Starting from August 2004, *Resonance* is publishing in the Classroom section, a series of short articles, 'Earthquake Tips', related to earthquakes, their effects on civil structures, and design and construction of earthquake resistant buildings. The concepts are clearly explained with sketches and analogies. We hope the *Resonance* readers will benefit from this series of articles.

Earthquake Tips have been brought out by the Department of Civil Engineering, IIT Kanpur, and sponsored by Building Materials and Technology Promotion Council, New Delhi, India. These articles are reproduced here with permission from IIT Kanpur and BMTPC, New Delhi.

C V R Murty
Indian Institute of Technology
Kanpur, Kanpur 208 016, India
Email:eqtips@iitk.ac.in

Learning Earthquake Design and Construction
9. How to Make Buildings Ductile for Good Seismic Performance?

Keywords
Ductile buildings, earthquake-resistant buildings.

Construction Materials

In India, most non-urban buildings are made in masonry. In the plains, masonry is generally made of burnt clay bricks and cement mortar. However, in hilly areas, stone masonry with mud mortar is more prevalent; but, in recent times, it is being replaced with cement mortar. Masonry can carry loads that cause *compression* (i.e., pressing together), but can hardly take load that causes *tension* (i.e., pulling apart) (*Figure* 1).

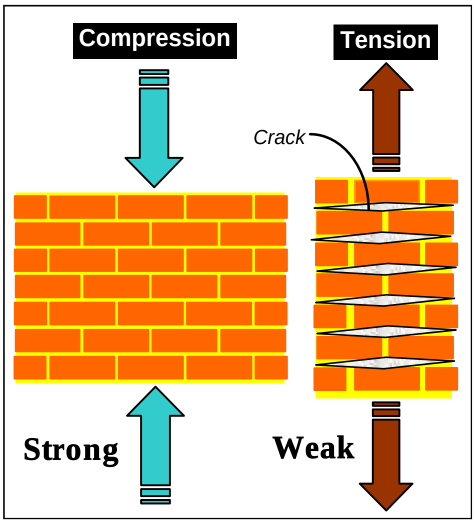


Figure 1. Masonry is strong in compression but weak in tension.

Concrete is another material that has been popularly used in building construction particularly over the last four decades. Cement concrete is made of crushed stone pieces (called *aggregate*), sand, cement and water mixed in appropriate proportions. Concrete is much stronger than masonry under *compressive* loads, but again its behaviour in tension is poor. The properties of concrete critically depend on the amount of water used in making concrete; too much and too little water, both can cause havoc. In general, both masonry and concrete are brittle, and fail suddenly.

Steel is used in masonry and concrete buildings as reinforcement bars of diameter ranging from 6mm to 40mm. Reinforcing steel can carry both tensile and compressive loads. Moreover, steel is a *ductile material*. This important property of ductility enables steel bars to undergo large elongation before breaking.

Concrete is used in buildings along with steel reinforcement bars. This composite material is called *reinforced cement concrete* or simply *reinforced concrete* (RC). The amount and location of steel in a member should be such that the failure of the member is by steel reaching its strength in tension before concrete reaches its strength in compression. This type of failure is *ductile failure*, and hence is preferred over a failure where concrete fails first in compression. Therefore, contrary to common thinking, providing too much steel in RC buildings can be harmful even!!

