

Chapter 5

Earthquake-Resistant Design of Buildings

5.1 INTRODUCTION

Buildings subjected to earthquake shaking at their base oscillate back and forth in all three directions. Under low levels of shaking, their amplitudes of shaking and directions of shaking are dependant on how they are proportioned geometrically and in terms of stiffness throughout the building in plan and elevation. Under strong earthquake shaking, buildings undergo damage also. Controlling the damage type and sequence of damage in various structural elements is the main focus of *earthquake-resistant design*. It is possible to get a reasonable understanding of the overall mechanism of failure of the building by suitable nonlinear static analysis. Many deficiencies discussed in this document can be identified at the design stage itself, and the structural configurations and design and detailing of members modified to make the building resist the earthquake effects generated in the building during strong earthquake shaking.

Displacement-controlled loading subjected at the base of the building during earthquake shaking and *inelastic actions* accrued in them during strong shaking, together make *earthquake-resistant design* of buildings exciting and special. Inter-relationships between *analysis*, *design* and *behaviour* determine the overall seismic performance of a building. These inter-relationships exist in design of buildings for other loading actions also (*e.g.*, wind, wave, snow, and temperature). But, it is the expected inelastic actions in buildings under seismic conditions and the absence of the same under other load actions, which makes *understanding earthquake behaviour of buildings* challenging. *Analysis* and *design* both influence the earthquake behaviour of buildings (Figure 5.1). *Understanding seismic behaviour* is possible only through *suitable analyses* of building that captures all behavioural actions *possible* in buildings during earthquakes. And, *controlling seismic behaviour* is possible only through *faithful design* that ensures all behavioural actions *considered* in buildings during analysis. Between design and analysis also there are relationships. For designing a new building, design should *reflect* the analysis performed, and for assessing an existing building, analysis should *assess* the design performed.

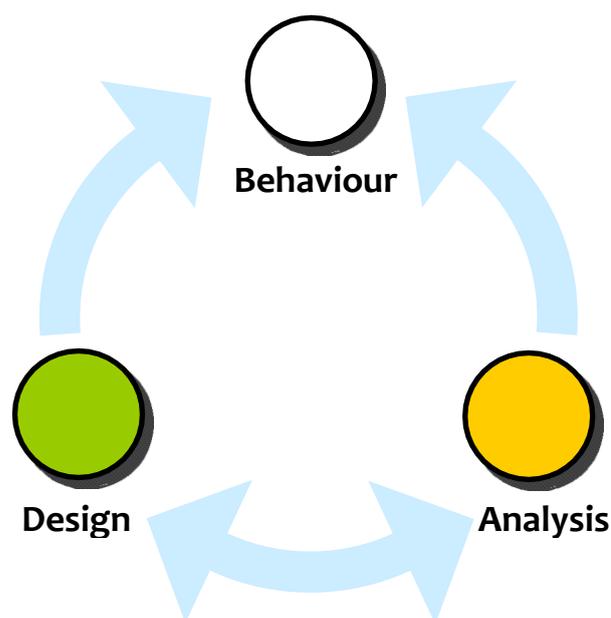


Figure 5.1: Inter-relations that affect Earthquake-Resistant Design of Buildings: Focus of earthquake-resistant design is desired earthquake behaviour

Thus, in earthquake-resistant design of *new buildings*, *design development process* involves (Figure 5.2):

- (1) Analysing the building to capture *desired* seismic behaviour, *i.e.*, performing suitable analyses of building to ensure *the limited expected behavioural actions ALONE* are realised in building during earthquake shaking;
- (2) Designing the building to reflect that *all assumptions made* in analysis *are honoured*, and thereby controlling desired seismic behaviour through design of the new building; and
- (3) Observing the building (during the next earthquake in the region where the building is built) to gain confidence in the design process or understand deficiencies in it.

But, in assessment of earthquake resistance of *existing buildings*, *safety assessment process* involves marginally separate steps (Figure 5.3) depending on whether the assessment is done after an earthquake or before it. For the pre-earthquake assessment, the steps involved are (Figure 5.3a):

- (1) Analysing the building to capture *possible* seismic behaviour, *i.e.*, performing suitable analyses of building to include *all possible behavioural actions* that can be CONCEIVED in building during earthquake shaking. Here, synthetic or recorded earthquake ground motions of *known characteristics* are employed to project the demand on the building;
- (2) Designing retrofit of each member (and thereby of the whole building) to *capture* the true behaviour that is *conceived in analysis* and *desired to be realized*, and thereby understanding the *likely seismic behaviour* of the existing building; and
- (3) Observing the building (during the next earthquake in the region where the building is built) to gain confidence in the retrofit design process or understand deficiencies in it.

