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Recent Trends in Advances Earthquake Resistant Construction Design

Ch. Sandeep Reddy
Department of Civil Engineering
Samskruti College of Engineering & Technology, Ghatkesar, Hyderabad
cholletisandeep@gmail.com

Janjirala Kiran Kumar
Department of Civil Engineering,
Samskruti College of Engineering & Technology,
Ghatkesar,Hyderabad
_janjiralakiran123@gmail.com

***Abstract*:** Earthquakes are the indication of transformation in the earth's internal structure. Seismic activity is common in most parts of the world, though the frequency of its occurrence is a function of local tectonic setup. The past earthquake experiences have demonstrated huge loss of life and building stock, affecting the social and economic conditions of a country. Though it is not possible to prevent an earthquake, the least that can be achieved in reducing the damage is to make the buildings earthquake resistant. With the advancement in our understanding of the earthquakes, most of the countries have mandated the incorporation of seismic provisions in building design and architecture.

In the event of an earthquake, the seismic waves originating from the focus is transmitted in all the possible directions. These shock waves propagate in the form of body waves and surface waves through the earth's interior and, are highly random in nature. These ground motions cause structures to vibrate and induce inertia forces in the structural elements. In the absence of seismic design, the building may fail, leading to a catastrophe. The seismic design philosophy aims to primarily ensure life safety and secures the functionality of the building. In conjunction with the design philosophy, it is essential to adopt earthquake-safe construction practices for the efficient seismic performance of a building.

No region in the whole of India can be considered as earthquake free due to the ongoing subduction of the Indian Plate under the Eurasian plate. The paper aims to create an awareness about the earthquake-safe buildings in various seismic zones. The most common building typologies encountered in the recent years are the moment resisting frame (RC frame), moment resisting frames with brick infill, and masonry buildings. This study investigates the construction practices adopted for these common building typologies. Recommendations are made for the local construction practices wherever found necessary with relevance to the codal provisions. In addition, the possible future trend in the earthquake resistant technology hasalso been discussed.

1. INTRODUCTION

Earthquakes are known to have tremendous potential in causing a devastating impact on the built environment and human life. India has witnessed over 9 severe earthquakes in the last two decades between 1990 and 2010 and reports claim the death rate to be around 30000. Although certain parts of the country are more prone to earthquakes (seismic zone V of IS 1893(Part 1)- 2016) than the rest, no region can be considered as free from earthquakes.

In the Indian scenario multiple microearthquakes are reported near the subduction zone (Himalayan belt) on a daily basis, whereas in the intraplate region (Deccanplateau) few major earthquakes have been witnessed over the years. The performance of the built environment during the past earthquakes has demonstrated its fragile nature and has created an urge among the engineers and architects to move towards seismically efficient buildings.

The majority of the Indian landmass (about 60%), is susceptible to moderate to very severe earthquakes. A great earthquake in an uninhabited area may produce minimal damage when compared to a moderate earthquake in a densely populated area. All the field survey studies conducted after a major earthquake implied that the maximum casualties reported were caused by building collapse. The lack of earthquake knowledge and its incorporation in the building design and execution leads to failure of buildings. A large part of the rural and urban dwellings are low rise non engineered buildings and these suffer maximum damage.

During an earthquake, the seismic waves propagate in all directions. However, among the various components, the horizontal vibration is considered to be most predominant in causing structural failure. The seismic waves tend to move the foundation of a building inducing inertial forces in various structural elements. The seismic performance of a structure during an earthquake depends on its overall shape, size, geometry and the nature of load path. The seismic design philosophy aims to ensure safety to structural components and human life. It states that the load-bearing structural elements must suffer no damage in the event of a (frequent) minor shaking, sustain reparable damage in the event of (occasional) moderate shaking and sustain severe damage without collapse under (rare) strong shaking.

The present paper outlines the building typologies encountered in the Indian subcontinent and their performance during earlier earthquakes. A glance through the current earthquake-safe construction practices has been attempted. Further, a brief description of the future trends in making buildings more resilient to earthquakes has been provided. Overall, in addition to effective and efficient seismic design philosophies, it is necessary to ensure strict code-compliant structural design and construction practices.

