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Novel Techniques for Seismic Performance of High Rise Structures in 21st Century: State-Of-The Art Review

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Abstract. Natural disasters like earthquakes are causing catastrophic failure for various structures in and around the world because of its unpredictable nature. Even in India, almost 80% of, India's capital, Delhi's buildings are not earthquake resistant. If at all there is a moderate earthquake in Delhi, millions of lives and huge of property will be lost. There are many places in India including four metropolitan cities, in which majority of high rise buildings are not earthquake resistant. It is important to account for damage caused by earthquakes, incorporating suitable resistant techniques for the safeguard of the people. The present study deals with highlighting the novel techniques adopted in the recent past to make the structures earthquake resistant. Performance based design is one such approach where in performance of structure is given the utmost importance unlike the existing standards. Lateral load resisting systems like chevron braces, knee braces in combination with aluminium shear links are found to reduce the impact of earthquake on the structures w.r.t its drift. It is also observed that the use of economical and feasible passive and active control vibration systems like dampers, isolation techniques led to revolutionary changes in the overall performance of high rise.

1. Introduction

An earthquake is sudden shaking of ground which is usually caused due to slip along the faults lines which results in sudden release of energy in the earth's crust. Due to this, seismic waves are generated. All structures in Civil Engineering entirely rest on foundations which eventually rest on the soil strata below them. So, when an earthquake occurs, it transfers its energy to the foundation and then to the structure. Hence understanding the ground motion is very important for taking precaution of structures and eventually saving lives of people. The structural components of the buildings such as beams and columns are designed in such a way that they can resist vertical loads due to gravity and horizontal loads due to wind and earthquake. The members which are actually carrying the loads are part of structural system, whereas all other members can be considered as non-structural. All types of loads acting on a structure under consideration must be transferred to the foundation with a continuous path. Also, the design of connections should be such that they can resist the loads and transfer them to the foundation. If some of the structural elements are not designed adequately, proper load transfer won't take place. Especially in India, we rarely find buildings built with earthquake resistant design. According some newspaper survey, 80% of India's capital Delhi's buildings are not earthquake resistant, which may lead to loss of life and property even in the case of a moderate earthquake. Generally, the seismic resistant buildings are costlier than the normal buildings. In spite of this fact, they are unable to provide enough resistance to the lateral seismic loads during earthquakes. Performance based design can give economic designs with more surety of safety. Nowadays, Reinforced Cement Concrete (RCC) Structures is the first priority of engineers as it is very economical. Recently tall buildings are being built in large scale. The main reason behind this is tremendous increase in population and scarcity of land. This tall RCC structures alone cannot resist these ground motions due to earthquake. According to code provisions seismic analysis is one of the major constraints for the design consideration of the building. But only

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providing more reinforcement in the structure doesn't ensure the increase in the ductile behaviour of the structure. In fact, the detailing is the most important part of the design.

In RCC structures, as the number of storeys (overall height) of the structure increases, the lateral loads due to wind also increase significantly. Various limits are imposed by codes of practice on the horizontal movement of the structure (sway).
These limits on lateral deflection of the structure are must so as:

- To avert restrictions on the use of building,
- To eliminate unfavourable changes in the behaviour of non-structural elements,
- To reduce the degradation in the appearance of the structure,
- Not to cause any discomfort for the residents

2. Performance Based Seismic Design

In brief, Performance Based Design can be defined as the design to achieve the desired results instead of sticking to prescribed means such as IS codes in India. PBD guidelines are expected to be in the next generation code. Engineers will be asked to design structures satisfying performance requirements. In this approach, instead of return period or partial safety factors concept, the probability requirements will be set to satisfy the performance requirements. At present, we do not have necessary reliability evaluation technique that will satisfy the professional requirements or
the deterministic community.
The PBD aims to develop a design system in which

- The owner and the structural designer of a building concurrently decide its performance level.
- The structural designer supposes appropriate structural system and elements selecting the suitable design and calculation methods.
- The structural designer checks whether the building satisfies the established performance level. [1]

Performance Based Seismic Design, the new evolving research for the design of the earthquake resistant structures which take into consideration the seismic loading and the performance of the structure during such events. It can be much more economical than the conventional design. It always ensures safety of the people.
The significance of this design system is summarized as follows:

a) Introduction of market principles into the field of structural engineering
b) Promotion of the development of building structural engineering technologies
c) Possibility of the more flexible design
d) International harmonization of structural engineering

Types of Evaluation Procedures [2]:

a) Proposed evaluation procedures
b) Conventional evaluation procedures
c) Small building evaluation procedures (no structural calculation required)
d) Other alternative evaluation procedures requiring expert judgement.