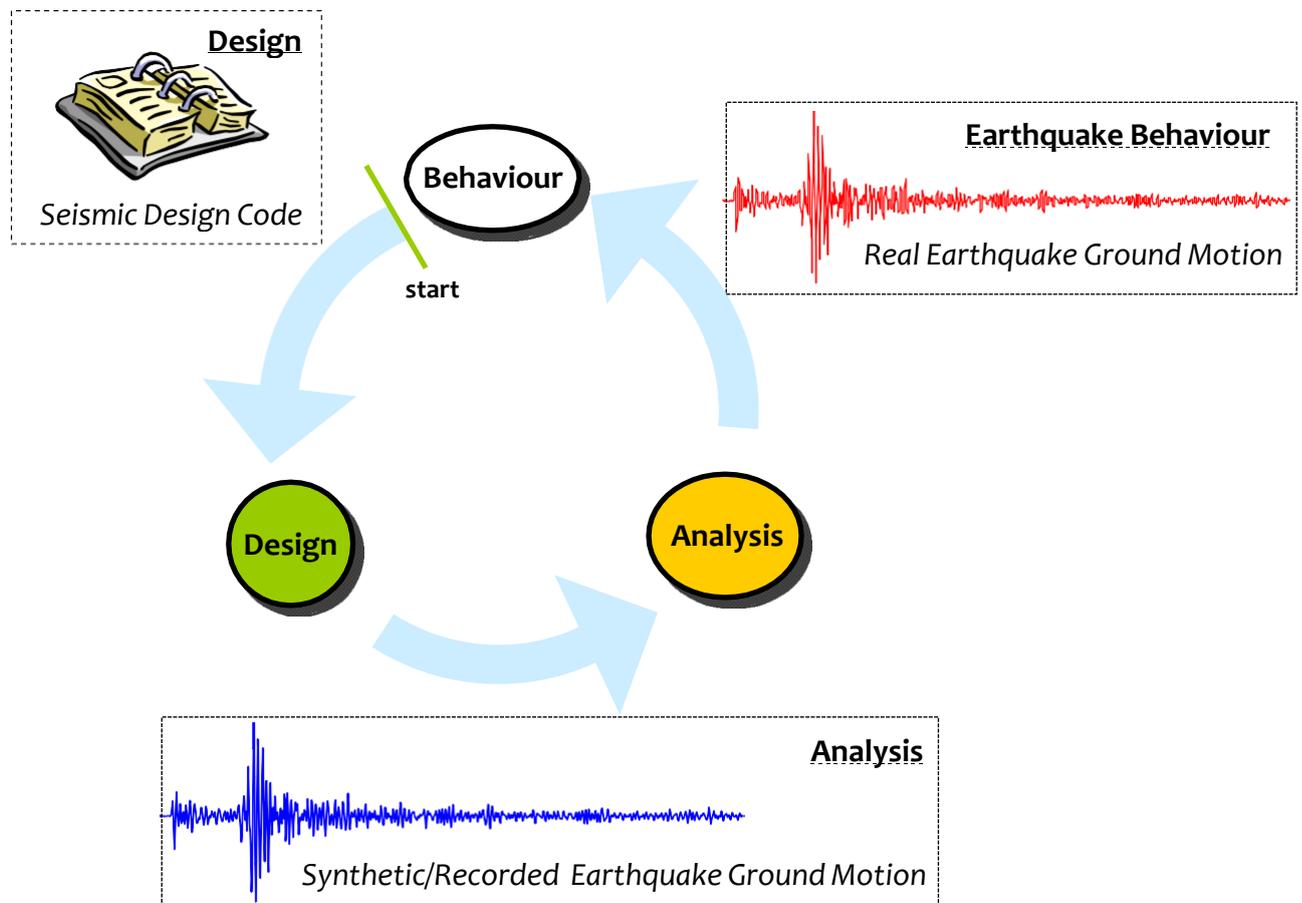
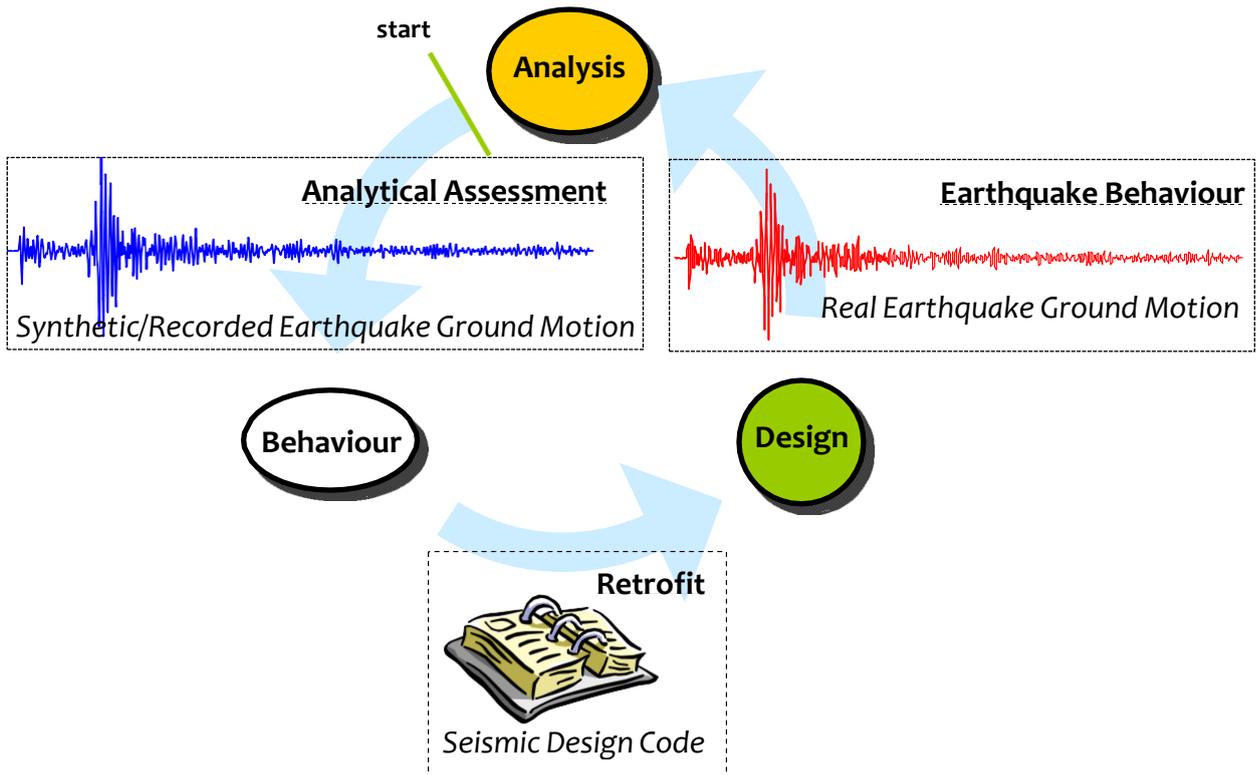