2. NECESSITY FOR THE EARTHQUAKE RESISTANT CONSTRUCTION

According to the 2011 census of India, there are over 330 million housing units in the country, (GOI,2011) with two-thirds of these being rural houses. The Geological Survey of India has classified the country into four seismic zones with varying seismic potential as shown in Figure 1.

Figure 1: Seismic Zonation Map of India. (IS 1893 (Part 1) - 2016).

Seismic zones IV and V constitute about 30% of the housing units. These rural building units are mainly constructed using locally available materials such as mud and unburnt bricks, stone walls or walls made of burnt bricks, all of which are quite vulnerable in the event of poor construction and maintenance (BMTPC,2006). In addition to the larger percentage of housing stock in the rural area, a rapid growth in the urban population has been witnessed over the last decade. The census of India indicates a 32% increase in growth of urban population from 286 million in 2001 to 377 million in 2011. The urban population by the end of 2030 is projected to be nearly 590 million. As per the statistics, 50% of the demand for construction activity in India comes from the infrastructure sector, the rest comes from industrial activities, residential and commercial development etc (Make India, 2015). Due to this rapid urbanization, there is an increased demand for infrastructure, essential basic amenities, residential layouts and community development.

The time of occurrence (day or night) of an earthquake plays a major role as they have a direct impact on the occupancy of buildings. For example, Latur earthquake (1993) occurred in the early hours around 3:53AM when the majority of the population in the affected area were asleep. On the contrary Bhuj earthquake (2001) occurred in the morning around 8.46AM, with the majority of the people awake and minimum occupancy of the building. These two earthquakes exhibited the poor performance of non engineered building units such as random rubble masonry in mud mortar with heavy roofs (Figure 3) as well as modern multi-story RC frameed buildings (Figure 2).

The past earthquake experience has demonstrated the lack of seismic design in modern residential buildings. At the same time, the importance of incorporation of seismic principles in structural design for a building to perform as a single unit during an earthquake has become clearer. It is necessary to empower rural communities in ensuring seismic safety of the building stock by creating awareness about earthquakes and importance of
Earthquake-resistant buildings. The built environment in urban sectors has to be planned and designed carefully in the initial stages so that the building configuration is favorable for good seismic performance.

Figure 2: Apartment collapse in 2001 Bhuj earthquake with separation of the lift shaft.

3. BUILDING TYPOLOGIES IN INDIA.

The buildings are classified as engineered and non engineered depending on the structural design and material that go in their construction.

Figure 3: The elevated water tank of Kautha (above) collapsed straight down into its crumpled supports and failure of building units made of rubble masonry (below) during Latur earthquake (1991). (Courtesy: NICEE).

Ideally, the classification based on construction-type should be based on the knowledge of the structural system, load transfer mechanism, the predominant construction material used, and the performance during past earthquakes. Buildings are classified based on the material type as follows

- Masonry and Mortar type
- Structural Concrete
- Steel
- Wooden Structure

Figure 4 depicts various types of buildings categorized under Masonry type in our country.

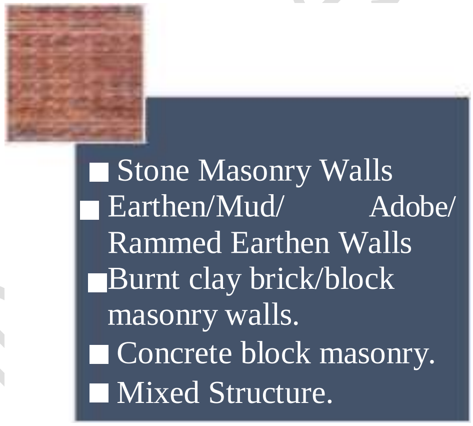

Figure 4: Classification of variousmasonry units.

Similarly, the classification of various building units under Structural Concrete, Steel, and Wooden Structures category are presented in the subsequent Figures 5, 6 and 7.

