Earthquake Effects on Buildings

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1) Earthquake Effects on Buildings

1.1 Introduction

After each major earthquake, in the engineering circles one discusses the damage which affected the buildings during the catastrophe, and possible means of prevention against the damage. From these discussions, many ideas usually emerge on alterations which should be introduced into the traditional building ways. But such is the human nature that, as soon as the first fears are over the feeling of security prevails, and nobody considers any further changes; moreover, even those which have been accepted immediately after an earthquake get forgotten. Another strong earthquake is needed to remind people that the building techniques should be further developed and improved.

The recent Messinian catastrophe has awaken us all and made us think of whether our own buildings could resist an earthquake of the strength similar to the one which affected the south of Italy on December 28th1908. Anyone who has carefully examined the pictures of destruction which affected the towns of Messina and Reggio would be convinced that the damage of a similar earthquake in Zagreb would be much smaller; nevertheless, it is certain that many mistakes are still being made and that damage could be quite large.

There are two sources of mistakes which would seriously endanger our buildings. The first come from ignoring the ways the earthquake affects the buildings; the other is the inadequate construction process.

The best building designs sometimes come into the hands of a builder who, as a result of the financial greed or unconscientious competition, performs his job quite poorly. It also happens that the building is made with the sole purpose to be sold immediately, with a profit made as high as possible. In these cases one does not take care of the quality of work, but the only aim is that a building as large as possible is built with expenses as low as possible. It is clear that such buildings cannot be strong enough to resist an earthquake; it is therefore upon the authorities to strictly ensure a highly solid building pro cedure for each building.

Many properly executed buildings are not safe against earthquakes, simply because their foundations were made without considering the earthquake hazard. Investigating the damage on buildings from some major earthquakes during recent years, I obtained results which confirm that some general rules can be formulated. Every contractor should take these rules into account when planning the buildings, especially the very tall ones, and the buildings designed in agreement with these rules would be almost completely safe against earthquakes. One cannot speak of the absolute safety, because it is not known how strong the strongest earthquake can be, and probably it is not even possible to construct the building which would not be damaged by an exceptionally strong earthquake.

Regarding the purpose the buildings are constructed for, one should distinguish between the monumental and the ordinary buildings. The first are erected with intention to have a long lifetime, and there is no economizing with the money or with the material. The goal is to leave such a building to future generations to be reminded of the nation, the city or the person who erected the monument in honour of his own riches, greatness or glory.

The normal buildings have the purpose that the capital invested into them may bring as much of the profit as possible. The calculation must take into account:

1. The invested funds and the costs of the maintenance, of the future big repairs, taxes and similar expenses, and any risks concerning the building;
2. The regular profits and the risks concerning these profits.

I wish to mention that many different hazards with which any proprietor is confronted include also the danger of earth quakes. The owner and the contractor have to take this danger into account, and include it into plans according to their means and to the building's expected lifetime. When a monumental building is constructed, one should be aware that in its long lifetime it will be subjected to some extremely strong – or even catastrophic – earthquakes, and it will have to be made strong enough to resist any earthquake. In the case of an ordinary building one asks how large is the probability that during the lifetime of the building one or more damaging earthquakes, or even a disastrous one, will occur. According to this probability the funds invested into the safety of the building will be more or less profitably returned.

Some regions are subjected to large earthquakes, in others only very weak earthquakes occur, or there are even such regions where the earthquake is an absolute rarity. The builder should therefore take account of the region in which the site is located. From the statistical data, collected by Professor Ki{pati}, Ph. D., during last 25 years, it follows that the most prone to strong earthquakes are the Zagreb and Vara`din counties, especially the town of Zagreb and its surroundings. In the second group is the whole Primorje region, from Rijeka to Senj and Karlobag. The third group comprises the Po`ega county. The other regions of our homeland are more or less safe from strong earthquakes.

From the data collected in the past, one can determine the probability of strong earthquakes in Croatia and Slavonia. In the last 50 years 91 strong earthquakes occurred in our region. Of these 57 earthquakes were in the Zagreb and Vara`din counties, 20 in Primorje and 30 in the Po`ega county. On the mountain of Medvednica (Zagreba~ka gora) there were 30 of them. It fol lows that in the surroundings of Mt. Medvednica, including the city of Zagreb, three strong earthquakes occur every five years

In the last 25 years there were 3 to 4 earthquakes which induced damage, and a disastrous one in the year 1880 with great damage. In the more distant past, the earthquake of March 26th 1502 is mentioned, when the tower of St. Mark’s collapsed, the other one of the year 1590 when the Medvedgrad Castle was destroyed, of 1699 when again the tower of St. Mark’s was destroyed, and another one of July 1st 1756. It is hard to estimate whether these earthquakes.

