Chapter 1

Earthquake-Resistant Buildings

1.1 DYNAMIC ACTIONS ON BUILDINGS – WIND *versus* EARTHQUAKE

Dynamic actions are caused on buildings by both *wind* and *earthquakes*. But, design for wind forces and for earthquake effects are distinctly different. The intuitive philosophy of structural design uses *force* as the basis, which is consistent in wind design, wherein the building is subjected to a *pressure* on its exposed surface area; this is *force-type* loading. However, in earthquake design, the building is subjected to random motion of the ground at its base (Figure 1.1), which induces inertia forces in the building that in turn cause stresses; this is *displacement-type* loading. Another way of expressing this difference is through the load-deformation curve of the building – the demand on the building is *force* (*i.e., vertical axis*) in force-type loading imposed by wind pressure, and *displacement* (*i.e., horizontal axis*) in displacement-type loading imposed by earthquake shaking.

Wind force on the building has a non-zero mean component superposed with a relatively small oscillating component (Figure 1.2). Thus, under wind forces, the building may experience small fluctuations in the stress field, but reversal of stresses occurs only when the direction of windreverses, which happens only over a large duration of time. On the other hand, the motion of the ground during the earthquake is cyclic about the neutral position of the structure. Thus, the stressesin the building due to seismic actions undergo many complete reversals and that too over the smallduration of earthquake.

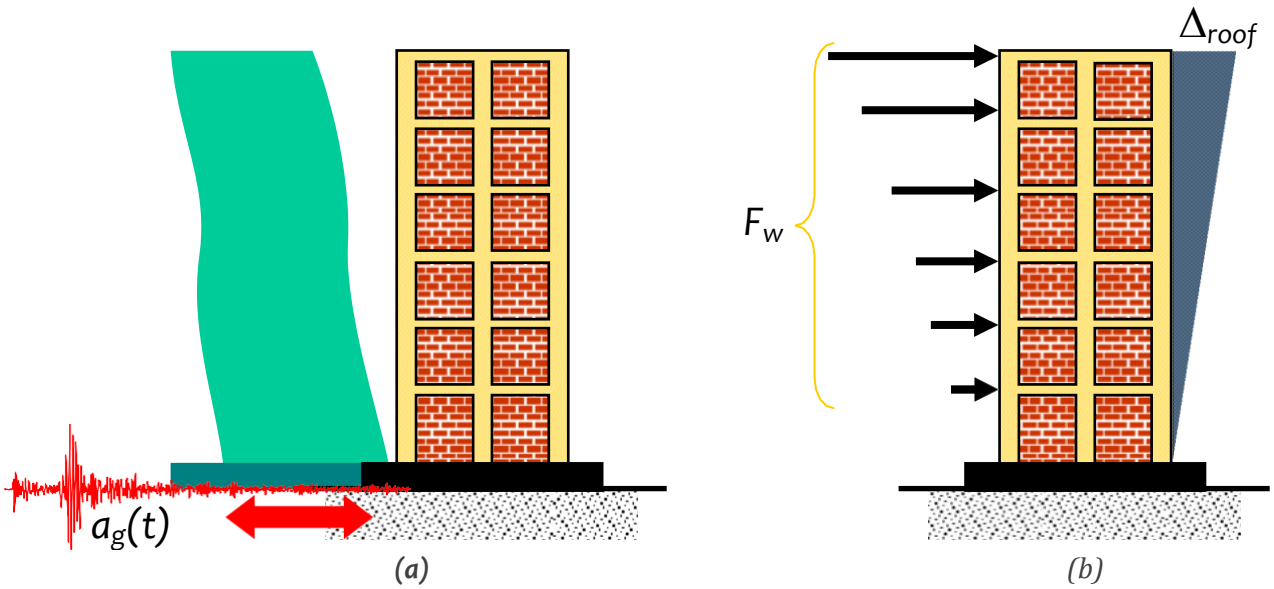


Figure 1.1: Difference in the design effects on a building during natural actions of (a) Earthquake *Ground Movement* at base, and (b) Wind *Pressure* on exposed area

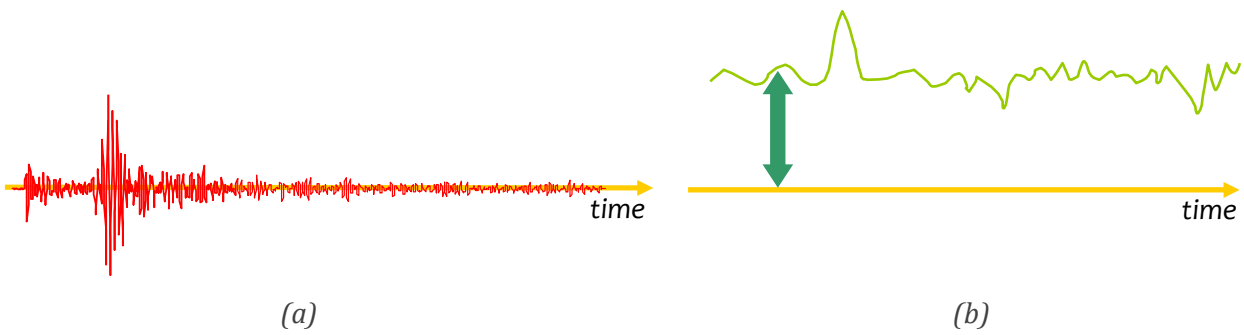


Figure 1.2: *Nature of temporal variations of design actions*: (a) Earthquake Ground Motion – zero mean,cyclic,

and (b) Wind Pressure – non-zero mean, oscillatory

1.2 BASIC ASPECTS OF SEISMIC DESIGN

The *mass* of the building being designed controls seismic design in addition to the building *stiffness*, because earthquake induces *inertia forces* that are proportional to the building mass. Designing buildings to behave elastically during earthquakes without damage may render the project economically unviable. As a consequence, it may be necessary for the structure to undergo damage and thereby dissipate the energy input to it during the earthquake. Therefore, the traditional *earthquake-resistant design* philosophy requires that normal buildings should be able to resist (Figure 1.3):

(a) *Minor (and frequent) shaking* with no damage to structural and non-structural elements;

(b) *Moderate shaking* with minor damage to structural elements, and some damage to non-structural elements; and

(c) *Severe (and infrequent) shaking* with damage to structural elements, but with NO collapse (to save life and property inside/adjoining the building).