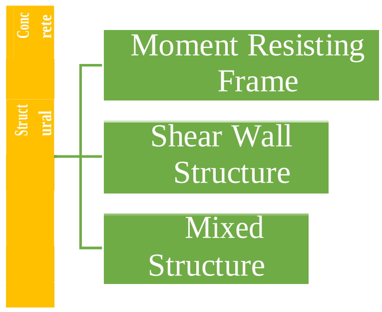

Figure 5: Classification of various load-bearing units under Structural Concrete.

The building models classified based on the materials used for their construction are further classified based on the vertical and/or lateral load resisting systems. For example, buildings under structural concrete may be moment resisting frames or shear wall buildings based on the load resisting system incorporated into the buildings. The buildings built with bamboo as a material have mostly thatched roof system.

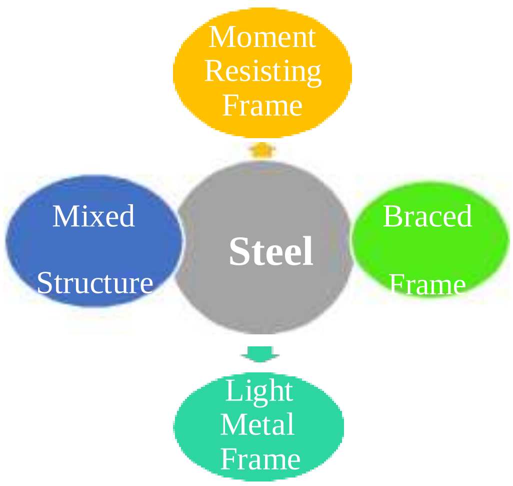

Figure 6: Classification of various load-bearing units of Steel.

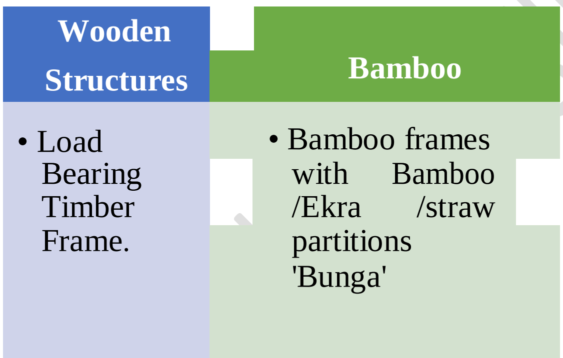

Figure 7: Classification of load-bearing units under Wooden and Bamboo structures.

In addition, various factors influence the Seismic performance of a building and are listed below.

- **The height of thebuilding** – the seismic response of a building to a ground vibration is a function of its natural

  frequency - in other words, its inherent mass and stiffness. These factors vary with the height of the building and hence, its vulnerability. As a result, in severe seismic zones, the building height is restricted in accordance with the seismic hazard estimation, specific to a region.
- **Irregularities** – The obstruction to the load path in transferring the forces from roof to the foundation is caused by the horizontal and vertical irregularities present in the building. A more detailed description about the irregularities is given in IS 1893.
- **Quality of Construction** – The quality imparted by the local construction practices in terms of compliance with codal provisions and the Status of maintenance or visual appearance is a major factor.
- **Ground Slope** - In several parts of the country such as in the Himalayas, along with the Eastern and Western Ghats and in North-Eastern states, the sloping terrain is often encountered, as a result of which, a large number of buildings are located on hill slopes. Depending on the sloping angle, the slopes are classified as the gentle slope ($\leq 20°$) and steep slope ($> 20°$). When houses are constructed on gentle slopes, the ground is typically leveled before construction. For a building constructed on a steep slope, the foundation will vary in terms of elevation along the plan of the building. This leads to vertical members with varying mass and stiffness resulting in vertical irregularity. The stability of the ground is also one of the major parameters that influence the seismic performance of a building.