Were stronger or weaker than the 1880 earthquake. These data show that in Zagreb we have one very strong earthquake each 100 years, one weaker but damaging earthquake every 10 years, and 3 moderate earthquakes within every 5 years.

It is assumed that an ordinary building has duration of 150 to 200 years. During its lifetime this building will have to withstand one very strong earth quake, about 100 moderate earthquakes, 100 weaker earthquakes and 1500 to 2000 very weak earthquakes, whose origin lies below the town of Zagreb or very near to it.

If we add those earthquakes which have their foci in the greater Zagreb area, and whose shaking is also felt in Zagreb, then the numbers we obtain are very large.

It follows that the danger of earthquakes must be carefully considered when building houses in Zagreb, and that it is profitable to pay more in order to make the building as safe against the earthquake as possible.

The safer our buildings will be, the lower will be the credit interests for such buildings, and the town will grow and develop faster if the foreign guests will be free of fear of earthquakes.

The building codes for the town of Zagreb contain several rules having the purpose to secure the building from the earthquake hazards. Nevertheless, there are still many mistakes in the ways of constructing the buildings which can be avoided without increasing the costs; there are some which could be easily avoided with only slightly increased costs, taking into account also the purpose the building will serve, and the durability it was designed for.

I decided to use these lines to explain to the highly esteemed gentlemen builders and contractors about the ways how the earth is trembling and how this trembling affects the buildings, and to stress some principles which every architect and every contractor should have in mind when building our houses.

In Europe, relatively little attention had been paid to the danger of earth quakes until now, and even today only the calculations of static loads are per formed. Only for towers and high chimneys, the action of the wind is being taken into account. In Japan in the last 15 years many investigations of the action of earthquakes on buildings were done, and the results found there make the starting point for my discussion.

Before beginning the examination of the effects of earthquakes on buildings, one should have a precise idea on the ways how the earth can shake be low buildings, and then to account for forces exerted by these trembling. Then one should examine in detail how these forces affect the building as a whole and its separate parts.

A building is a very complex object, and the action of an earthquake on it is very complicated. Normally the buildings have the windows and the doors one above the other. The part of the wall standing between the windows or doors is the column. Buildings are normally made of certain number of such

Columns, which are carrying the loads of the floors and of the roof, and are mutually connected between the windows, i.e. at the floor levels, by using arches or long straight girders.

Building material also varies: it is mostly the wood (timber), brick, stone or the reinforced concrete, but there are buildings built with the combination of materials. Certain floors and the roof can be made of timber or of the reinforced concrete, but also using some mixture of various building material.

1.2 How Earthquakes Affect Buildings

Permanent ground deformations can tear a structure apart. Some foundation types are better able to resist these permanent ground deformations than others. For example, the use of pile foundations, with the piles extending beneath the anticipated zone of soil liquefaction, can be effective in mitigating the hazard's effects. The use of heavily reinforced mats can also be effective in resisting moderate ground deformation due to fault rupture or lateral spreading. Most earthquake-induced building damage, however, is a result of ground shaking. When the ground shakes at a building site, the building's foundations vibrate in a manner that's similar to the surrounding ground.

Brittle elements tend to break and lose strength. (Examples of brittle elements include unreinforced masonry walls that crack when overstressed in shear, and unconfined concrete elements that crush under compressive overloads.) Ductile elements are able to deform beyond their elastic strength limit and continue to carry load. (Examples of ductile elements include tension braces and adequately braced beams in moment frames (see Steel Structures that Provide Earthquake Resistance, below.)

For economic reasons, building codes permit buildings to be damaged by the infrequent severe earthquakes that may affect them, but prevent collapse and endangerment of life safety. For buildings that house important functions essential to post-earthquake recovery, including hospitals, fire stations, emergency communications centers, etc., codes adopt more conservative criteria that's intended to minimize the risk that the buildings would be so severely damaged they could not be used for their intended function.