Therefore, buildings are designed only for a fraction (~8-14%) of the force that they would experience, if they were designed to remain elastic during the expected strong ground shaking (Figure 1.4), and thereby permitting damage (Figure 1.5). But, sufficient initial stiffness is required to be ensured to avoid structural damage under minor shaking. Thus, seismic design balances reduced cost and acceptable damage, to make the project viable. This careful balance is arrived based on extensive research and detailed post-earthquake damage assessment studies. A wealth of this information is translated into precise seismic design provisions. In contrast, structural damage is not acceptable under design wind forces. For this reason, design against earthquake effects is called as *earthquake-resistant design* and not *earthquake-proof design*.

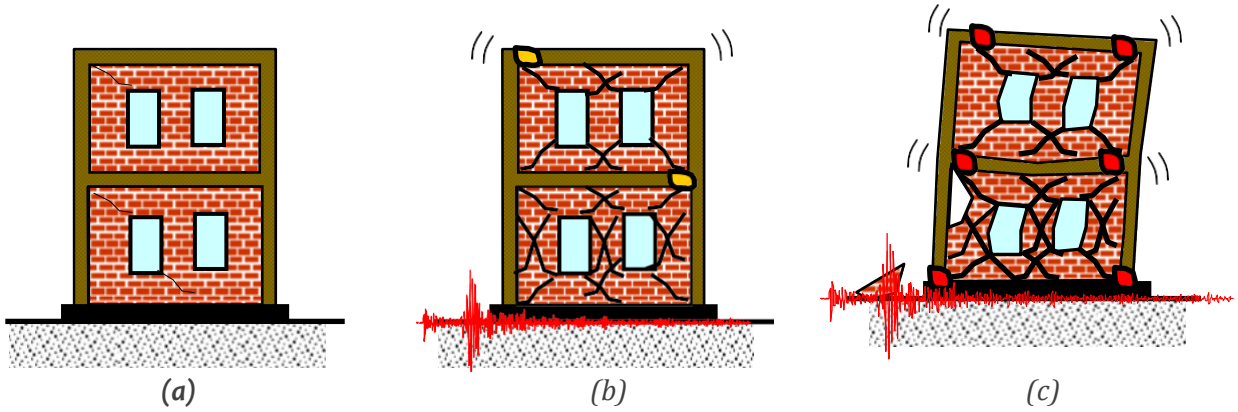


Figure 1.3: *Earthquake-Resistant Design Philosophy for buildings*: (a) *Minor (Frequent) Shaking* – No/Hardly any damage, (b) *Moderate Shaking – Minor structural damage, and some non-structural damage*, and (c) *Severe (Infrequent) Shaking* – Structural damage, but NO collapse

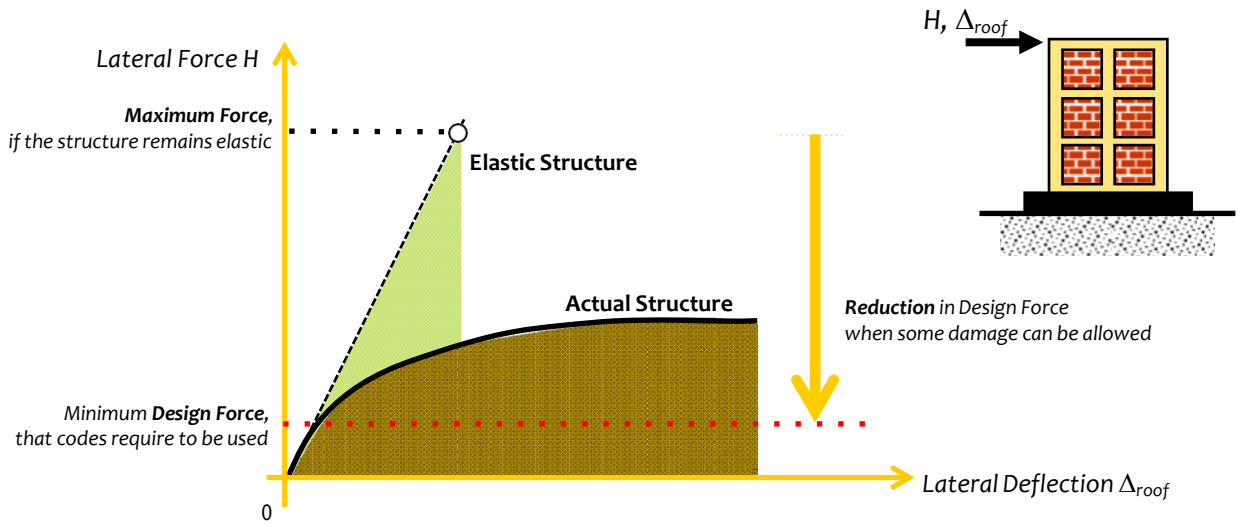


Figure 1.4: *Basic strategy of earthquake design*: Calculate maximum elastic forces and reduce by a factor to obtain design forces.