4. EARTHQUAKE RESISTANT CONSTRUCTION PRACTICES FOR MASONRY BUILDINGS

Masonry is the most commonly used structural material from times immemorial. Many of the greatest structures such as The Taj Mahal (Agra), Pyramids (Cairo, Egypt), Colosseum (Rome, Italy) and many other structures are live examples of masonry construction from the earlier civilization. In general, masonry buildings are brittle in nature and are most vulnerable to ground motions. Previous earthquake experiences have witnessed a

catastrophic failure of masonry buildings in rural areas. These masonry buildings need to be engineered in order to make them sustain earthquakes. Over the years several researchers have been working relentlessly in finding an effective solution for improving the seismic resistance of masonry structures. These investigations have led to the development of new seismic resistant technology and construction systems. A variety of masonry units are used in the country, e.g., clay bricks (burnt and unburnt), concrete blocks (solid and hollow), stone blocks.A masonry building has three major components (roof, wall, and foundation) out of which the walls are most vulnerable to damage caused by horizontal forces due to the earthquake.

To ensure good seismic performance, the following conditions must be applied.

a. Walls are the weaker components and when loaded in its weaker direction can lead to failure. In order to prevent this type of failure, it is necessary to ensure that a good bond exists between adjacent walls so that loaded in their weak direction can take advantage of the good lateral resistance offered by walls loaded in their strong direction. In addition, the tendency of a wall to topple when pushed in the weak direction can be reduced by limiting its length-to-thickness and height to-thickness ratios.
b. The window and door openings serve as a weak spot in masonry walls and hence, the size of the openings must be restricted to a minimum value.Steel bars must be provided in the wall all around the openings to restrict theinitiation and propagation of cracks.
c. The vulnerability of the junction can be improved by ensuring good interlocking of the masonry courses.
d. Low porosity bricks must be used and they have to be pre-soaked before use to minimize the amount of water drawn from the mortar.
e. The strength of the mortar binding the bricks is also one of the crucial contributing factors. In this regard, Cement-sand mortar with lime is the most preferred mixture as this mortar mix provides excellent workability for laying bricks, stretches without crumbling at low earthquake shaking, and bonds well with bricks.
f. During Bhujearthquake,building configuration similar to that of a box type structure performed well with minimal damages. This box axction is possible only when the walls are tied to the roof and foundation to preserve their overall integrity.
g. To ensure box type action, horizontal seismic bands are provided and these bands tie all the walls together. There are four types of bands in a typical masonry building, namely gable band, roof band, lintel band and plinth band as shown in Figure 8. The Indian Standards IS:4326-2016 and IS:13828 (1993) provide sizes and details of the bands.

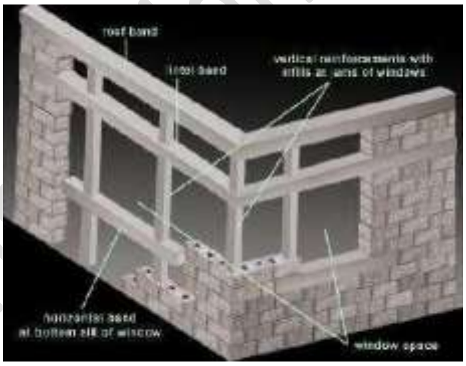

Figure 8: Horizontal bands in a masonry building (http://www.ultrabricks.com/features.htm)

h. The vertical reinforcement bars are embedded in the edges of the wall piers and anchored to the foundation at the bottom and in the roof band at the top. This procedure forces the masonry structure to undergo bending instead of rocking. Figure 9 shows the placing of vertical reinforcement.

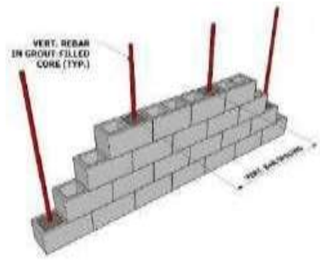

Figure 9: Vertical reinforcement in masonry walls (http://www.arch.ttu.edu/)

i. Most of the construction practices involve, erecting columns and beams (frames)

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followed by the stacking up of masonry infill. This method leads to diagonal tension in the infill walls and leads to spalling of the material. Hence, an alternate way to ensure earthquake resistance of RC frames with brick infill is Confined masonry. This construction technique is exactly opposite of the conventional method. The walls are built first and the concrete is poured into the tie columns and beams. This produces a structure of optimal capacity and it is also safe to build multi-storey buildings in seismic prone areas. A typical example of confined masonry is the faculty quarters and student's hostel in IIT Gandhi Nagar. Figure 10 shows the construction sequence.