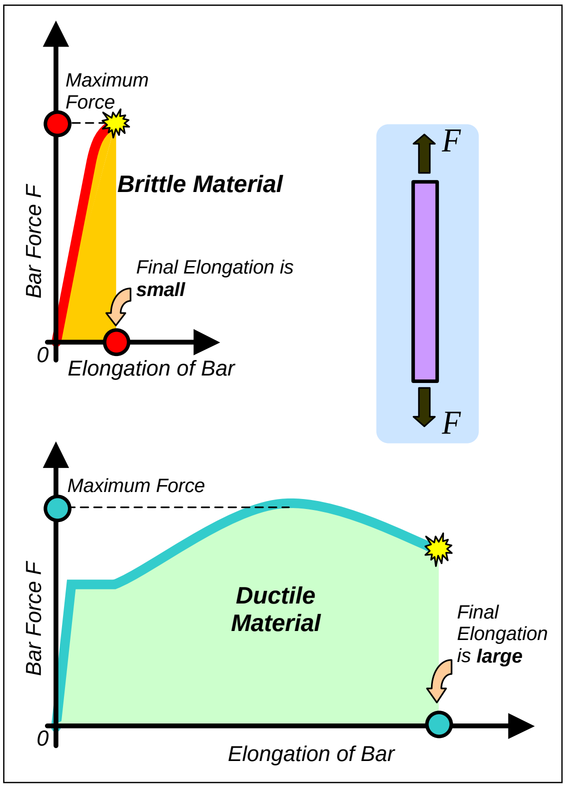


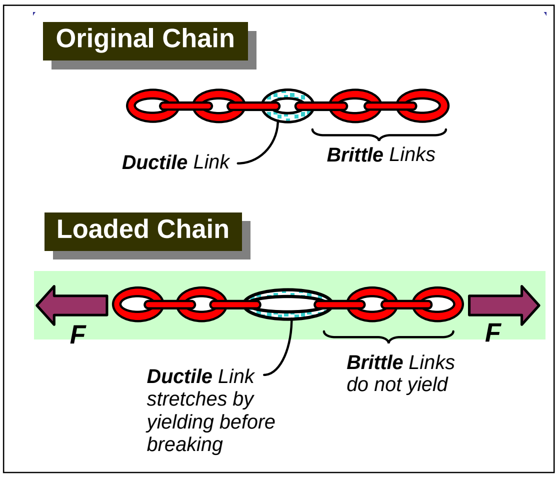
Figure 2. Tension Test on Materials – ductile versus brittle materials.

Capacity Design Concept

Let us take two bars of same length and cross-sectional area – one made of a ductile material and another of a brittle material. Now, pull these two bars until they break!! You will notice that the ductile bar elongates by a large amount before it breaks, while the brittle bar breaks suddenly on reaching its maximum strength at a relatively small elongation (*Figure* 2). Amongst the materials used in building construction, steel is *ductile*, while masonry and concrete are *brittle*.

Now, let us make a chain with links made of *brittle* and *ductile* materials (*Figure* 3). Each of these links will fail just like the bars shown in *Figure* 2. Now, hold the last link at either end of the chain and apply a force F. Since the same force F is being transferred through all the links, the force in each link is the same, i.e., F. As more and more force

Figure 3. Ductile chain design.



is applied, eventually the chain will break when the *weakest link* in it breaks. If the ductile link is the *weak* one (i.e., its capacity to take load is less), then the chain will show large final elongation. Instead, if the brittle link is the weak one, then the chain will fail suddenly and show small final elongation. Therefore, if we want to have such a *ductile* chain, we have to make the ductile link to be the *weakest* link.

Earthquake-Resistant Design of Buildings

Buildings should be designed like the ductile chain. For example, consider the common urban residential apartment construction – the multi-storey building made of reinforced concrete. It consists of horizontal and vertical members, namely *beams* and *columns.* The seismic inertia forces generated at its floor levels are transferred through the various *beams* and *columns* to the ground. The correct building components need to be made ductile. The failure of a column can affect the stability of the whole building, but the failure of a beam causes localized effect. Therefore, it is better to make *beams* to be the ductile weak links than *columns.* This method of designing RC buildings is called the *strong-column weak-beam* design method (*Figure* 4).

By using the *routine* design codes (meant for design against non-earthquake effects), designers may not be able to achieve a ductile structure. Special design provisions are required to help designers improve the ductility of the structure. Such provisions are usually put together in the form of a special *seismic* design code, e.g., IS:13920-1993 for RC struc-tures. These codes also ensure that adequate ductility is provided in the members where damage is expected.

Quality Control in Construction

The capacity design concept in earthquake-resistant design of buildings will fail if the strengths of the brittle links fall below their minimum assured values. The strength of brittle construction materials, like masonry and concrete, is highly sensitive to the quality of construction materials, workmanship, supervision, and construction methods. Similarly, special care is needed in construction to ensure that the elements meant to be ductile are indeed provided with features that give adequate ductility. Thus, strict adherence to prescribed standards of construction materials and construction processes is essential in assuring an earthquake-resistant building. Regular testing of construction materials at qualified laboratories (at site or away), periodic training of workmen at professional training houses, and on-site evaluation of the technical work are elements of good quality control.