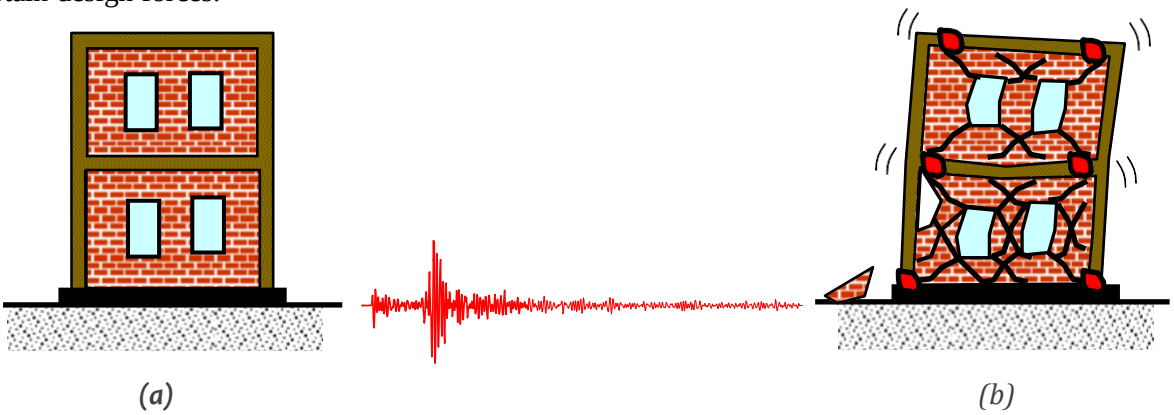


Figure 1.5: *Earthquake-Resistant* and NOT *Earthquake-Proof:* Damage is expected during an earthquake in normal constructions (a) undamaged building, and (b) damaged building.

The design for only a fraction of the elastic level of seismic forces is possible, only if the building can stably withstand large displacement demand through structural damage without collapse and undue loss of strength. This property is called *ductility* (Figure 1.6). It is relatively simple to design structures to possess certain lateral strength and initial stiffness by appropriately proportioning the size and material of the members. But, achieving sufficient ductility is more involved and requires extensive laboratory tests on full-scale specimen to identify preferable methods of detailing.

In summary, the loading imposed by earthquake shaking under the building is of *displacement-type* and that by wind and all other hazards is of *force-type*. Earthquake shaking requires buildings to be capable of resisting certain relative displacement within it due to the imposed displacement at its base, while wind and other hazards require buildings to resist certain level of force applied on it (Figure 1.7a). While it is possible to estimate with precision the maximum force that can be imposed on a building, the maximum displacement imposed under the building is not as precisely known. For the same maximum displacement to be sustained by a building (Figure 1.7b), wind design requires only *elastic* behaviour in the entire range of displacement, but in earthquake design there are two options, namely design the building to remain elastic or to undergo inelastic behaviour. The latter option is adopted in normal buildings, and the former in special buildings, like critical buildings of nuclear power plants.