Throughout the 20th century, the intent of seismic design in building codes was to avoid earthquake-induced damage that would pose a significant risk to safety while still permitting economical designs. Thus, building code provisions were developed that would permit some damage to occur, but protect against damage likely to lead to either local or partial collapse, or the generation of dangerous falling debris. When these building codes were first developed, the technical community didn't have a good understanding of ground shaking, its magnitude, the dynamic response characteristics of structures, or nonlinear behavior. Today's codes still seek to protect life safety vs. minimize damage, but do so through a variety of prescriptive criteria based on observation, as well as laboratory and analytical research.

Research has spawned numerous innovations now common in earthquake engineering, including ductile detailing of concrete structures, improved connections for moment frames, base isolation technology, energy dissipation technology, and computing tools.

Current research activities are focused on three areas:

1) Performance-based design,

2) Development of damage-resistant systems, and

3) Improvement in the ability to predict the occurrence and intensity of earthquakes.

The concept of performance-based design is that a designer can be inventive in terms of the combinations of structural framing systems and detailing chosen vs. adhering to prescriptive criteria contained in building code. But this approach presumes that the designer can demonstrate, typically through simulation, that the structure is capable of performing acceptably. The ability to actually implement performance-based design is becoming more practical. As this trend continues, designers will find that they're no longer constrained to certain structural systems and configurations, or have to adhere to minimum design base shears, drift, or detailing criteria, which provides more freedom in the design of structures of the future.

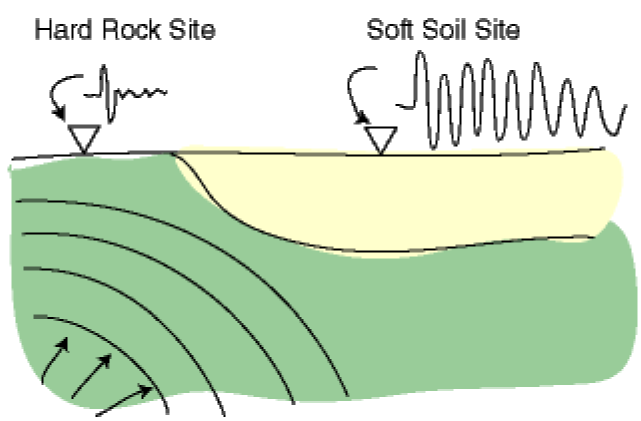
1.3 Direct Shaking Hazards and Human-Made Structures

Most earthquake-related deaths are caused by the collapse of structures and the construction practices play a tremendous role in the death toll of an earthquake. In southern Italy in 1909 more than 100,000 people perished in an earthquake that struck the region. Almost half of the people living in the region of Messina were killed due to the easily collapsible structures that dominated the villages of the region. A larger earthquake that struck San Francisco three years earlier had killed fewer people (about 700) because building construction practices were different type (predominantly wood). Survival rates in the San Francisco earthquake was about 98%, that in the Messina earthquake was between 33% and 45%) (Zebrowski, 1997). Building practices can make all the difference in earthquakes, even a moderate rupture beneath a city with structures unprepared for shaking can produce tens of thousands of casualties.

Although probably the most important, direct shaking effects are not the only hazard associated with earthquakes, other effects such as landslides, liquefaction, and tsunamis have also played important part in destruction produced by earthquakes.

1.4 Geologic Effects on Shaking

When we discussed earthquake intensity we discussed some of the basic factors that affect the amplitude and duration of shaking produced by an earthquake (earthquake size, distance from fault, site and regional geology, etc.) and as you are aware, the shaking caused by seismic waves can cause damage buildings or cause buildings to collapse. The level of damage done to a structure depends on the amplitude and the duration of shaking. The amplitudes are largest close to large earthquakes and the duration generally increases with the size of the earthquake (larger quakes shake longer because they rupture larger areas). Regional geology can affect the level and duration of shaking but more important are local site conditions. Although the process can be complicated for strong shaking, generally shaking in soft sediments is larger and longer than when compared with the shaking experienced at a "hard rock" site.