The technique of Performance Based Seismic Design (PBSD) was given more importance by the engineering and research community from 1994 [Northridge Earthquake]. Performance based Plastic design (PBPD), derived from PBSD method, is said to be ideal method for seismic design of structural elements in the future. The design of the structural elements is based on the performance of the structure predicted when the structure is subjected to earthquake. The main requirement is that the structure should be designed in such a manner that it should meet certain performance objectives when it is subjected to the rarer seismic events that might be experienced by it in its lifetime. Suggestions are given to

- Clarify and simplify the steps for PBSD of structures, based on the capacity design.

- Compare the two methods of seismic design of the structure (force-based method and displacement-based method) and decide its acceptability [3].

The performance based seismic design theory originated from the displacement approach of seismic design whereas the current method of seismic design of structures is force-based. The main objective of the displacement based method is to control the sway [lateral displacement]. The confusion is always there because different codes suggest different performance characteristics. This confusion can be avoided by using the Performance Based Seismic Design. The damages of non-structural elements should also be prevented. For this the displacement checks are carried out in the serviceability stage. Detailing is the most important thing which is responsible for the energy-consuming capacity and ductility of structure [4]. Traditional earthquake resistant design considers the base shear (force/strength approach), to achieve the most important goal i.e. to ensure safety of lives of people. Various numerical examples are demonstrated to prove the applicability of the simple procedure suggested. The proposed design procedure of "performance-based design" is transparent and very easy to use [5]. In the seismic resistant design, the emphasis is changing from "strength" to "performance". Initially strength and performance have been considered to be synonymous. The capacity spectrum approach, the N2 method are force based procedures. Two performance limit states Fully Operational and Damage Control performance limits should be considered [6].

- New performance verification procedures involve
  - Use of ESDOF system (Equivalent Single Degree of Freedom) for the application of equivalent linearization technique
  - Analysis of the structure with the help of response spectrum method
- Earlier procedures were based on the structure's ultimate capacity of resisting the lateral loads [7].

PBSD is based on the methodology of elastic design. It depends on the probable performance of the structure when subjected to various ground acceleration. Performance Based Plastic design method, a derivative of the PBSD method, is a direct design method This method begins from the pre-quantified objectives of performance. The plastic design is performed to detail the structural elements and connections so that the structure can achieve the intended yield mechanism and behaviour [8].

3. Lateral Load Resisting Systems

The structure under consideration has to resist the lateral loads due to wind and earthquake. The loads on the structure won't have any effect on the beams. But the complete lateral loads will be resisted by the columns alone. The entire structure can be considered as a vertical cantilever. The structure has loads in both the lateral directions so the moment of inertia in both the directions should be more. The provision of extra structural members (shear walls, bracings) in the structure is basically to increase the moment of inertia of the structure in lateral directions.

The tube system basically shifts the columns to the outer region of the structure which were initially at the inner region of the structure making it hollow and thus increasing the moment of inertia. Shear walls are very large in length in one direction as compared to the other direction. Therefore, they have more moment of inertia in one direction. Thus, building is stiffer in the direction parallel to the length of the shear wall then the direction perpendicular to it.

Lateral Sway is the displacement of a structure in lateral [horizontal] direction caused due to any of the following reasons:

1. Columns with different heights.
2. Columns with different sectional properties.
3. Due to differential settlement or unsymmetrical loading.
4. Due to lateral loads such as earthquake and wind acting on the structure.

Ways to Minimize the Sway

- A stiffer moment resisting frame can be made by increasing the size of members (Uneconomical for more than 7 or 8 storeys).
- Stiffness of the flexible structure can be increased by providing shear on the external walls, lift shaft or the stair well (a core).
- To provide a tubular arrangement of columns which basically changes the arrangement of columns making the structure a hollow cantilever perpendicular to the ground.
- To provide bracings
- Constructing a very rigid beam-column joint which permit moment transfer across the joint. (Monolithically-poured reinforced concrete structures inherently have moment-resisting joints).

Traditional Lateral Load Resisting Systems mainly include.

3.1 Bracing Systems

The concept of bracings, as shown Fig 1, is explained with the help of two simple structures. When two structures one, normal square structure and the other, square with diagonal are laterally loaded [shear force], the normal square structure will deform easily whereas square structure with diagonal resists more lateral load. A normal square structure requires rigid joints if used as a lateral system to resist wind/seismic loads. Axial rigidity doesn't come into picture in case of square. In case of square structure with diagonal, part of the shear load is resisted by the diagonal element [axially].