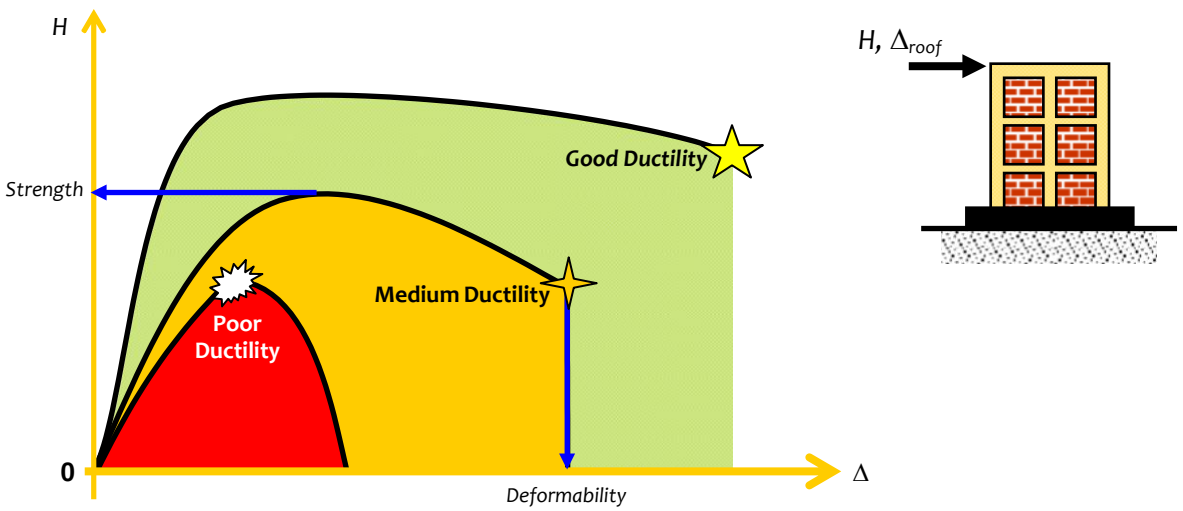
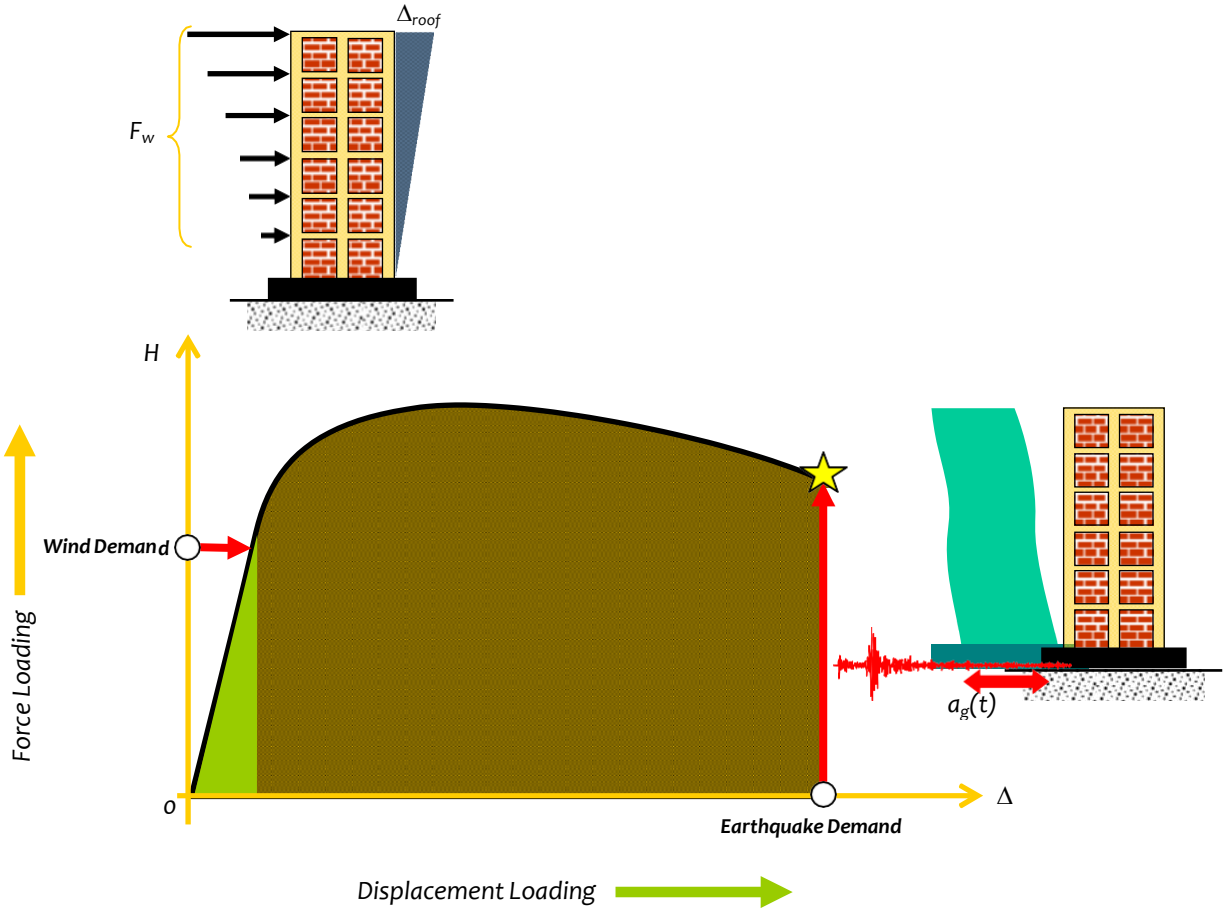
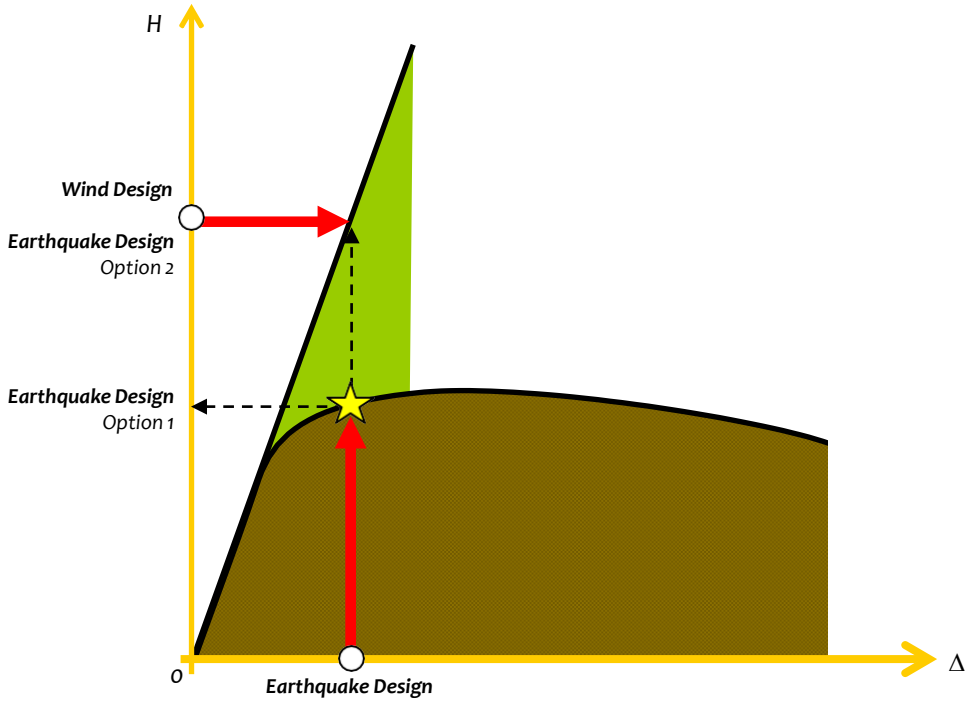


Figure 1.6: *Ductility*: Buildings are designed and detailed to develop favorable failure mechanisms that possess specified lateral strength, reasonable stiffness and, above all, good post-yielddeformability.



(a)



(b)

Figure 1.7: *Displacement Loading versus Force Loading*: Earthquake shaking imposes displacement loading on the building, while all other hazards impose force loading on it

1.3 THE FOUR VIRTUES OF EARTHQUAKE RESISTANT BUILDINGS

For a building to perform satisfactorily during earthquakes, it must meet the philosophy of *earthquake-resistant* design discussed in Section 1.2.

1.3.1 Characteristics of Buildings

There are four aspects of buildings that architects and design engineers work with to create the earthquake-resistant design of a building, namely *seismic structural configuration*, *lateral stiffness*, *lateral strength* and *ductility*, in addition to other asepcts like form, aesthetics, functionality and comfort of building. Lateral stiffness, lateral strength and ductility of buildings can be ensured by strictly following most seismic design codes. But, good seismic structural configuration can be ensured by following coherent architectural features that result in good structural behaviour.

(a) Seismic Structural Configuration

Seismic structural configuration entails three main aspects, namely (a) geometry, shape and size of the building, (b) location and size of structural elements, and (c) location and size of significant non-structural elements (Figure 1.8). Influence of the geometry of a building on its earthquake performance is best understood from the basic geometries of *convex* and *concave* lenses from school-day physics class (Figure 1.9). The line joining any two points within area of the convex lens, lies completely within the lens. But, the same is not true for the concave lens; a part of the line may lie outside the area of the concave lens. Structures with *convex* geometries are preferred to those with concave geometries, as the former demonstrate superior earthquake performance. In the context of buildings, convex shaped buildings have direct load paths for transferring earthquake shaking induced inertia forces to their bases for any direction of ground shaking, while concave buildings necessitate bending of load paths for shaking of the ground along certain directions that result in stress concentrations at all points where the load paths bend.