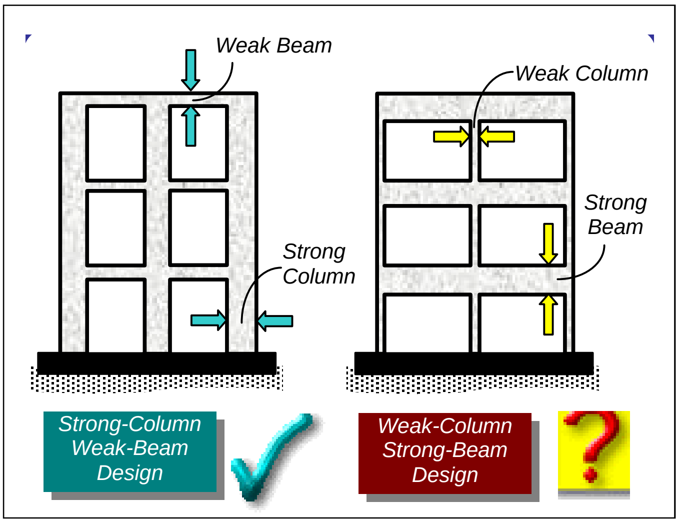


Figure 4. Reinforced Concrete Building Design: the beams must be the weakest links and not the columns – this can be achieved by appropriately sizing the members and providing correct amount of steel reinforcement in them.

Suggested Reading

[1] T Paulay and M J N Priestley, *Seismic Design of Reinforced Concrete Buildings and Masonry*, John Wiley, USA, 1992.

[2] F M Mazzolani and V Piluso, *Theory and Design of Seismic-Resistant Steel Frames*, E&FN Spon, UK,1996.

Suggestions/comments may be sent to: eqtips@iitk.ac.in.

C V R Murty
Indian Institute of Technology
Kanpur, Kanpur 208 016, India
Email:eqtips@iitk.ac.in

Learning Earthquake Design and Construction
10. How Flexibility of Buildings Afffects their Earthquake Response?

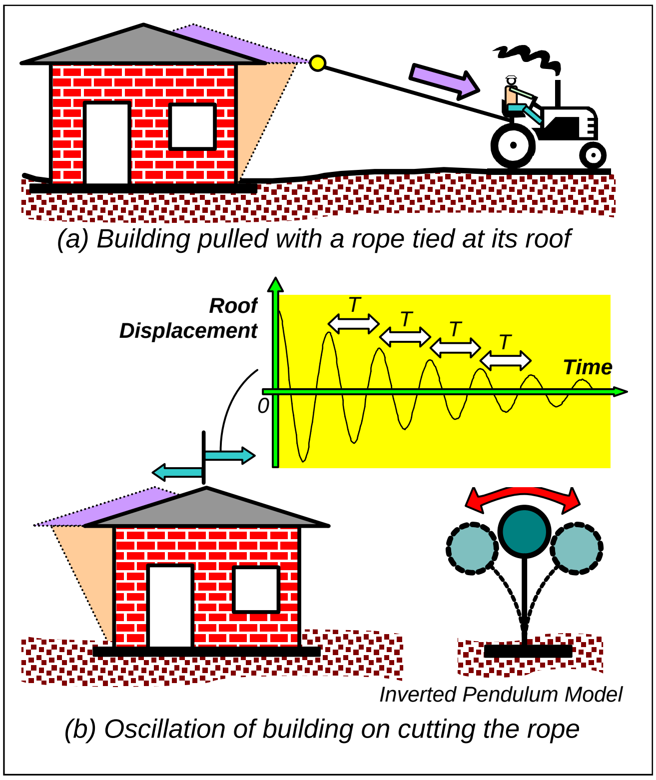
Oscillations of Flexible Buildings

When the ground shakes, the base of a building moves with the ground, and the building swings back-and-forth. If the building were rigid, then every point in it would move by the same amount as the ground. But, most buildings are flexible, and different parts move back-and-forth by different amounts.