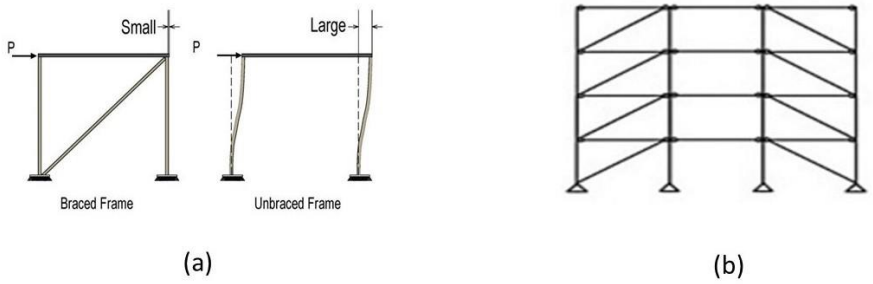


Fig 1. (a) Difference between Braced and Unbraced Structures [24]; (b) Single diagonal bracing

Bracing are provided in the structure:

- To minimize the buckling of the main structural elements
- To help in load distribution
- Dimensional control.

Types of Bracing (shown in Fig 2 (a) – Fig 2 (d))

1. Single Diagonal Bracing
2. Cross Bracing
3. V Bracing
4. Eccentric Bracing
5. K Bracing

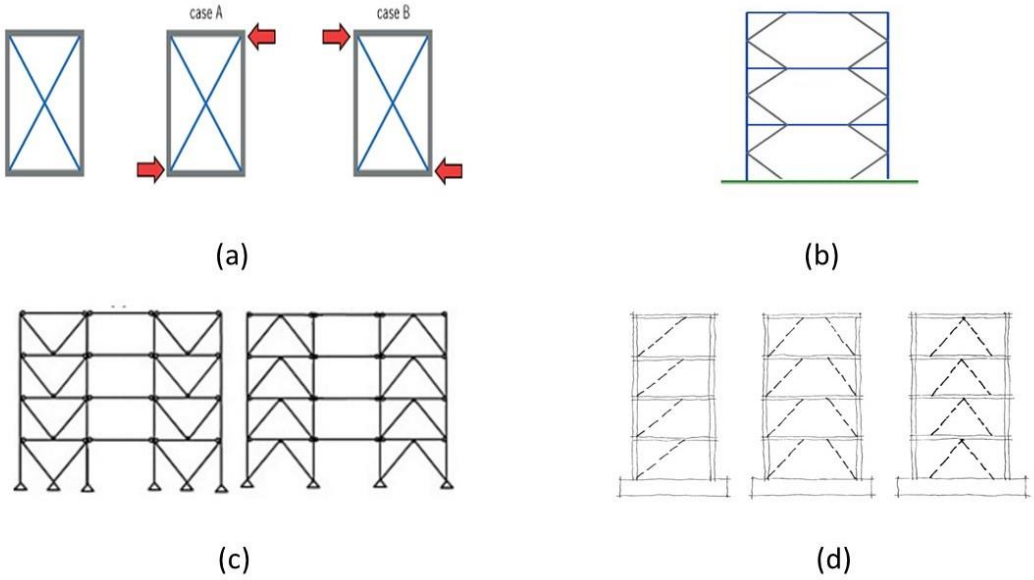


Fig 2., (a) Cross Bracing, (b) K-Bracing, (c) V-Bracing, (d) Eccentric Bracing [25]

3.2 Tube Systems

The idea of tube system basically depends on the comparison between building and a vertical cantilever. A structure can be thought of as a hollow cantilever beam which resists lateral loads due to wind and earthquake. Typically, in the tube system, the columns are closely spaced on the perimeter of the building which are held together with the help of beam elements via moment connections. Such combination of structural elements forms a stiffer frame which minimizes the lateral displacements of the structure. A graph showing comparison between different types of lateral load resisting systems is shown in Fig 3.

The exterior columns which are placed on the exterior of the building are designed adequately so that they can resist all lateral loads due to wind and earthquake. This allows structural engineers to design the interior columns of the building based on the gravity loads alone. The number of interior columns is very less as compared to exterior columns and they are located near the geometrical centre of the plan of the building. The space between the exterior and interior columns is connected with beams/trusses (depending on the distance between them) and is column-free. Thus, the efficiency of the outside tube is maximized by transferring some gravity loads of the structure to it. It also increases the ability of the structure to resist overturning due to lateral loads such as wind and earthquake.