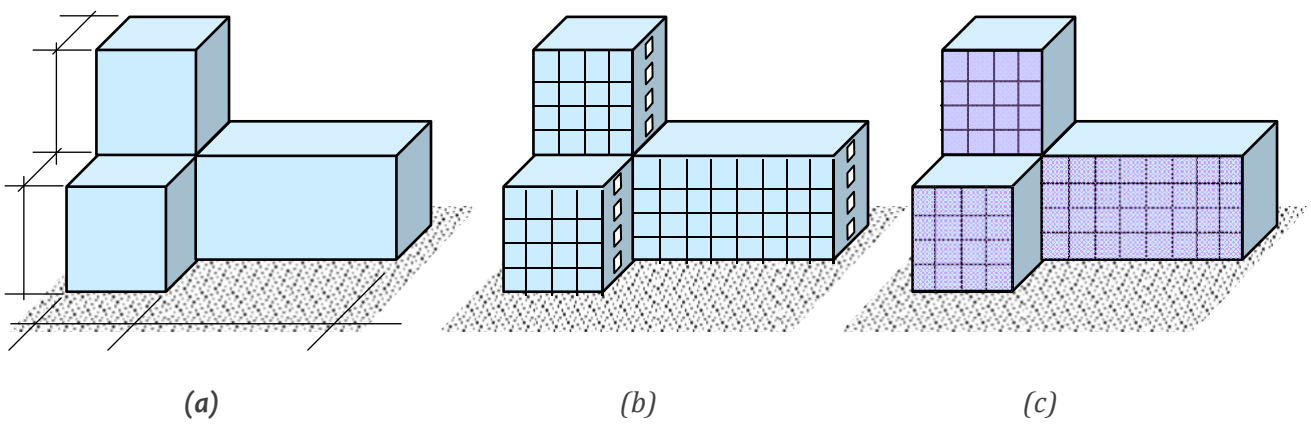
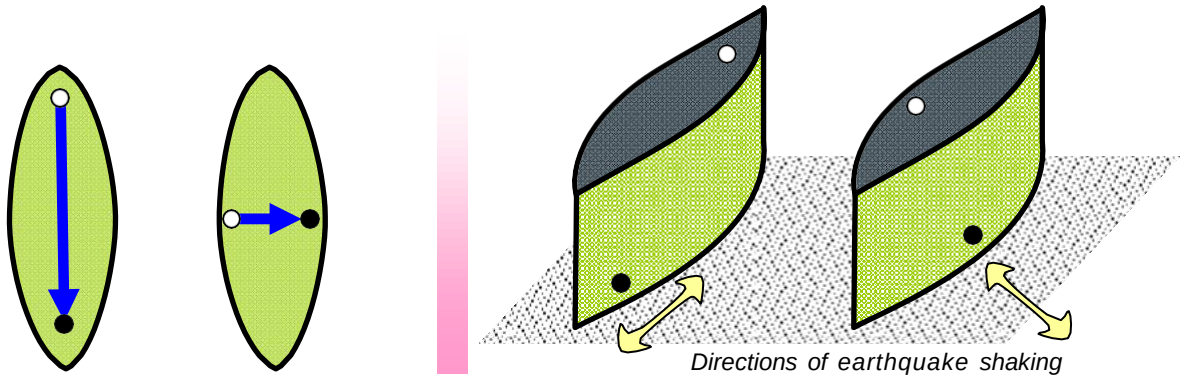
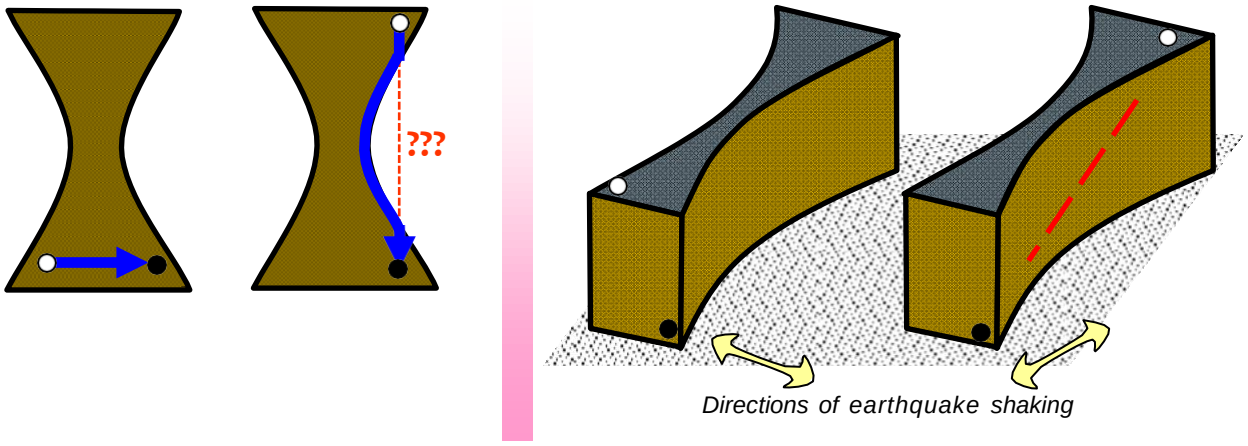


Figure 1.8: *Components of seismic structural configuration*: (a) overall geometry, (b) structural elements (*e.g.*,

moment resisting frames and structural walls), and (c) significant non-structural elements(*e.g.*, façade glass)