Figure 10: Construction sequence for confined masonry (Jain S K et al, 2016)

j. With the advancement of our knowledge and technology, more innovative products are being introduced into the market. The patented Porotherm seismic clay block is a brick specially designed for seismic applications. It has a unique shaped vertical mortar pocket with a window that provides a tooth-likethe connection between the block and the mortar in the butt joint. This creates an excellent bond between the mortar and increases mechanical strength. Buildings built using these blocks can withstand the horizontal displacements resulting due to ground motions. (Figure 11).

Figure 11: Porotherm seismic clay block (https://clay-wienerberger.com/expertise/brick-buildings-for-seismic-prone-areas)

k. Another invention contributing to the improved seismic resistance of masonry buildings is SISBRICK. This is a special type of brick specifically designed for partition walls. This brick can withstand lateral forces up to three times the usual brick and act as an isolator by arresting the transfer of forces from the partition wall to the main wall. The product has been patented and hence, not much information about the material that goes into making these is available. It possesses certain orthotropic properties, enabling it to resist loads in the desired direction. With this absorption of movements and presenting less rigidity than the brick partition and the structure of the building, it hinders the formation of diagonal compression rods that cause damage to the heads and bases of the pillars, and damage to the partition (http://sisbrick.com). These bricks arranged in a specific manner leads to a smaller amount of required bricks to achieve seismic isolation. (Figure 12)

Figure 12: SISBRICK stacked along with the conventional bricks arranged in a specific manner.(http://sisbrick.com)

5. EARTHQUAKERESISTANT CONSTRUCTION PRACTICES FOR RC BUILDINGS:

The modern construction has been replacing the traditional masonry building units with RC buildings. Concrete can be poured into any mould of desirable shape and the steel imparts the necessary tensile strength to the structure. As a result, RC buildings find wide applications and are commonly adopted in towns and cities. The RC frame is the major lateral load resisting unit in a structure. The inertial forces induced by earthquakes are proportional to the mass and these forces are transferred from one building component to another and get accumulated near the base of the building. Hence, the columns and walls at lower storeys experience higher earthquake-induced forces. The amount and location of steel in an RCmember 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 a ductilefailure and hence is preferred over a failure where concrete fails first in compression.The structures require additional ductile detailing inorder to ensure good seismic performance.These provisions are put together in the form of a special seismic design code, IS13920-1993 for RC structures. There are various types of RC structures as follows.

- Designed for gravity loads only (predating seismic codes i.e. no seismic features)
- Designed with seismic features
- Frame with unreinforced masonry infill walls
- Flat slab structure
- Precast frame structure
- Frame with concrete shear walls (dual system)
- Open ground story structure
- Walls cast in-situ (shear wall buildings)
- Precast wall panel structure (shear wall buildings)
- With a load-bearing masonry
- With composite steel
- With timber, bamboo or others

In order to ensure the good seismic performance of the RC structures during an earthquake, the following structural criteria must be satisfied.

➢ The failure of a column leads to the overall failure of the structure (global failure) whereas the failure of a beam tends to have localized damage. Therefore, it is preferred to make the beams weaker than the columns so that the failure of beams precedes column failure providing sufficient warning for evacuation of the building. Also, repair and retrofitting of beams is much easier than columns.

➢ The beam column joint is one of the potential weak zones causing immense damage to the entire structure. Hence, an effective ductile reinforcement detailing is required for this region. Diagonal cracking & crushing of concrete in the joints should be prevented. Providing large column dimensions is effective in achieving good seismic performance. In addition, closely spaced closed-loop steel ties are required around column bars to hold together concrete in joint region and to resist shear forces (Murty CVR (2005). IS:13920-1993 recommends continuing the transverse loops around the column bars through the joint region. In practice, this is achieved by preparing the cage of the reinforcement (both longitudinal bars and stirrups) of all beams at a floor level to be prepared on top of the beam formwork of