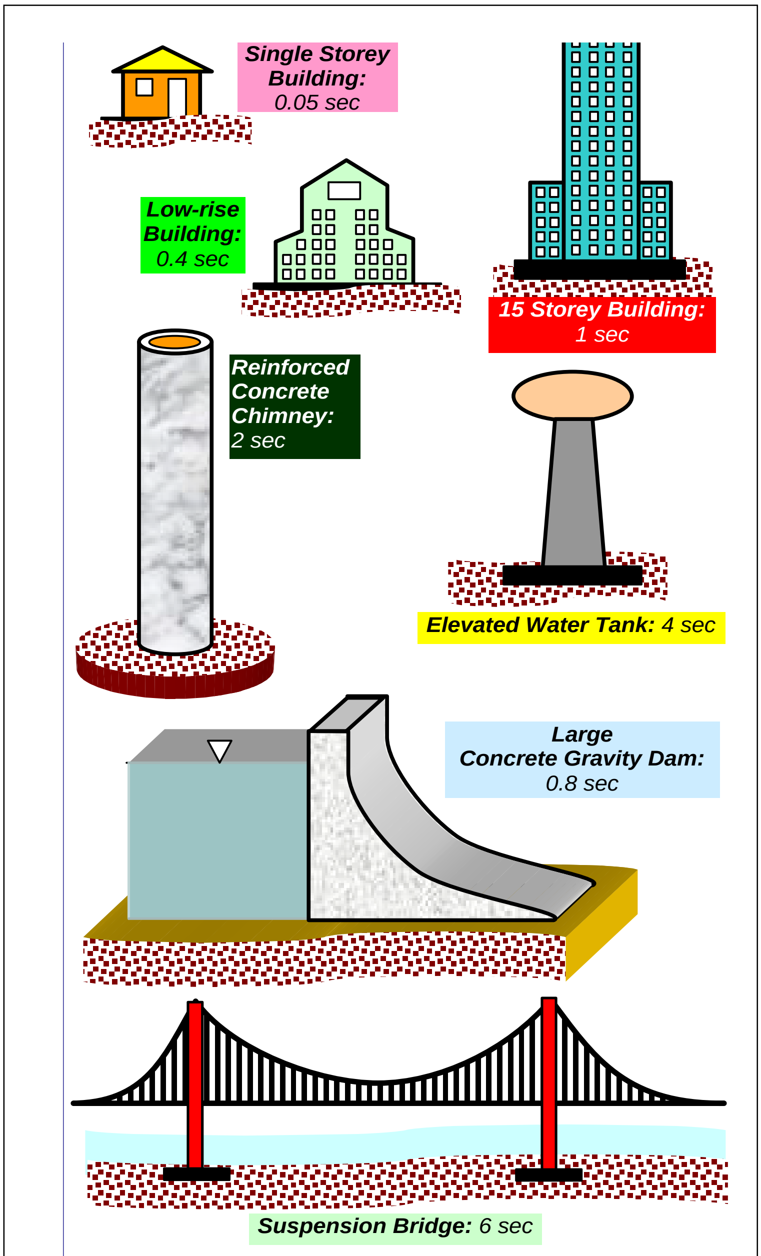
Keywords
Flexible buildings, earthquake response of buildings.

Take a fat coir rope and tie one end of it to the roof of a building and its other end to a motorized vehicle (say a tractor). Next, start the tractor and pull the building; it will move in the direction of pull (*Figure* 1a). For the same amount of pull force, the movement is larger for a more flexible building. Now, cut the rope! The building will oscillate back-and-forth horizontally and after some time come back to the original position (*Figure* 1b); these oscilla-tions are periodic. The time taken (*in seconds*) for each complete cycle of oscillation (i.e., one complete *back-and-forth* motion) is the same and is called *Fundamental Natural Period T* of the building. Value of T depends on the building flexibility and mass; more the flexibility, the longer is the *T*, and more the mass, the longer is the *T*. In general, taller buildings are more flexible and have larger mass, and therefore have a longer *T*. On the contrary, low-to medium-rise buildings generally have shorter *T* (less than 0.4 sec).

Figure 1. Free vibration response of a building: the back-and-forth motion is periodic.


(a) Building pulled with a rope tied at its roof

(b) Oscillation of building on cutting the rope



Adapted from: **Newmark, (1970),** *Current trends in the Seismic Analysis and Design of High Rise Structures*, **Chapter 16, in Wiegel, (1970),** *Earthquake Engineering*, **Prentice Hall, USA.**

Figure 2. Fundamental natural periods of structures differ over a large range. The natural period values are only indicative; depending on actual properties of the structure, natural period may vary considerably.

Fundamental natural period T is an inherent property of a building. Any alterations made to the building will change its T. Fundamental natural periods T of normal single storey to 20