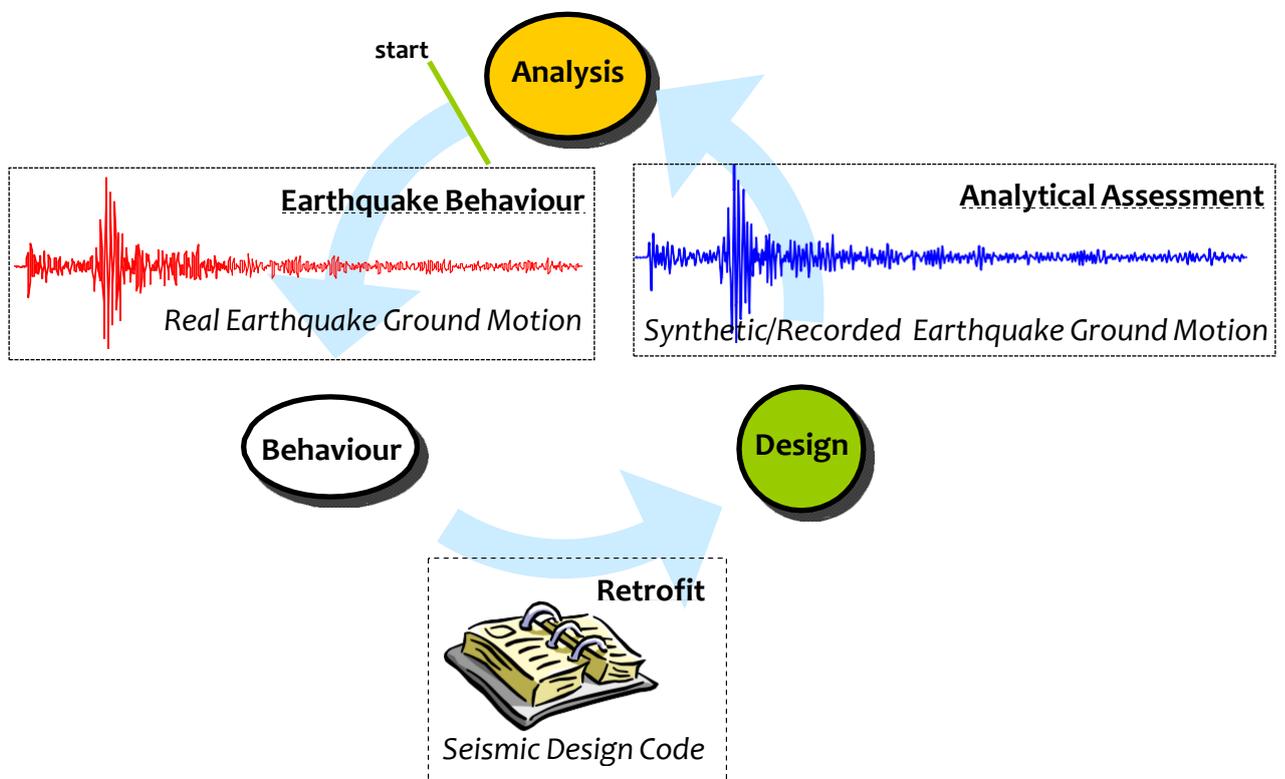
Figure 5.2: Earthquake Performance Assessment of NEW Buildings