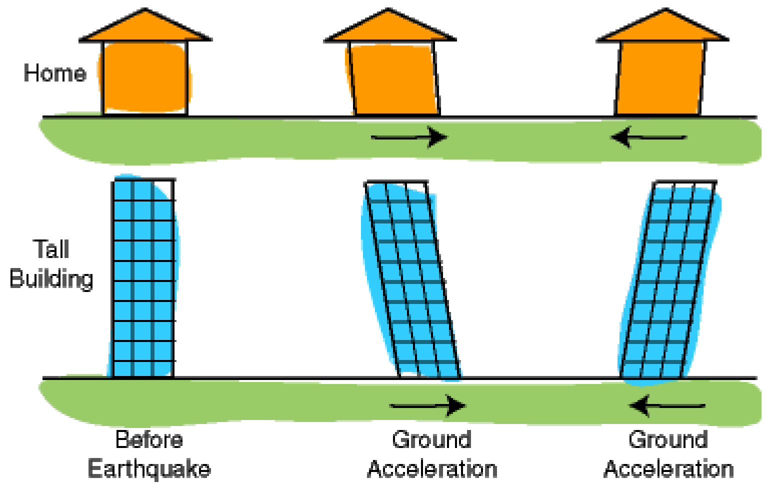
2) How to reduce Earthquake Effects on Buildings

2.1 Why Earthquake Effects are to be Reduced

Conventional seismic design attempts to make buildings that do not collapse under strong earthquake shaking, but may sustain damage to non-structural elements (like glass facades) and to some structural members in the building. This may render the building non-functional after the earthquake, which may be problematic in some structures, like hospitals, which need to remain functional in the aftermath of the earthquake. Special techniques are required to design buildings such that they remain practically undamaged even in a severe earthquake. Buildings with such improved seismic performance usually cost more than normal buildings do. However, this cost is justified through improved earthquake performance.

Two basic technologies are used to protect buildings from damaging earthquake effects. These are Base Isolation Devices and Seismic Dampers. The idea behind base isolation is to detach (isolate) the building from the ground in such a way that earthquake motions are not transmitted up through the building, or at least greatly reduced. Seismic dampers are special devices introduced in the building to absorb the energy provided by the ground motion to the building (much like the way shock absorbers in motor vehicles absorb the impacts due to undulations of the road).

2.2 Preparing Structures for Shaking



The first step in preparing structures for shaking is to understand how buildings respond to ground motions- this is the field of study for earthquake and structural engineers.

When the ground shakes, buildings respond to the accelerations transmitted from the ground through the structure's foundation. The inertia of the building (it wants to stay at rest) can cause shearing of the structure which can concentrate stresses on the weak walls or joints in the structure resulting in failure or perhaps total collapse. The type of shaking and the frequency of shaking depends on the structure. Tall buildings tend to amplify the motions of longer period motions when compared with small buildings. Each structure has a resonance frequency that is characteristic of the building. Predicting the precise behavior of buildings is complicated, a rule of thumb is that the period of resonance is about equal to 0.1 times the number of stories in the structure. Thus Macelwane Hall resonates at about 0.3 seconds period, and Griesedeck at about 1.4 seconds.

Taller buildings also tend to shake longer than short buildings, which can make them relatively more susceptible to damage. Fortunately many tall buildings are constructed to withstand strong winds and some precautions have been taken to reduce their tendency to shake. And they can be made resistant to earthquake vibrations.

In many regions of limited resources and/or old structures, the structures are not very well suited to earthquake induced strains and collapse of adobe-style construction has caused thousands of deaths in the last decade. The worst possible structure for earthquake regions is the unreinforced masonry (which is common in the St. Louis area).