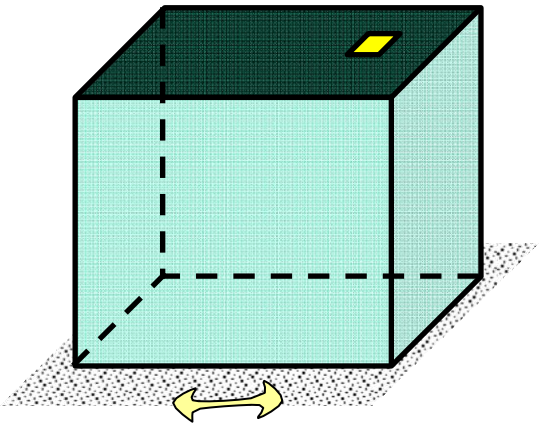
(a)



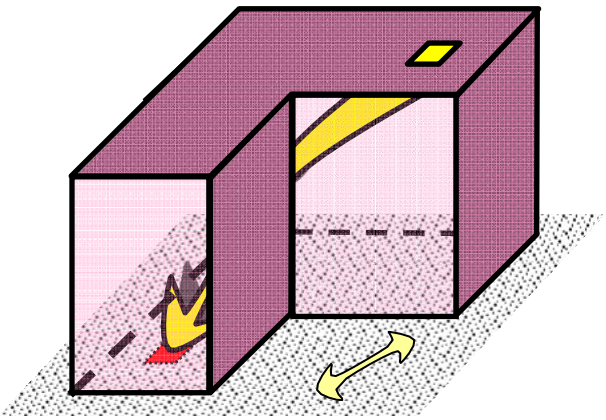
(b)

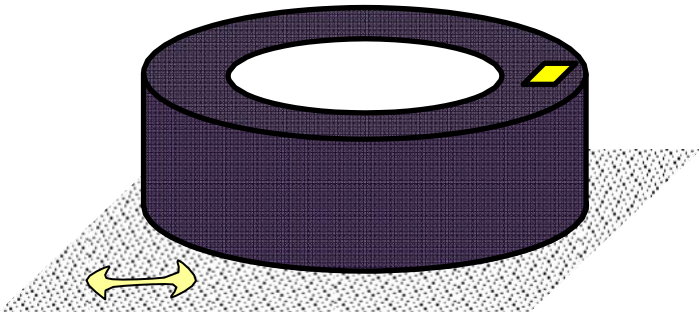
Figure 1.9: *Basic forms of seismic structural configuration*: Two geometries of architectural forms (a) convex, and (b) concave

Based on the above discussion, normally built buildings can be placed in two categories, namely *simple* and *complex* (Figure 1.10). Buildings with rectangular plans and straight elevation stand the best chance of doing well during an earthquake, because inertia forces are transferred without having to bend due to the geometry of the building (Figure 1.10a). But, buildings with setbacks and central openings offer geometric constraint to the flow of inertia forces; these inertiaforce paths have to bend before reaching the ground (Figure 1.10b, 10c)



(a)





(b) *(c)*

Figure 1.10: *Classification of buildings*: (a) Simple, and (b), (c) Complex

(b) Structural Stiffness, Strength and Ductility

The next three overall properties of a building, namely *lateral stiffness*, *lateral strength* and *ductility*, are illustrated in Figure 1.11, through the *lateral load – lateral deformation* curve of the building. *Lateral stiffness* refers to the *initial* stiffness of the building, even though stiffness of the building reduces with increasing damage. *Lateral strength* refers to the maximum resistance that the building offers during its entire history of resistance to relative deformation. *Ductility* towards lateral deformation refers the ratio of the maximum deformation and the idealised yield deformation. The maximum deformation corresponds to the maximum deformation sustained by it, if the load-deformation curve does not drop, and to 85% of the ultimate load on the dropping side of the load-deformation response curve after the peak strength or the lateral strength is reached, if the load-deformation curve does drop after reaching peak strength.