And, for the post-earthquake assessment, the steps involved are (Figure 5.3b):

- (1) Observing the building (during the earthquake that occurred in the region where the building is built) to gain confidence in the design process or understand deficiencies in it;
- (2) Designing retrofit of each member (and thereby of the whole building) to *capture* the true behaviour that is *desired to be realized*, and thereby understanding the *likely seismic behaviour* of the existing building in the next earthquake; and
- (3) Analysing the building to capture *possible* seismic behaviour, *i.e.*, performing suitable analyses of building to include *all possible behavioural actions* that can be CONCEIVED in building during earthquake shaking. Here, synthetic or recorded earthquake ground motions of *known characteristics* are employed to project the demand on the building.



(a)



(b)

Figure 5.3: Earthquake Performance Assessment of EXISTING Buildings: (a) BEFORE Earthquake, and (b) AFTER Earthquake

5.2 EARTHQUAKE-RESISTANT DESIGN METHODS

The ideal lateral load-deformation (backbone) curve of a building under monotonic lateral displacement loading in pushover analysis reflects three clear features, namely *linear behaviour*, *onset of nonlinear behaviour* and *plastic behaviour* (Figure 5.4). These features may be used to identify three dominant ranges of structural behaviour in the sequence in which they appear, namely *elastic behaviour*, *early inelastic behaviour* and *ductile inelastic behaviour*. An important consequence of all these three characteristics together is *inelastic energy dissipation capacity* of the building.