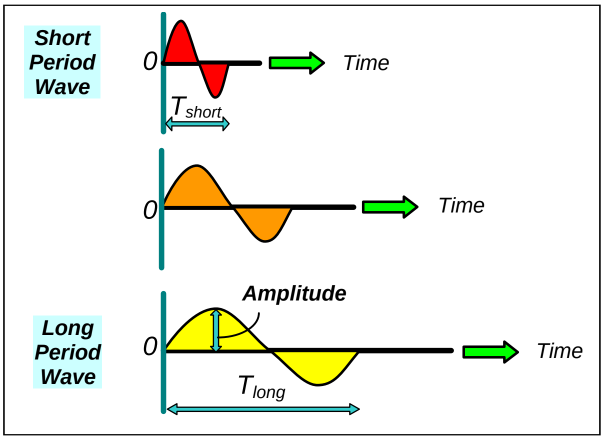


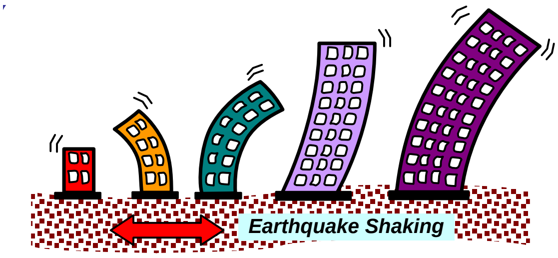
Figure 3. Strong Earthquake ground motion is transmitted by waves of different periods.

storey buildings are usually in the range 0.05-2.00 sec. Some examples of natural periods of different structures are shown in *Figure* 2.

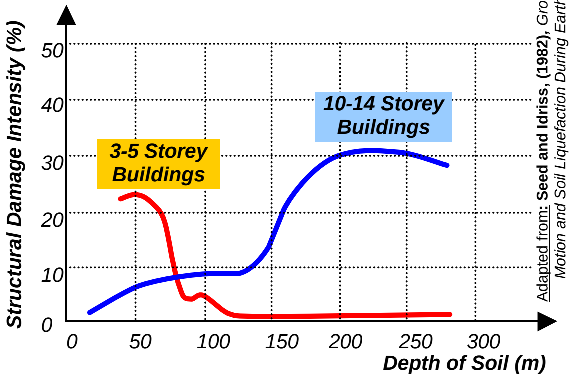
Importance of Flexibility

The ground shaking during an earthquake contains a mixture of many sinusoidal waves of different frequencies, rang-ing from short to long periods (*Figure* 3). The time taken by the wave to complete one cycle of motion is called *period of the earthquake* wave. In general, earthquake shaking of the ground has waves whose periods vary in the range 0.03-33sec. Even within this range, some earthquake waves are stronger than the others. Intensity of earthquake waves at a particular building location depends on a number of factors, including the *magnitude* of the earthquake, the *epicentral distance*, and the type of ground that the earthquake waves travelled through before reaching the location of interest.

Figure 4. Different buildings respond differently to same ground vibration.



(a) Buildings in a city lie on different soils



Adapted from: **Seed and Idriss, (1982),** *Ground Motion and Soil Liquefaction During Earthquakes,* **EERI, USA.**

(b) Intensity of damage depends on thickness of underlying soil layer: 1967 Caracas Earthquake

In a typical city, there are buildings of many different sizes and shapes. One way of categorizing them is by their *fundamental natural period T*. The ground motion under these buildings varies across the city (*Figure* 4a). If the ground is shaken back-and-forth by earthquake waves that have short periods, then *short period buildings* will have large response. Similarly, if the earthquake ground motion has long period waves, then *long period buildings* will have larger response.

Thus, depending on the value of T of the buildings and on the characteristics of earthquake ground motion (i.e., the periods and amplitude of the earthquake waves), some buildings will be shaken more than the others.

During the 1967 Caracas earthquake in South America, the response of buildings was found to depend on the thickness of soil under the buildings. *Figure* 4b shows that for buildings 3-5 storeys tall, the damage intensity was higher in areas with underlying soil cover of around 40-60m thick, but was minimal in areas with larger thick-ness of soil cover. On the other hand, the damage intensity was just the reverse in the case of 10-14 storey buildings; the damage intensity was more when the soil cover was in the range 150-300m, and small for lower thickness of soil cover. Here, the soil layer under the building plays the role of a filter, allowing some ground waves to pass through and filtering the rest.

Flexible buildings undergo larger relative horizontal displacements, which may result in damage to various nonstructural building components and the contents. For example, some items in buildings, like glass windows, cannot take large lateral movements, and are therefore damaged severely or crushed. Unsecured shelves might topple, especially at upper stories of multi-storey buildings. These damages may not affect safety of buildings, but may cause economic losses, injuries and panic among its residents.

Suggested Reading

[1] **R Wiegel, *Earthquake Engineering,* Prentice Hall Inc., USA, 1970.**

[2] **A K Chopra, *Dynamics of Structures – A Primer,* Earthquake Engineering Research Institute, USA, 1980.**

Related Tip

Earthquake Tip 2: How the Ground Shakes?
Earthquake Tip 5: What are the Seismic Effects on Structures?

Suggestions/comments may be sent to: eqtips@iitk.ac.in.