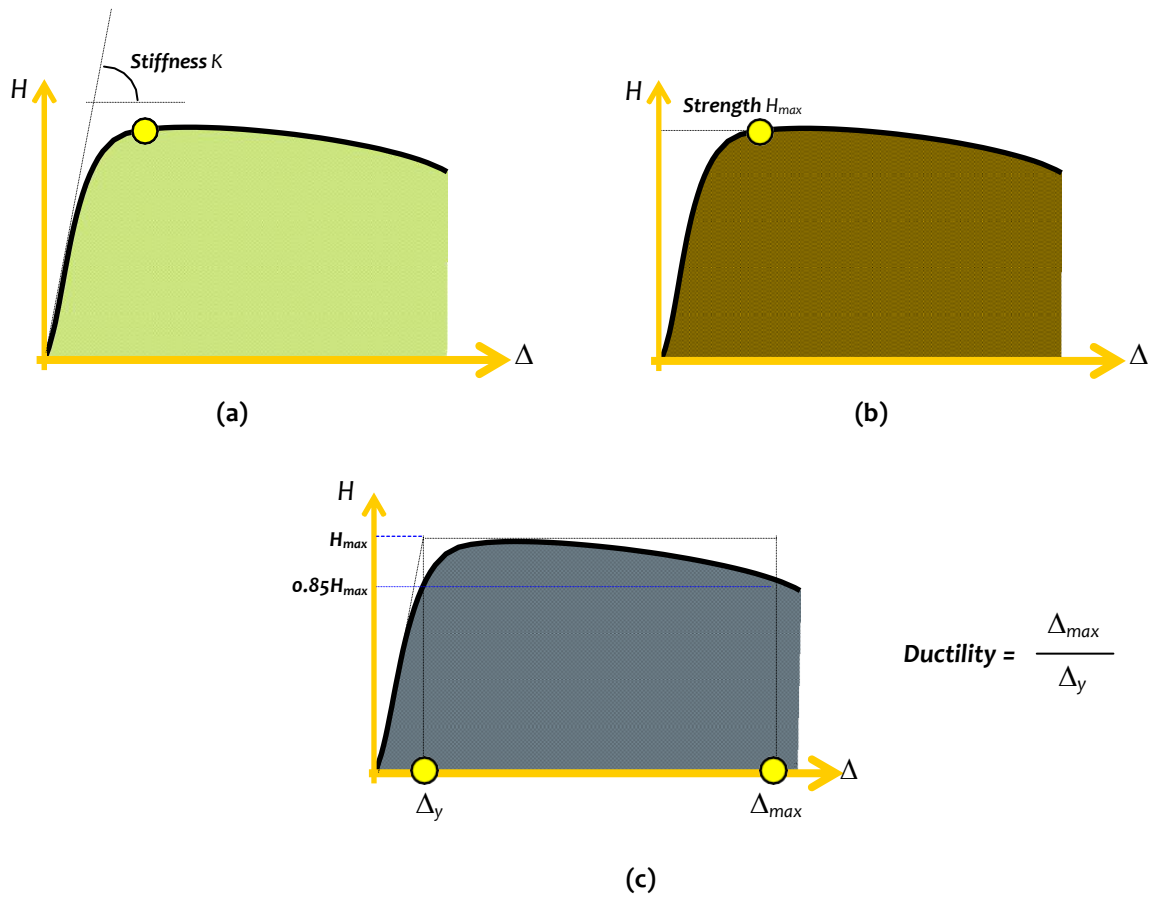


Figure 1.11: *Structural Characteristics*: Overall load deformation curves of a building,

indicating (a)lateral stiffness, (b) lateral strength, and (c) ductility towards lateral deformation

1.3.2 What are the Four Virtues?

All buildings are vertical cantilevers projecting out from the earth's surface. Hence, when the *earth shakes*, these cantilevers experience whiplash effects, especially when the shaking is violent. Hence, special care is required to protect them from this jerky movement. Buildings intended to be earthquake-resistant have competing demands. Firstly, buildings become expensive, if designed not to sustain any damage during strong earthquake shaking. Secondly, they should be strong enough to not sustain any damage during weak earthquake shaking. Thirdly, they should be stiff enough to not swing too much, even during weak earthquakes. And, fourthly, they should not collapse during the expected strong earthquake shaking to be sustained by them even with significant structural damage. These competing demands are accommodated in buildings intended to be *earthquake- resistant* by incorporating four *desirable* characteristics in them. These characteristics, called the *four virtues of earthquake-resistant buildings*, are:

1. Good *seismic configuration*, with no choices of architectural form of the building that is detrimental to good earthquake performance and that does not introduce newer complexities inthe building behaviour than what the earthquake is already imposing;
2. At least a minimum *lateral stiffness* in each of its plan directions (uniformly distributed in both plan directions of the building), so that there is no discomfort to occupants of the building and no damage to contents of the building;
3. At least a minimum *lateral strength* in each of its plan directions (uniformly distributed in bothplan directions of the building), to resist low intensity ground shaking with no damage, and nottoo strong to keep the cost of construction in check, along with a minimum *vertical strength* to be able to continue to support the gravity load and thereby prevent collapse under strongearthquake shaking; and
4. Good overall *ductility* in it to accommodate the imposed lateral deformation between the base and the roof of the building, along with the desired mechanism of behaviour at ultimate stage.

Behaviour of buildings during earthquakes depend critically on these four virtues. Even if any one of these is not ensured, the performance of the building is expected to be poor.

(a) Who Controls the Four Virtues?

Henry Degenkolb, a noted earthquake engineer of USA, aptly summarized the immense importance of seismic configuration in his words: "*If we have a poor configuration to start with, all the engineer can do is to provide a band-aid - improve a basically poor solution as best as he can. Conversely, if we start-off with a good configuration and reasonable framing system, even a poor engineer can't harm its ultimate performance too much*." Likewise, Nathan M. Newmark and Emilo Rosenbleuth, eminent Professors of Earthquake Engineering in USA and Mexico, respectively, batted for the concepts of earthquake-resistant design in their foreword to their book: *"If a civil engineer is to acquire fruitful experience in a brief span of time, expose him to the concepts of earthquake engineering, no matter if he is later not to work in earthquake country."*

In many countries, like India, in the design of a *new building*, the *architect* is the team leader, and the engineer a team member. And, in the design of *retrofit of an existing building*, the *engineer* isthe team leader, and the architect a team member. What is actually needed is that both the architect and the engineer work *together* to create the best design with good interaction at all stages of the process of the design of the building. Here, the architect brings in perspectives related to *form*, *functionality*, *aesthetics* and *contents*, while the engineer brings the perspectives of *safety* and *desired earthquake performance* during an expected earthquake. There is a two way influence of the said parameters handled both by the architect and by the engineer; their work has to be in unison.

(b) How to Achieve the Four Virtues?

The four virtues are achieved by inputs provided at all stages of the development of the building, namely in its *planning*, *design*, *construction* and *maintenance*. Each building to be built is only one of the kind ever, and no research and testing is performed on that building, unlike factory- made products like aircrafts, ships and cars. The owner of the building *trusts* the professionals (*i.e.*, architect and engineer) to have done due diligence to design and construct the building. Thus, professional experience is essential to be able to conduct a safe design of the building, because itaffects the safety of persons and property.

Traditionally, in countries that have advanced earthquake safety initiatives, governments have played critical role through the enforcement of techno-legal regime, wherein the municipal authorities arrange to examine, if all requisite technical inputs have been met with to ensure safety in the building, before allowing the building to be built, the construction to be continued at different stages, or the users to occupy the building. These stages are: (1) conceptual design stage, (2) design development stage through peer review of the structural design, (3) construction stage through quality control and quality assurance procedures put in place. Senior professionals (both architects and engineers) are required to head the team of professionals to design a building; these senior professionals should have past experience of having designed buildings to resist strong earthquakesunder the tutelage of erstwhile senior professionals.