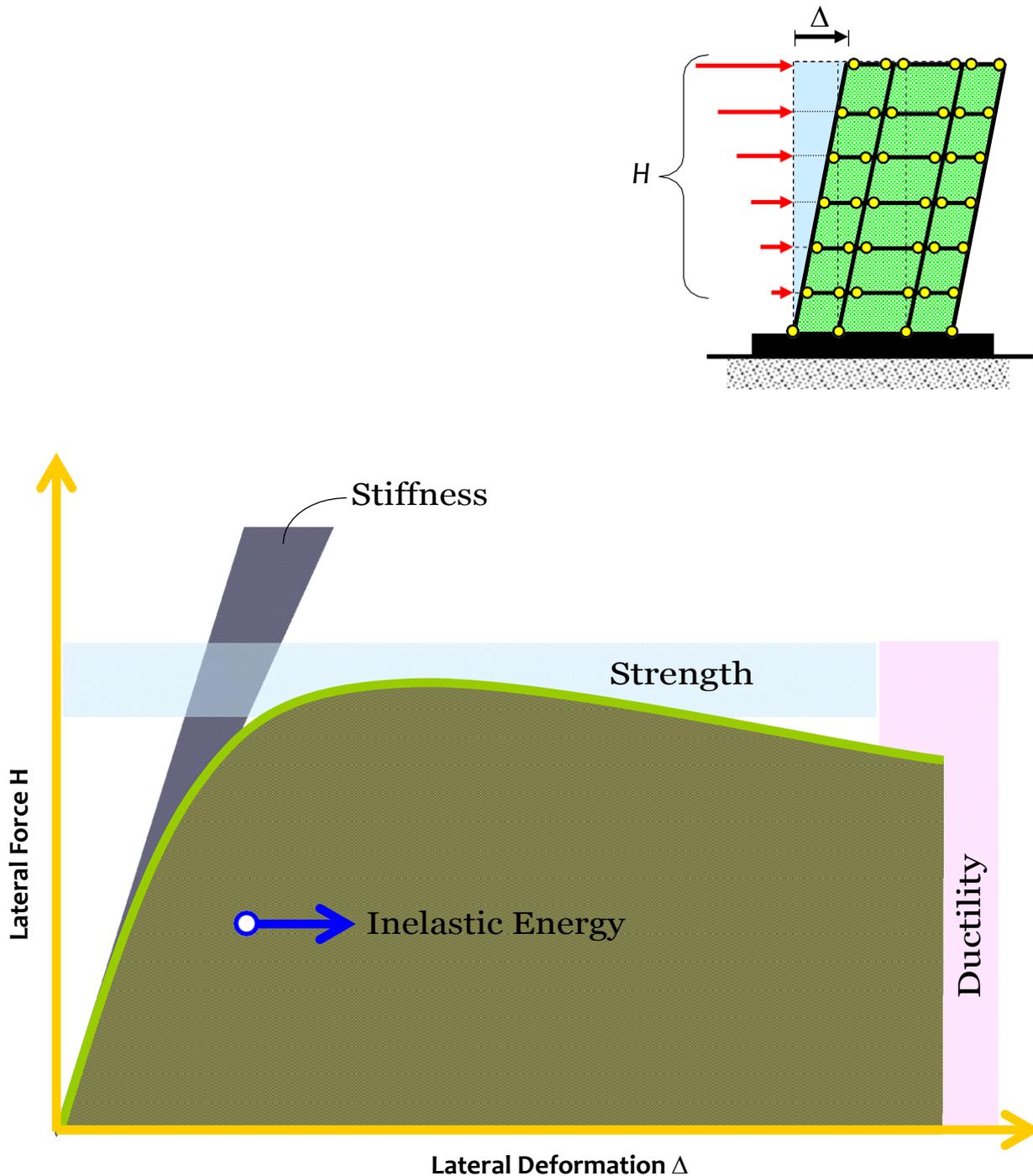
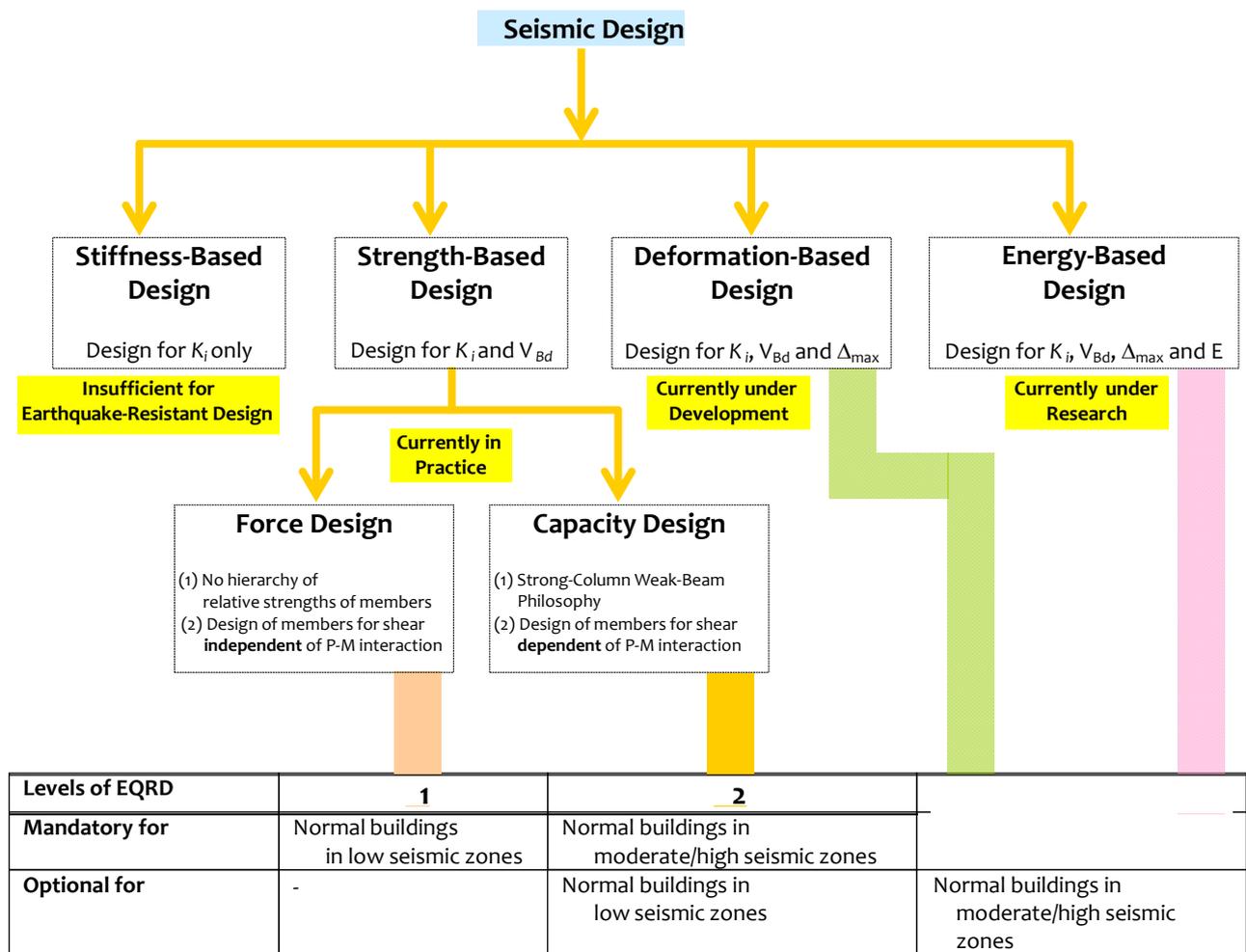