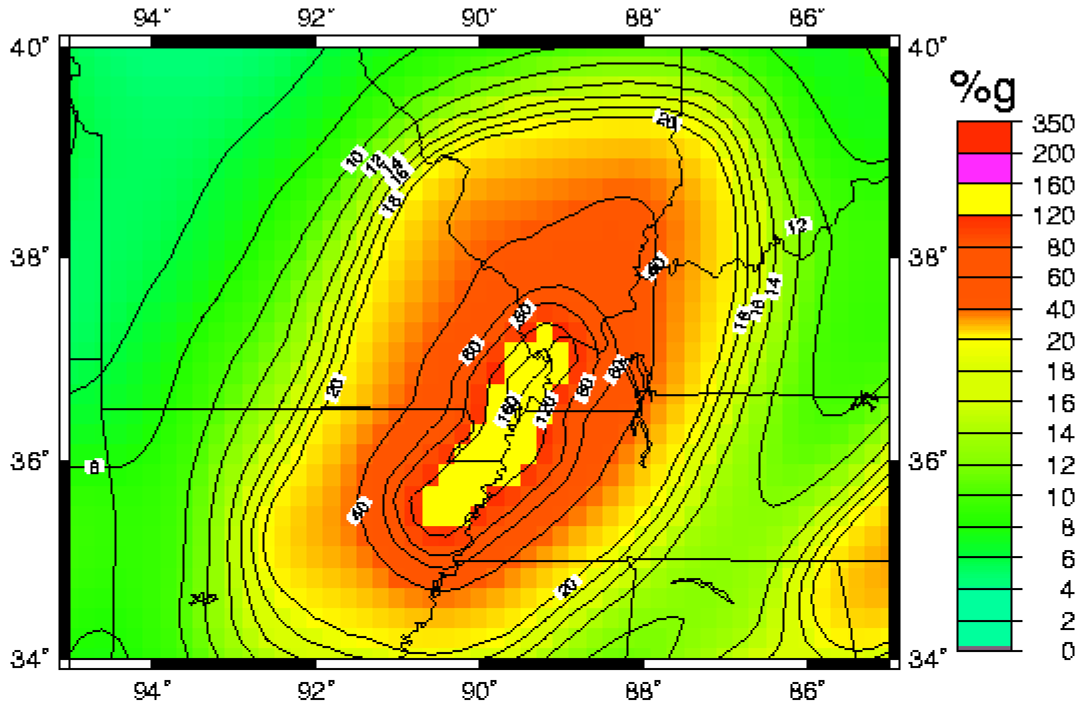
2.3 Estimating Hazards

Preparing structures (either new or old) for earthquakes is expensive and the level of investment is a social and political decision. The choice of building design is a compromise between appearance, function, structure, strength, and of course, cost. Standards are instituted through the establishment of Building Codes, which regulate the design and construction of buildings. Most of our building codes are designed to protect first the building occupants, and second the building integrity. Building codes are usually drafted to meet the demands of the expected shaking in a given region that are summarized by seismologists and earthquake engineers in hazards maps. Hazard maps are constructed by examining:

- The earthquake history of the region to estimate the probability of an earthquake
- The expected shaking intensity produced by the earthquake (often expressed as a peak acceleration)
- The frequency of the shaking, the distance from the fault
- The regional geology and site conditions

To estimate the maximum level of shaking expected during the lifetime of a building. Constructing accurate hazard maps is a challenge and remains the focus of much Geoscience research. For the Midwest you may want to check out the WWW site of a large multidisciplinary effort to help prepare the eastern US for the low-probability, but high consequence earthquake hazards (check out the Mid-America Earthquake Center).

Peak Acceleration (%g) with 02% Probability
in 50 Years



2.4 Strengthening Structures

We have two approaches for preparing buildings for earthquakes: you either secure the building components (walls, floors, foundation, etc.) together and have the entire structure behave as a single stiff unit that moves with the ground, or you construct a strong and flexible structure that distorts but doesn't break and absorbs some of the shaking energy. Either approach can be expensive so we cannot build all our structures to withstand the largest possible earthquake. We must make compromises and accept some risk (this is not unlike the risks that we accept every day, driving on a freeway, flying in an airplane, living in flood-prone regions, tornado "alley", hurricane-prone regions, etc.).

We need different levels of resistance for different classes of structures. Critical structures such as hospitals, power, water-treatment, and chemical plants, dams, etc. must not only survive the shaking, but must remain in operation. These structures require the largest investment of resources to insure that they can provide services following an earthquake.

More general requirements for other structure include having our buildings

- Sustain little damage in small-to-moderate quakes ($M < 5.5$)
- Sustain some repairable damage for moderate quakes ($5.5 < M < 7.0$)
- Not collapse in large earthquakes ($M > 7.0$)

To insure that we meet these goals we can take a number of steps, beginning with thoughtful and responsible planning and zoning laws. Since we know that sites with soft, water-saturated foundations are prone to damage, we should resist the temptation to build on those sits and we should certainly not put critical structures on such sites, and avoid building on these sites at all if possible. If that's not possible, try to compact the soft sediments before the constructing or anchor the structure in the basement.

We can take a number of steps to strengthen buildings including using steel frame construction, adequately securing the structure to the ground through a solid foundation, incorporating shear walls and or cross-bracing into the structure, or more sophisticated approaches such as using rubber or steel pads to isolate the structure from the shaking.