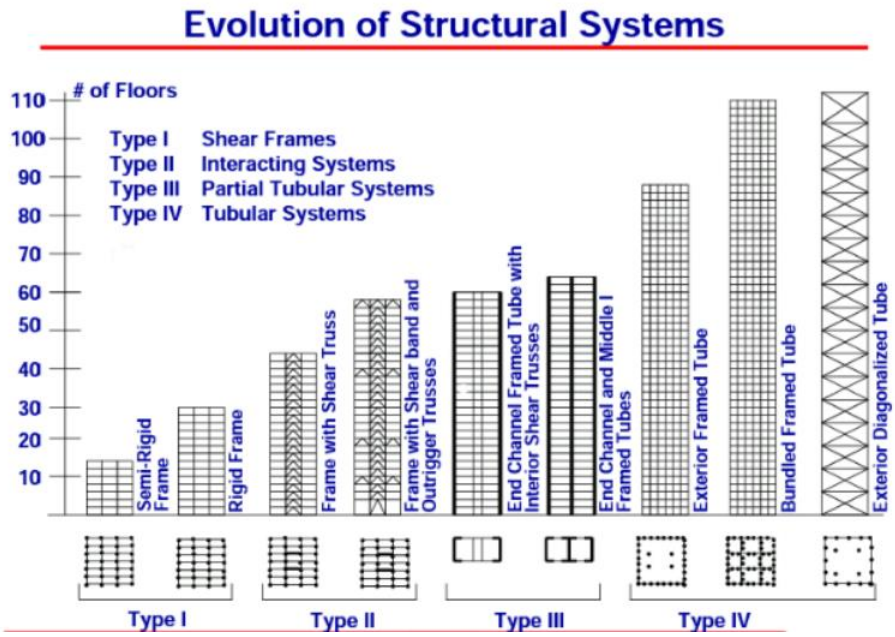


Fig 3. Comparison between Tube System and Other Systems [28]

Tube system can be defined as 3-D space structure formed by joining various structural elements to form a structural system, which resembles vertical tube, capable of resisting horizontal forces due to wind and earthquake in any direction. The tube system is formed by the closely spaced interconnected exterior columns. Horizontal loads, like wind for example, are supported by the structure as a whole. Almost more than half of the exterior surface can be used for openings such as windows. As the number of interior columns is very less, framed tubes have more usable floor space. Wherever very large openings such as garage doors are required, the tube system has to be interrupted. In such case, transfer girders can be used to maintain the integrity of the structure.

Bracings can help to resist the lateral loads of the buildings with number of storeys less than sixty. The four different types of tube systems are given below:

1. Framed Tube System: This system is a normal structure with most of the columns placed along the periphery very close to each other.
2. Braced Tube System: This system is a tube system along with the X bracings at the exterior of the building which help in reducing the shear lag to maximum possible extent.
3. Tube in Tube System: In this system, there will be one more tubular structure along with the exterior tubular structure which helps in reducing the shear lag.
4. Bundled Tube System: In this system, multiple numbers of individual tubes are assembled to resist the maximum possible lateral loads and minimize the shear lag **[9]**.

For a building more than 60m in height, only beam column moment resisting joints are not sufficient to resist all the lateral loads. So, to achieve this goal, additional lateral load resisting systems should be used. The graph [Maximum Deflection vs Building Height] showing the permissible deflection and computed deflection is drawn. Generally, the computed deflection of the building of a particular height should always be less than the permissible deflection. The height at which the computed deflection starts overtaking the permissible deflection is the maximum permissible height of the structure to be built with the lateral load resisting system under consideration. In case of Tube in Tube system, a separate analysis is done for both core as well as frame. The fact that the lateral load resisting capacity of the core (inner tube) goes on reducing with increase in height [10]. The main objective of this study is to study the effects of changing various design parameters and compare. The performance of a 40-story building is

studied by varying the values of the design parameters using ETABS. Using multiple internal tubes helps reducing the shear lag and the interior columns also resist some part of the lateral loads along with the gravity loads. The non-linear stress distribution caused in the tube system is due to the shear lag. Increase column depth, decreases corner columns axial force and increases middle columns axial force and subsequently distribution of axial forces become closer to the ideal state [11]. The concept of negative shear lag is explained in this paper with detailed explanation of its origin. The column axial force distribution is separated in two different types- positive shear lag and negative shear lag. The behaviour of a hollow box girder is similar to that of a framed tube structure [12].