Figure 5.4: *Four Virtues of Earthquake-Resistant Buildings* control earthquake performance of buildings: *Stiffness*, *Strength* and *Ductility* directly affect load-deformation behaviour of buildings, while *Seismic Structural Configuration* affects these three virtues indirectly; *Energy Dissipation Capacity* is an overall consequence of all the four virtues of buildings

In keeping with the key characteristics of buildings (Figure 5.4), structural design of buildings can be *stiffness-based* (considering only *stiffness*), *strength-based* (considering *stiffness* and *strength*), *deformation-based* (considering *stiffness*, *strength* and *ductility*) or *energy-based* (considering *stiffness*, *strength*, *ductility* and *energy dissipation capacity*) (Figure 5.5). Strength-based design can be further classified as *Force Design* and *Capacity Design*. In the *former*, the design is based simply on the design lateral force on the building; members are designed to resist the stress-resultants obtained from linear structural analysis of the building subjected to code-specified design lateral forces. There is no pre-determined hierarchy of strengths across adjoining members and within each member. Within each member, the shear design of RC members is performed using the shear forces obtained from above structural analysis, and is *independent* of the design for axial forces and bending moments. In the *latter*, the design is based on BOTH the stress-resultants obtained from linear structural analysis of the building subjected to code-specified design lateral forces AND equilibrium-compatible stress-resultants derived from the pre-determined collapse mechanism. A pre-determined hierarchy of strengths is ensured both across adjoining members and within each member. Again within each member, the shear design of RC members is performed using larger of (a) the shear forces obtained from above structural analysis, and (b) plastic hinge based shear forces that are dependant on axial forces and bending moments.



CURRENT Earthquake Resistant Design Philosophies

Figure 5.5: Four broad methods available for Earthquake-Resistant Design: Rigour increases in each higher level method

Of the four methods of design, the *deformation-based design method* is the most advanced, and is expected to give best earthquake performance. It requires more engineering experience and judgment, but the results build more confidence in designers to arrive at a building that is more likely to perform as intended. Therefore, this method is best suited for special buildings, where earthquake performance of the building should be guaranteed, *e.g.*, critical and lifeline buildings that are required to remain functional after the earthquake. The *capacity design method* is best suited for normal buildings that are required to sustain moderate to severe seismic shaking. The *energy-based design method* is still under research. The *force design method* is known not to result in good seismic behaviour, and hence should be discouraged even in low seismic regions. But, owing to lack of adequate manpower and arguments of economy, it may be practiced for some more time.

5.3 EARTHQUAKE-RESISTANT DESIGN PROCEDURE

In keeping with the sequence in which the characteristics of buildings appear in the load-deformation behaviour of buildings (Figure 5.4), the current process of designing buildings has three stages, namely *Stiffness Design Stage*, *Strength Design Stage*, and *Ductility Design Stage*. Details are given below of steps involved in each of the three stages of seismic design of buildings.

5.3.1 Stiffness Design Stage

The main activities in this stage are:

- (1) *Choosing a seismic structural configuration*, that is expected to give desirable earthquake behaviour
 - (a) *Overall geometry* of the building of required height should be *convex*. It should be well proportioned, in keeping with elevation slenderness ratios and plan aspect ratios that have been observed in well-designed buildings. For instance, the proportioning of the building should be such that
 - (i) the maximum slenderness ratio (H/B) achieved in different well-designed buildings worldwide is generally found to be around 10, and that of maximum plan aspect ratio (L/B) to be around 4;
 - (ii) the absolute dimensions of buildings should not be unduly long to attract differential ground motion under different parts; for this a seismic wavelength analysis is required to understand the relative dimension of the building with respect to the predominant seismic wave;
 - (iii) the absolute plan area of the building should not be too large to attract large inertia force; and
 - (iv) the obvious irregularities as stated in the design codes and literature of standard should be minimised, if not entirely eliminated.
 - (b) *Structural system* chosen should be suitable for good earthquake performance, with vertical and horizontal members of lateral load resisting system (LLRS) that can carry earthquake effects safely during strong earthquake shaking. For instance, the structural system should
 - (i) be symmetrical in both directions in plan,
 - (ii) be regular in stiffness along elevation with gradually increasing stiffness towards the lower levels of the building (for instance, open ground storey buildings are unacceptable with sudden drop in lateral storey stiffness and lateral storey strength in the lower storey),
 - (iii) have many direct and short load paths, *i.e.*, the building should have large redundancy, but there should be no unexpected load paths that are not known at the time of design *e.g.*, short-column effects owing to lateral restraint offered by infills are unacceptable,
 - (iv) have no or only limited offsets in plan of the building, and
 - (v) no cut-outs in horizontal LLRS elements, *e.g.*, slabs should not have any cut-outs along their edges.