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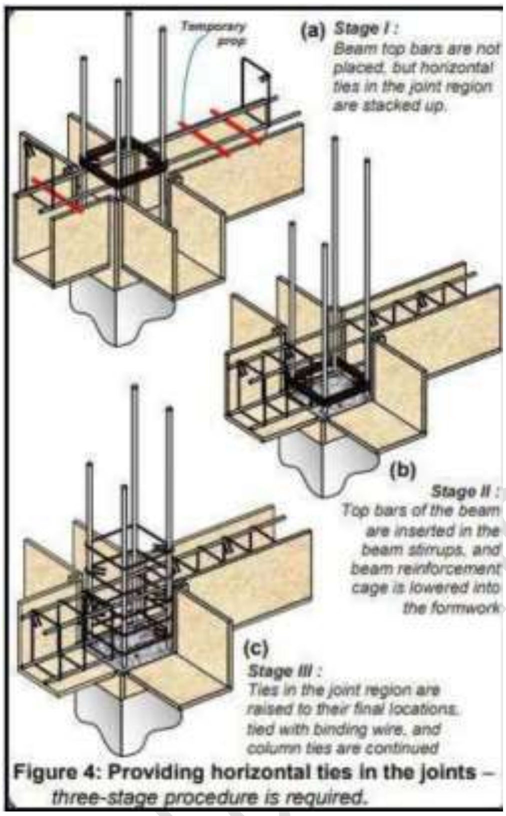
that level and lowered into the cage (Figure 13)

➢ The building plan must be simple and regular in shape. Any form of horizontal and vertical irregularity as illustrated in IS 1893 (2016) must be avoided.

➢ The grade of concrete and steel as specified in the code must be adopted for construction.

a)



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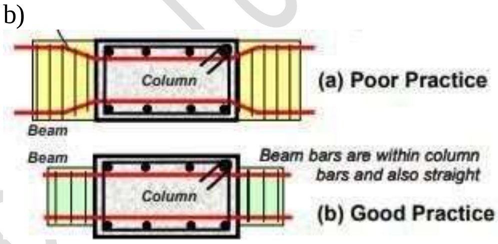

Figure 13: a) The three-stage process for placing horizontal ties in the beam-column joint b) Anchorage of beam bars in interior joints ((Murty CVR (2005))

➢ Strict adherence to prescribed standards of construction materials and construction processes is essential in assuring an earthquake-resistant building.

6. MODERN CONSTRUCTION TECHNIQUES FOR EARTHQUAKE RESISTANT BUILDINGS:

❖ *Prestressed concrete members in earthquake-resistant construction* - this ensures proper connection between various components of a structure. Further, this technology has been widely adopted in New Zealand.

❖ *Shape-memory alloys* - exhibit unique characteristics desirable in an earthquake-resistant building. They have the ability to dissipate significant energy without significant degradation or permanent deformation.The most common shape-memory alloys are made of metal mixtures containing copper-zinc-aluminum-nickel, copper-aluminum-nickel or nickel-titanium. This specific smart material is being widely researched to explore its extensive applications.

The important structures such as hospitals, fire stations,and other public buildings need to remain functional after an earthquake. In order to make this possible, the response of the building to seismic load must be controlled using suitable control devices such as:

❖ *Base isolation*is one of the widely accepted and adopted approaches for protecting the building from seismic forces. It is a collection of structural elements responsible for decoupling superstructure from the substructure. When the ground supporting the foundation of the building shakes, this component undergoes lateral displacement while keeping the structure intact. There is considerable interest now in base-isolated systems among earthquake engineers – especially in countries like Japan, USA,and New Zealand – with an eye towards developing cheaper systems with broader applications.

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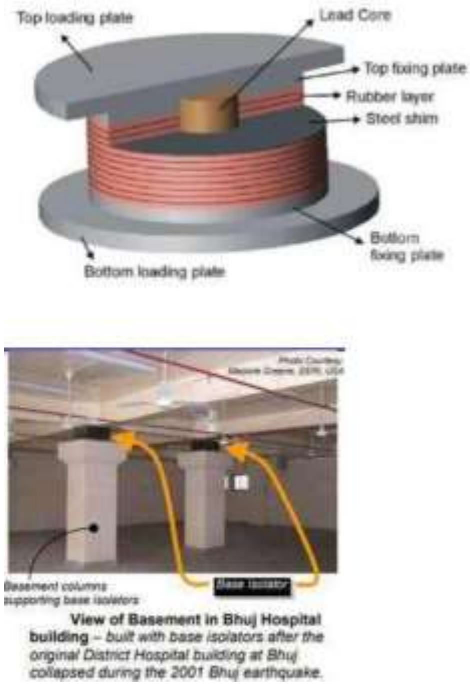