2.5 Base Isolation

The concept of base isolation is explained through an example building resting on frictionless rollers (Figure 1a). When the ground shakes, the rollers freely roll, but the building above does not move. Thus, no force is transferred to the building due to shaking of the ground; simply, the building does not experience the earthquake. Now, if the same building is rested on flexible pads that offer resistance against lateral movements (Figure 1b), then some effect of the ground shaking will be transferred to the building above. If the flexible pads are properly chosen, the forces induced by ground shaking can be a few times smaller than that experienced by the building built directly on ground, namely a fixed base building (Figure 1c).

The flexible pads are called base-isolators, whereas the structures protected by means of these devices are called base-isolated buildings. The main feature of the base isolation technology is that it introduces flexibility in the structure. As a result, a robust medium-rise masonry or reinforced concrete building becomes extremely flexible. The isolators are often designed to absorb energy and thus add damping to the system. This helps in further reducing the seismic response of the building. Several commercial brands of base isolators are available in the market, and many of them look like large rubber pads, although there are other types that are based on sliding of one part of the building relative to the other. A careful study is required to identify the most suitable type of device for a particular building. Also, base isolation is not suitable for all buildings. Most suitable candidates for base-isolation are low to medium-rise buildings rested on hard soil underneath; high-rise buildings or buildings rested on soft soil are not suitable for base isolation.