Also, just moment resisting frames may be unsuitable for resisting effects due to strong earthquake shaking in RC buildings; RC walls or braces should be used in buildings meant to be built in moderate to severe seismic zones.

This *proportioning of the building geometry* and *choosing the most suitable seismic structural configuration* is best achieved by an objective negotiation effort between the *architect* and *structural engineer* involved in the project.

(2) *Proportioning of Vertical LLRS members* in the structural system of the building

- (a) The structural plan density of vertical LLRS elements should be at least 4-8% along each direction in plan. Often, this cannot be achieved with just moment frames; structural walls are required, which run full height of the building and oriented along each plan directions.
- (b) The building should have at least a minimum amount of lateral stiffness, to ensure that deformation (and hence damage) is small under low and moderate shaking. In general, buildings with large lateral stiffness are preferred over those with small lateral stiffness.
- (c) The cross-section of each vertical member and its design (be it a structural steel or an RC column or structural wall) should be designed ideally to have the maximum axial load demand less than 30% of its uniaxial axial compression capacity.
- (d) The cross-section of each vertical column or structural wall should be such that difficulties do not arise with adjoining horizontal members in detailing of reinforcement bars in RC members and of connections in structural steel members.
- (e) The cross-section strengths of each vertical column or structural wall should be such that the vertical members are stronger than the adjoining horizontal members framing into them.

(3) *Modeling the structural system* of the building for structural analysis (on a computer)

Prepare a basic structural analysis model of the building with the dimensions and details obtained from preliminary design strategies. The analytical model of the building should

- (a) be a 3-dimensional one to be able to study dynamic behaviour, with all possible stiffness and masses of the building included in it; two-dimensional models are unacceptable, because seismic design codes require all buildings to be analysed with torsional effects with at least a minimum eccentricity between mass and stiffness at each floor level of the building; (classical literature requires that cracked moment of inertia properties be used in modeling moment frame members, e.g., $0.35I_{gross}$ for beams and $0.7I_{gross}$ for columns); and
- (b) include effect of soil flexibility where the underlying soil layers are either flexible or weak; in most such cases, the associated constitutive relation of soils is nonlinear. Sometimes, even a linear idealization of the soil flexibility can reveal significantly different structural actions.

(4) *Studying dynamic modes of oscillation* of the building

This is a critical step in evaluating suitability of the overall geometry, seismic structural configuration, and distribution of mass and stiffness of the building. An important feature that should be ensured is that

- (a) The building should have minimum, if not no, asymmetry in plan. In particular, the early modes of vibration should be the *pure LATERAL TRANSLATIONAL* modes of vibration, and NOT either the *diagonal translational* or the *torsional mode(s)* of vibration that result in poor performance of the building; and
- (b) The modal mass of early pure translational modes together should account for at least 90% of the mass of the building along each plan direction of the building, excluding that of the torsional modes of vibration. If this is not being achieved, the structural configuration, member proportioning, connectivity and/or material properties need to be changed to seek the desired pure translational behaviour in the early modes of vibration.

- (5) *Performing Linear Elastic Structural Analysis* of the building
- (a) Prepare the improved structural analysis model of the building with the dimensions and details obtained from the preliminary design calculations performed above. Estimate the approximate fundamental translational natural period T_a of the building, and calculate the design seismic base shear V_B on the building by the *Equivalent Lateral Force Design* procedure (sometimes called the *Seismic Coefficient Method*).
 - (b) Apply seismic code specified design lateral forces Q_i at each floor i of the building on the analytical model of the building, perform linear elastic structural analysis, and estimate the stress-resultants from all load combinations given in the seismic code. Estimate the lateral deformation in the building, under the various load combinations. If the governing lateral deformation is within the permissible lateral deformation in the building specified in the seismic design codes, the structural configuration and sizing adopted may be accepted. Else, the vertical LLRS should be made stiffer to arrive at a revised structural configuration of the building.
 - (c) Perform *Linear Dynamic Structural Analysis* of the building for buildings that are irregular, tall, long, important and in high seismic zones. This can be done in two ways, using *recorded/synthetic ground motion time histories* or *design response spectrum*. Some codes categorically require that the *seismic base shear* from the *Response Spectrum Method* of analysis should not fall below that obtained from the *Seismic Coefficient Method*, even though the displacements estimated by the former method can exceed those by the latter.