The main problems which need to be addressed in case of tube systems:

1. Positive and Negative Shear Lag
2. No space for windows and other openings
3. Deep beams

3.3 Shear Walls

Shear Walls also come under the category of structural elements (along with slabs, beams and columns). Shear walls typically start from foundation level and they span the complete height of the building. The thickness of shear walls ranges from as low as 150mm to as high as 400mm (in high rise structures). These walls are generally provided along both the horizontal directions (length as well as width of buildings). Shear walls can be thought as vertical deep beams which carry lateral loads due to wind and earthquake downwards to the substructure. The structures incorporated with shear walls, which are adequately designed and properly detailed, have shown good resistance in past earthquakes.

Special care has to be taken while detailing shear walls in buildings which are higher seismic zones. Though the previous statement is correct, it is seen that buildings with adequate shear walls (not specially detailed, but had properly distributed reinforcement) did not collapse in past earthquakes. Buildings with shear walls are preferred in many earthquake prone countries. They are cost efficient, at the same time they are effective in minimizing the damage in structural as well as non-structural elements due to lateral loads such as wind and earthquake.

The columns in a RCC structure generally carry vertical loads such as gravity loads (dead load and live load of the building). Shear walls have very large moment of inertia in the direction of their orientation. Hence, they provide large stiffness to the buildings in the direction of their orientation. This reduces lateral displacement or sway of the building drastically. Thus, damage to structure and its contents is reduced.

Main problem with providing Shear walls is that it can result in large overturning. Thus, special attention is required while designing the foundation of shear walls. Shear walls should be provided in both directions. If, due to some reason, they have to be provided along only one direction, then a proper orientation of the other structural elements in the vertical plane has to be provided along the other direction to resist lateral loads in that direction.

New and Innovative Lateral Load Configurations

1. Steel Plate Shear Wall (SPSW)

Why better than conventional reinforced concrete shear wall?

- Lighter weight resulting less inertia forces and in turn less foundation cost
- For architects, the increased versatility and space savings
- Faster construction which compress the project duration Shop-welded/field-bolted SPSW thus better-quality control
- Construction activity relatively pollution free
- Overall cost: Much economical than RC shear wall

Some better properties of SPSW

- Post buckling strength significant enabling use of very thin panel
- High initial stiffness thus effective in drift control for serviceability
- Large energy dissipation hence efficient in high seismic zone
- Ductility Superior resulting lighter structural configuration

2. Expanded Mesh Shear Wall (EMSW)

An earthquake resisting system which is a combination of:

- Expanded Metal Mesh (EMM), A sheet metal, slit and stretched into uniform-sized, diamond-shaped openings.
- Boundary frames similar to SPSW

EMSW resembles same configurations as that of SPSW (except solid infill expanded mesh is used).

Structural elements in multi-story steel building frames can be damaged and may need repair after strong earthquakes. Conventional structural systems, like moment resisting frames, concentric or eccentric braced frames, are not advantageous in respect to reparability. For this reason, two innovative systems with dissipative fuses were introduced and studied in the frame of a European Research Program with the name "FUSEIS" (1, 2). The first, FUSEIS 1, which is described here, is composed of two closely spaced strong columns rigidly connected to a number of beams between floors. Energy dissipation and potential damage during strong ground motions concentrate in these short beams only that constitute the fuse elements. Repair work, if needed, is therefore limited to the fuses only. Actually, the fuses may be completely replaced, an easy task given their small dimensions and the fact that they are connected by bolted connections to the columns. An exterior beam-column joint detail is shown in Fig 4.

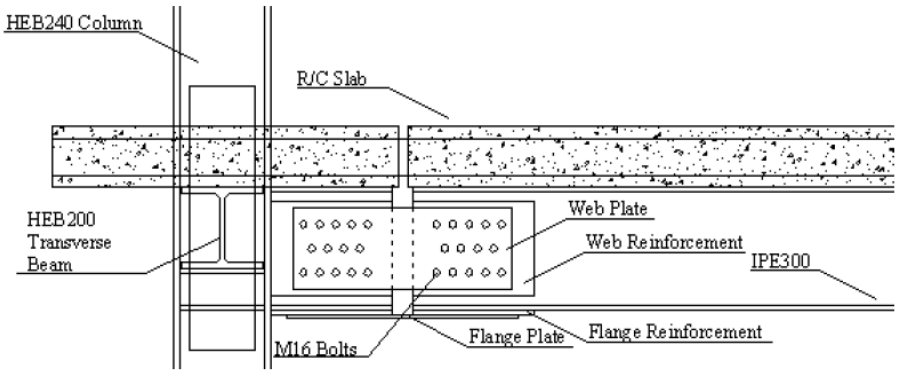


Fig 4. Exterior Beam-Column Joint Detail [27]

The FUSEIS system combines strength, stiffness, ductility and architectural transparency. It is cost-effective in respect to initial installation and replacement/repair. The fuse elements and the overall system were studied experimentally and analytically [13].