Figure 14: Base isolation device ((Murty CVR (2005))

❖ *Seismic Dampers* **-** Diagonal braces in a moment resisting frame were used as an effective lateral load resisting system. However, recent developments in the area of structural seismic response control have led to the replacement of these bracings with seismic dampers as shown in Figure 15. 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 reduce the magnitude of the force acting on a structure. 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).In India, friction dampers have beenprovided in an 18-story RC frame structure in Gurgaon.

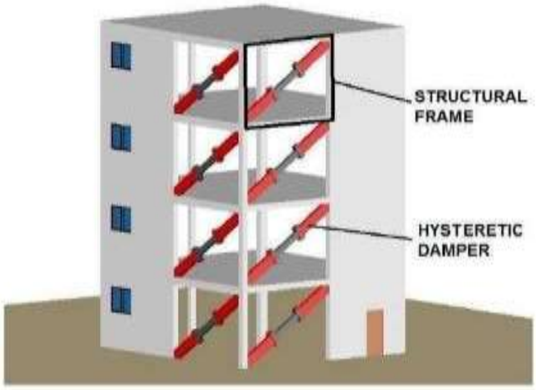

Figure 15: Seismic Energy Dissipation Devices (Abarkane et al, 2017)

❖ *Steel Plate Shearwalls*–Shear walls are considered as an essential component of a lateral load resisting systems and steel is well known for its ductile behavior. Combining these two desirable properties, an effective load resisting system was developed and has found wide applications in Japan and North America. These walls are designed in such a way that they bend instead of buckling under the action of lateral loads. These walls are significantly thinner and lighter, thereby reducing the building weight. Further, these walls need not be cured and hence, speeding up the construction process.

❖ *Carbon Fibres* – the tensile characteristics and the stable nature of a spider web was studied by various researchers in Japan. An Earthquake-Resistant Building Made with Carbon Fabric - resembling a giant spider web has been constructed in Nomi City of Ishikawa Prefecture in Japan. This is the world's first seismic reinforcement structure made of carbon fiber material.

Figure 16: The use of carbonfibers for constructing an office building resembling a spider web (http://www.ecobuildingpulse.com)

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7. **FUTURE TRENDS**:

❖ Blue mussels can be found clinging to rocks and sea decks all along the coast of New England. They are anchored in place by a stringy outcrop of cabling that emerges from between their twin shells. Usually, even the most vicious of high tides can't pry them loose. To stay attached to their precarious perches, mussels secrete sticky fibers known as byssal threads. Some of these threads are stiff and rigid, while others are flexible and elastic. Researchers are trying to incorporate this particular feature into structures in order to make the building withstand earthquakes.

Figure 17: A Blue mussel found along the coast of New England. (https://www.nbcnews.com/science

❖ A team at Blume Earthquake Engineering Centre, USA, led by Deierlein are working on an innovative technology known as the rocking frame, which consists of three basic components -- steel frames, steel cables, and steel fuses. During a seismic event, energy-dissipation is allocated to a fuse while the post-tensioning (PT) cables restore the frame to its initial configuration. When an earthquake strikes, the steel frames rock up and down. All of the energy gets directed downward to a fitting that houses several tooth like fuses. The teeth of the fuses gnash together and may even fail, but the frame itself remains intact. Once the shaking has stopped, the steel cables in the frame pull the building back into an upright position. Workers then inspect the fuses and replace any that are damaged. The advantage is that the building can be reoccupied quickly after an earthquake.

❖ Seismic Invisibility Cloak – A series of the borehole is dug around the periphery of the structure that needs to be protected. These boreholes appear to work as a ―seismic cloak‖ that could hide a building—or perhaps an entire city—from an earthquake's deadly waves. This makes the use of isolators, dampers, and other vibration response control devices obsolete.