5.3.2 Strength Design Stage

The main activities in this stage are:

- (6) *Choosing relative member flexural strength ratio* to seek desired collapse mechanism
- (a) Identify a desired collapse mechanism of the structural system in which the building should deform in, under the extreme condition of collapse, if ever, when the strong earthquake shaking exceeds the design earthquake shaking for which buildings are normally designed. Determine the locations and type of inelastic actions that are desired in the building.
 - (b) Perform *Capacity Design* of all members, to ensure strength hierarchy is such that *shear failure* is preceded by *large flexural plastic actions*, and that the plastic actions are localized to only to the desired locations as identified in step 6(a) above. In doing so, the *beam-to-column design moment strength ratio* in *moment-resisting frame buildings* or *frame-structural wall buildings* may take values much higher than those normally recommended in some seismic codes.
- (7) *Performing seismic design* of all structural elements of the building
- (a) Design the slabs of the building.
 - (b) Design each beams for *flexure* for the governing moment demand obtained from the load combinations. Then, design these beams for *shear*, by the *capacity design method* and in line with the plastic hinges in the identified desired collapse mechanism.
 - (c) Design all columns and structural walls for *flexure*, for the governing axial force and bending moment combinations specified by the seismic design code, and for the stress-resultants arising out of an additional special load combination of the building with overstrength plastic moment hinges as per identified desirable collapse mechanism. Then, design the columns for *shear*, for the shear demand from the load combinations specified by the seismic design code and for that arising out of an additional special load combination based on the capacity design method for design of shear considering the plastic hinges in beams as per identified desirable collapse mechanism. RC columns and RC walls should be designed to have all design points within the tension failure region on the *P-M* interaction diagram, *i.e.*, usually to have axial load demand to be about less than 30% of the uniaxial compression capacity of the section. Members of RC moment-resisting frame buildings need to have few more important features, namely:
 - (i) the column should be much wider than the beam (in both directions) to allow beam bars to be passed into/through column without cranking;

- (ii) the longitudinal bars in beams should adopt standard hook detailing at the end, to avoid constructional difficulties of anchoring beam bars into the adjoining column.
- (d) Design the beam-to-column and beam-to-wall joints to have shear stresses within the permissible values specified in seismic design code.
- (e) Design foundation(s) of the building in keeping with the capacity of the soil underneath it.

5.3.3 Ductility Design Stage

The main activities in this stage are:

- (8) *Detailing all members and their connections* to ensure ductility in required members and prevent undesired actions in other members
 - (a) Provide confining transverse reinforcement in all ductile RC beams as per the requirements specified in the seismic detailing code (including close spacing, closed loops with 135° hooks, and at least the minimum specified lengths at hook ends).
 - (b) Provide design transverse reinforcement in all RC columns and RC walls as per design calculations (including close spacing, closed loops with 135° hooks, and at least the minimum specified lengths at hook ends).
- (9) *Verifying that the desired mechanism is generated in the building*
 - (a) *Prepare the structural analysis model* for performing *nonlinear quasi-static displacement pushover analysis (PoA)* and *nonlinear time history analysis (NL THA)*.
 - (b) *Perform PoA* of the building with lateral force profile as per code-specified distribution of design lateral forces. Understand the deformability under design lateral force loading and collapse mechanism generated. And, determine if the design of the building needs to be revised. If the collapse mechanism obtained is not the desirable one, revise the seismic structural configuration and repeat the above steps from step 1, till the desired mechanism is achieved. If the collapse mechanism obtained is the desirable one, go to the next step 9(c).
 - (c) *Choose a suite of ground motions* that reflect possible ground motions that are likely to occur at the location of the building. These could include far field type motions, and near-field type motions, if applicable. And, they could reflect the type of soil on which the building is constructed. Ensure that the level of their intensity and frequency spectrum are at least those specified by the seismic design code. *Perform NL THA* of the building under all ground motions identified, to capture the type of mechanism that can be generated under the building. Study the collapse mechanism generated, if any.
 - (d) If the desirable mechanism is not achieved, make suitable changes in the building in step 1 (*e.g.*, through design of members, structural system, ductile detailing, and/or choice of materials), and perform all activities under *stiffness design* and *strength design stages*.
 - (e) If the desired mechanism is achieved, prepare requisite structural drawings as per the detailing chosen in design and analysis.