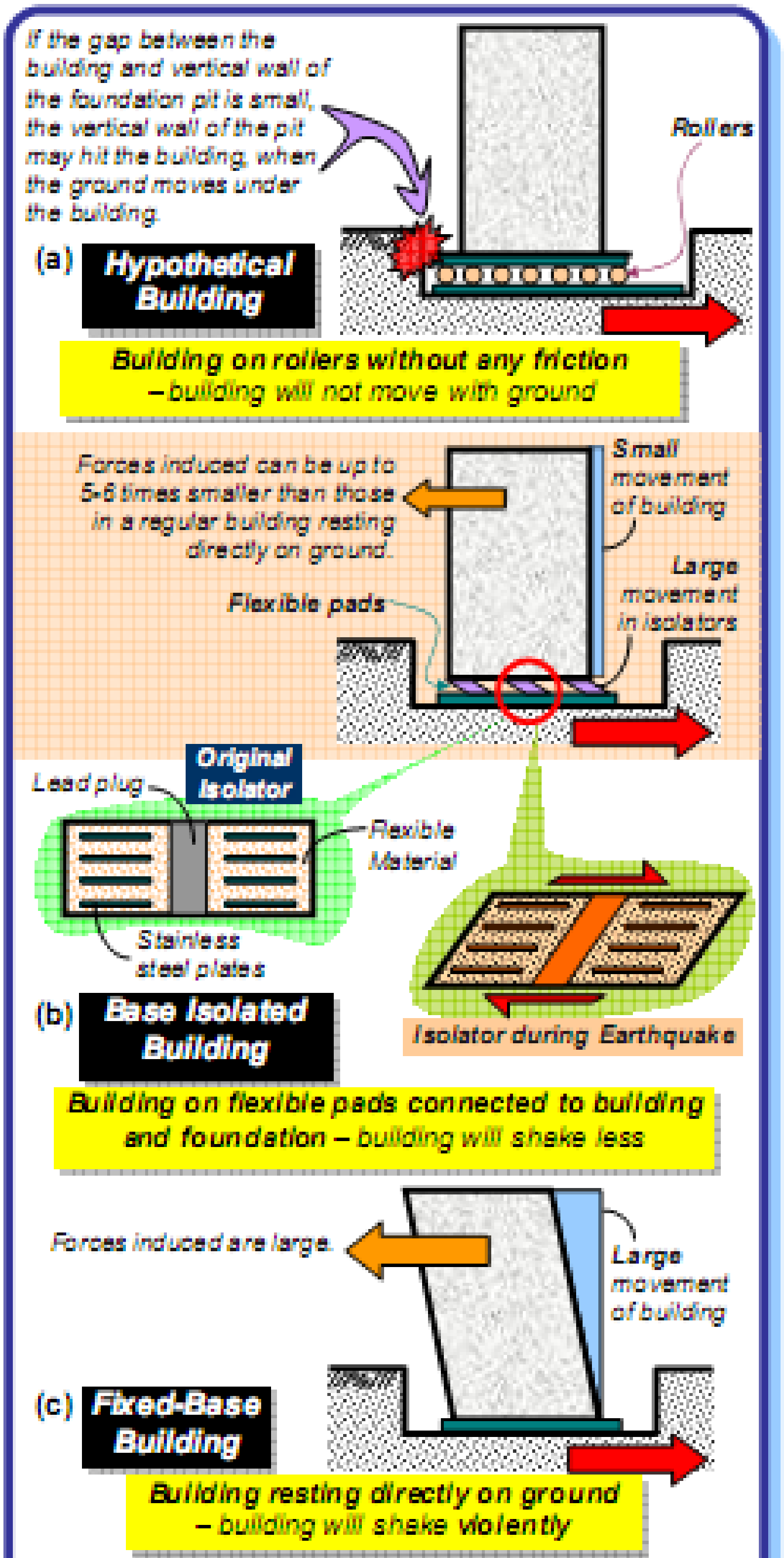


Figure 1: Building on flexible supports shakes lesser – *this technique is called* ***Base Isolation***.

2.6 Base Isolation in Real Buildings

Seismic isolation is a relatively recent and evolving technology. It has been in increased use since the 1980s, and has been well evaluated and reviewed internationally. Base isolation has now been used in numerous buildings in countries like Italy, Japan, New Zealand, and USA. Base isolation is also useful for retrofitting important buildings (like hospitals and historic buildings). By now, over 1000 buildings across the world have been equipped with seismic base isolation. In India, base isolation technique was first demonstrated after the 1993 Killari (Maharashtra) Earthquake [EERI, 1999]. Two single storey buildings (one school building and another shopping complex building) in newly relocated Killari town were built with rubber base isolators resting on hard ground. Both were brick masonry buildings with concrete roof. After the 2001 Bhuj (Gujarat) earthquake, the four-storey Bhuj Hospital building was built with base isolation technique (Figure 2).

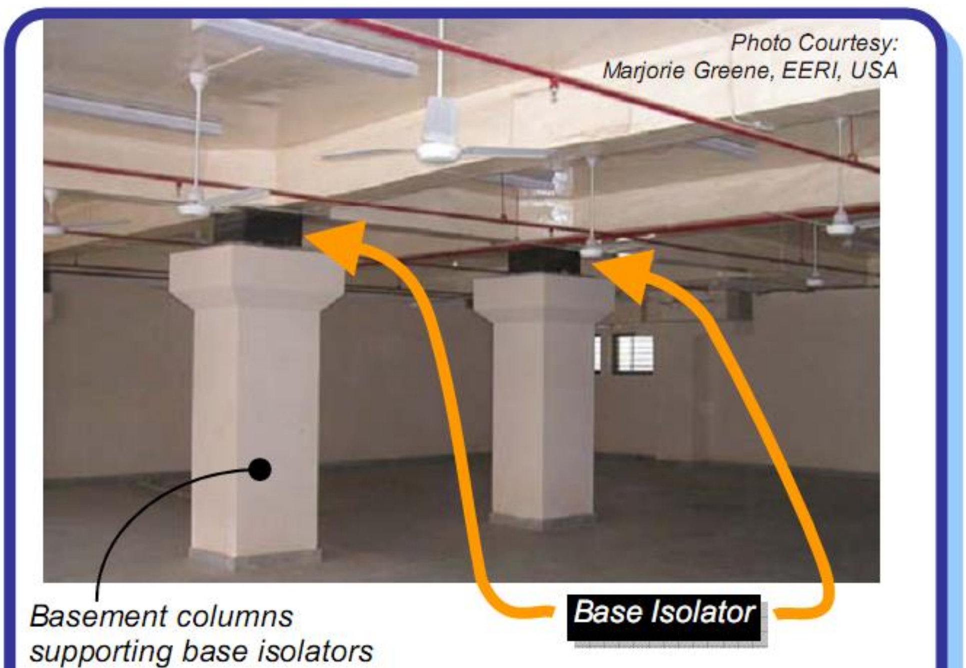


Figure 2: View of Basement in Bhuj Hospital building – *built with base isolators after the original District Hospital building at Bhuj collapsed during the 2001 Bhuj earthquake.*