Figure 18: Sensors fitted on top of the concrete blocks to monitor the seismic waves near the boreholes (http://www.pbs.org)

❖ A cardboard can become a sturdy, durable construction material. Japanese architects have designed several structures that incorporate cardboard tubes coated with polyurethane as the primary framing elements. The Transitional Cathedral -- in Christchurch, New Zealand was constructed using 98 giant cardboard tubes reinforced with wooden beams. The cardboard-and-wood structure is extremely light and flexible and it performs much better than concrete during seismic events. And if it does collapse, it's far less likely to crush people gathered inside.

Figure 19: The Cathedral in Christ Church, New Zealand. (https://science.howstuffworks.com)

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❖ Levitating Houses – A Japanese company has developed an idea where a house in stable condition rests on a deflated airbag. When the sensors detect a vibration, they switch on the compressor which turns pumps the air into this bag. This airbag lifts the house by 3cm from its foundation. The structure will hover for the duration of the quake and then the airbag deflates and the structure settles to its original condition. This technique can be fitted to new homes of appropriate weight and also, can be used to retrofit the existing house.

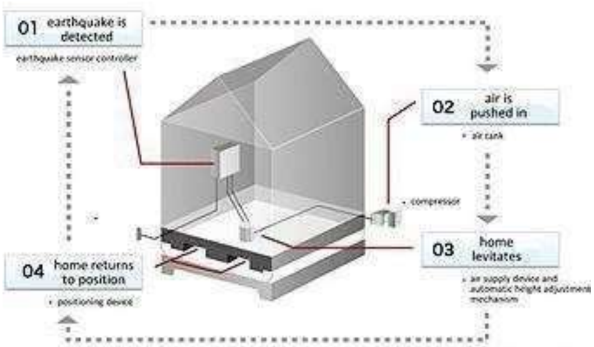

Figure 20: Levitating house by deploying airbags. (http://award.designtoimprovelife.dk/nomination/243)

❖ Another research team from ARX PAX (California) has filed a patent for the levitating house. The mechanism is quite different from the Japanese and this may find wide applications is tall buildings. This technique consists of a three-part foundation system for supporting a building. They are a containment vessel, a buffer medium,and a construction platform. The building can be constructed on the construction platform while the buffer medium can be a fluid, a gas or a liquefiable solid. The containment vessel is subjected to lateral forces which transfer the load to the buffer medium. This medium acts as a damper and significantly reduces the forces being transmitted to the building. The system can levitate the building for around 90seconds which are considered as the average time of the earthquake.

❖ *Eco-friendly ductile cementitious composite (EDCC) spray* – A research team from the University of British Columbia (Vancouver, Canada) has developed a new radical approach to make the buildings resist earthquakes. EDCC combines cement with polymer-basedfibers, flyash, and other additives in making it eco-friendly and has been engineered at a molecular level to be strong and malleable at the same time. This material when applied as a thin coating (10mm), was found to have improved seismic resistance of the structure by withstanding an earthquake of intensity 9 to 9.1 on Richter scale (Tohoku earthquake, Japan, 2011). At present, this technique has been suggested for retrofitting of the existing structures such as an elementary school building in Vancouver.

Figure 21: Plastering a wall with Seismic resistant concrete. (https://news.ubc.ca)

8. CONCLUSION:

The researchers all over the world are attempting to produce cost-effective and efficient construction technology by making use of the locally available materials. For example, in Peru, researchers have made traditional adobe structures much stronger by reinforcing walls with plastic mesh. In India, engineers have successfully used bamboo to strengthen concrete. And in Indonesia, some homes now stand on easy-to-make bearings fashioned from old tires filled with sand or stone. It wasalso found that even the non-engineered constructions sometimes possess the required resistance to earthquake ground motions. For example, the Assam-type traditional housing in North-eastern states and the Dhajji-Diwari buildings in Kashmir have good earthquake resistance. The earthquake-safe construction technology should mainly involve usage of materials of ductile nature, earthquake resilient building configuration, lightweight structural components to reduce the seismic forces and robust architectural forms.

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