concentration of masses at the top of a building will similarly impose heavy demands on both the lower storeys and the foundations of the structure.

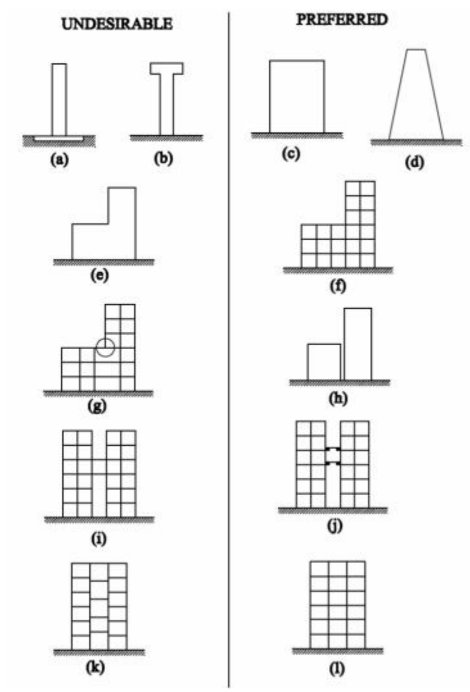

Fig. 13.14: Vertical Configurations of the Buildings

An abrupt change in elevation, such as shown in Fig. 13.14, also called a setback, may result in the concentration of structural actions at and near the level of discontinuity. The magnitudes of such actions, developed during the dynamic response of the building, are difficult to predict without sophisticated analytical methods. The separation into two simple, regular structural systems, with adequate separation between them, is a preferable alternative. Irregularities within the framing system, such as a drastic interference with the natural flow of gravity loads and that of lateral-force-induced column loads at the center of the frame must be avoided.

13.6 Stiffness Irregularity

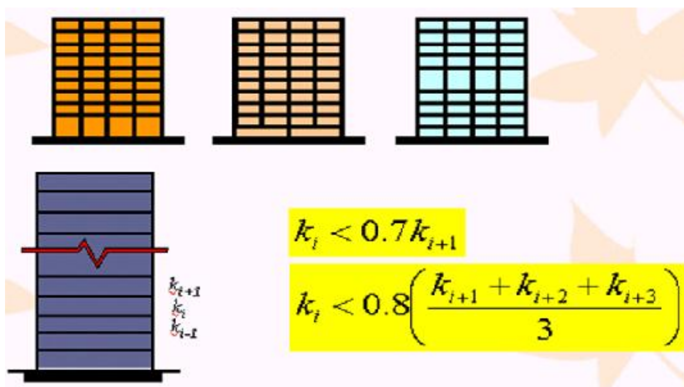

Fig. : Stiffness irregularity- Soft storey

A Soft Story is defined as one in which the lateral stiffness is less than 70% of that in the story above or less than 80% of the average stiffness of the three stories above (Fig.). In Extreme Soft Story the lateral stiffness is less than 60% of that in the story above or less than 70% of the average stiffness of the three stories above. A weak storey is defined as one in which the storey lateral strength is less than 80% of that in the storey above. The storey lateral strength is the total strength of all seismic resisting elements sharing the storey shear for the direction under consideration.

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