2.7 Seismic Dampers

Another approach for controlling seismic damage in buildings and improving their seismic performance is by installing seismic dampers in place of structural elements, such as diagonal braces. These dampers act like the hydraulic shock absorbers in cars – much of the sudden jerks are absorbed in the hydraulic fluids and only little is transmitted above to the chassis of the car. When seismic energy is transmitted through them, dampers absorb part of it, and thus damp the motion of the building. Dampers were used since 1960s to protect tall buildings against wind effects. However, it was only since 1990s, that they were used to protect buildings against earthquake effects. Commonly used types of seismic dampers include viscous dampers (energy is absorbed by silicone-based fluid passing between piston-cylinder arrangement), friction dampers (energy is absorbed by surfaces with friction between them rubbing against each other), and yielding dampers (energy is absorbed by metallic components that yield) (Figure 3). In India, friction dampers have been provided in a 18-storey RC frame structure in Gurgaon

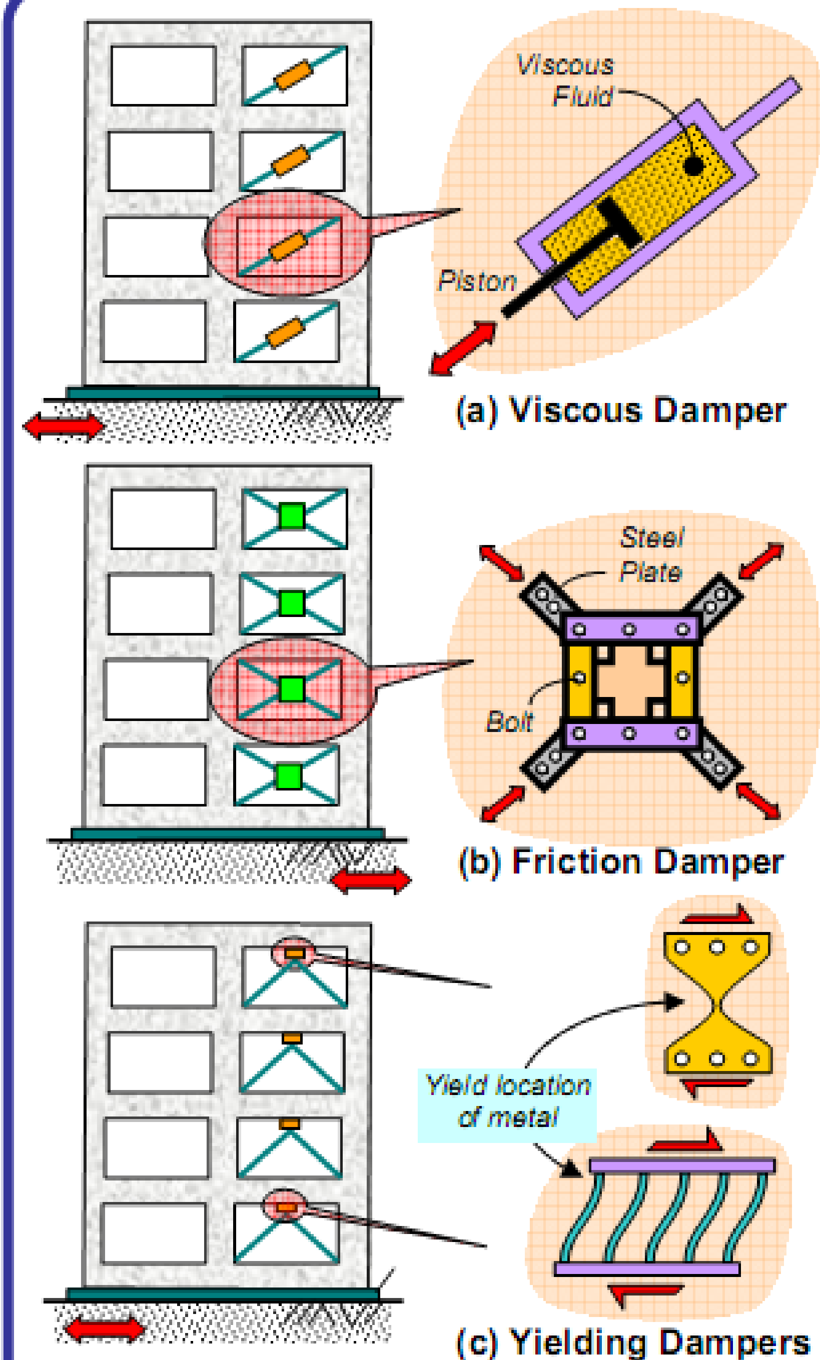


Figure 3: Seismic Energy Dissipation Devices – *each device is suitable for a certain building.*

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