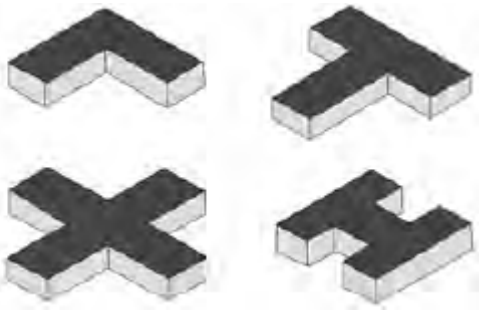


Figure 1.12 Buildings with re-entrant corners

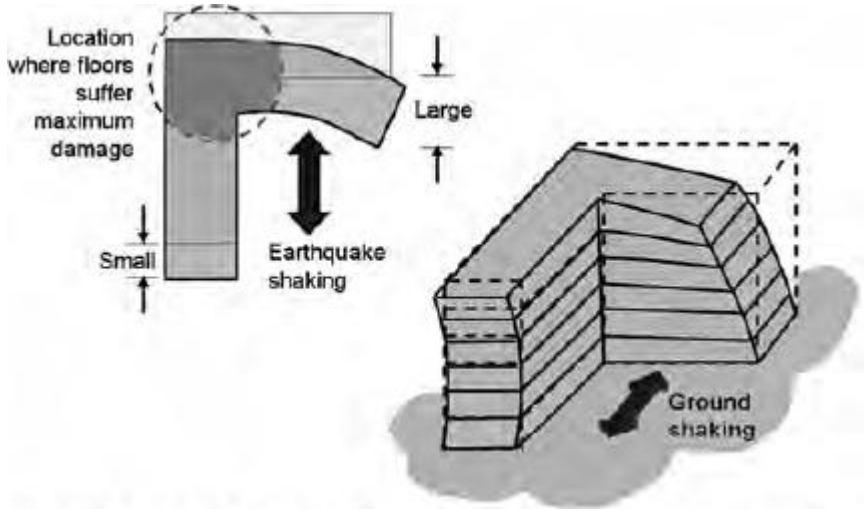


Figure 1.13 Poor earthquake behaviour of buildings with re-entrant corners

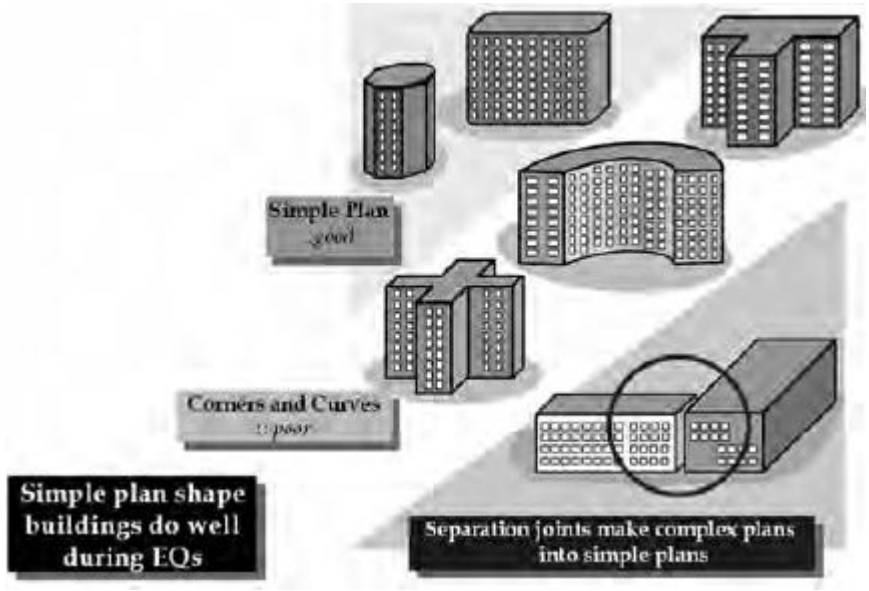


Figure 1.14Plan configuration for earthquake performance

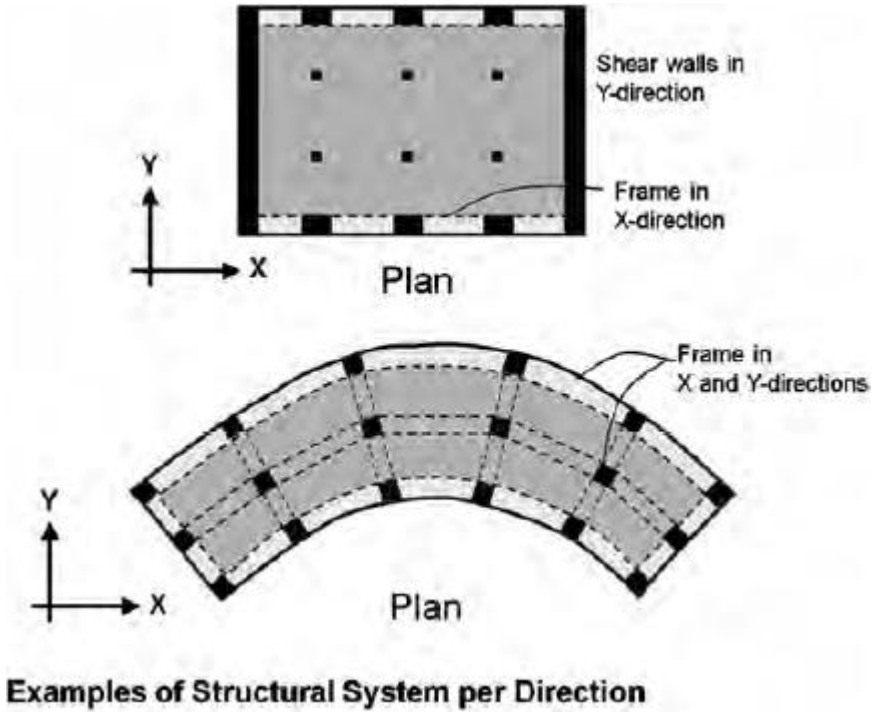


Figure 1.15 Illustration of how to use two lateral-load-resisting systems in plans