4. Aluminium Shear Link

Aluminum shear links are provided in a structure to increase its lateral load caring capacity. Whenever a structure is subjected to a lateral load such as wind load or earthquake loads it is venerable to failure. In extreme cases the designed RC frame structure is not sufficient to take the seismic loads. The main reason a building fails is because it cannot withstand the deflection caused by the earthquake due to insufficient energy dissipation which results in the loss of lives and property on large scale. Discovering an economical method to design the structure to sustain a large scale earthquake and remain operable

with minimum repair is a big challenge for a structural engineer. Large amount of work is being put into the research of such methods. One such method is the use of Aluminum Shear Link in bracing [18].

Many of the structures that fail in an earthquake are mainly because of insufficient lateral load resisting strength or stiffness and inadequate potential to dissipate the energy of earthquake. There are many ways to increase the seismic performance of RC structures of which one such way is the use of Steel Bracings. Bracing is a very effective method to increase the global stiffness of the structure which reduces the design requirement against the seismic loads for the RC structure. However, there are few disadvantages of bracing system. Due to the lack of energy dissipation potential of the steel bracing, the take up large amount of residual deformation after a heavy earthquake which result in buckling. This buckled bracing needs to be replaced which again highly labor intensive and expensive. In addition, bracing transmits high action to the foundation which may require the upgradation of the existing foundation at the bracing location. Many devices have been developed to dissipate the energy of the earthquake and to reduce the damage in the Primary structure. This device can be used to eliminate the limitations of the Steel Bracing system.

The use of Aluminum Shear Links is one of the methods to reduce the damage to the structure. They can be used as a passive Energy dissipation system using to control the seismic response of the structure. Flanged section of a ductile aluminum alloy can control the load transferred to the primary structure due to dynamic loading. This is achieved by the shear yielding of the aluminum section which mitigates the effect of this loads and also act as an energy dissipater. This system can also be understood as a damping device which absorbs the energy induced due to earthquake in the form of inelastic deformation which reduces the energy dissipation demand of the primary structure. This makes the Aluminum shear links a good option as a lateral force resisting system.

Aluminum Shear links work on the principal of Metallic Hysteresis i.e. under the action of cyclic loading aluminum links exhibits fully symmetric loop due to shear yielding. Aluminum is used due to its high ductility and low yield strength. On testing the links with cyclic loading to test the hysteretic behaviors, it was observed that the material shows fully symmetric behaviors and can be used as an energy dissipation. Mainly two types of alloy of aluminum are used which are Aluminum (3003-O) and Aluminum (6061-O). This links was also tested for fast cyclic loading rate such as 5 Hz, 10 Hz, 17 Hz to study the effect of strain rate. Full hysteresis loops were observed until 10 % shear strain which means the links can be used for a high range of strain values without hindering its performance [19].

Seismic Strengthening of a RC structure can be achieved using Aluminum Shear links as passive energy dissipating devices to enhance the lateral dynamic load bearing capacity. The link can be connected to the existing RC beam with a collector beam and chevron braces such whenever the structure is loaded under lateral forces, the link deforms under shear. As the main function of this links is to dissipate the input energy, proper load transfer mechanism from the existing RC columns and beams should exist. The aluminum shear link is not directly connected to the existing RC frame; instead, the frame lateral load was indirectly transferred to the shear link through a shear collector beam placed just below the existing RC beam and connected to the RC columns through pinned connections. Experimental arrangement to test Aluminum Shear Link is shown in Fig 5.

The top flange of the Shear link is connected to the collector beam which primarily carries the axial force under the action of lateral loads. Whereas the bottom flange od the link is attached to the chevron bracings. These bracings are designed such that they remain elastic for the axial force which is greater than the failure strength of shear links. Since the shear link reduce the lateral load demand on the existing RC structure through energy dissipation, no additional strengthening needs to be done.

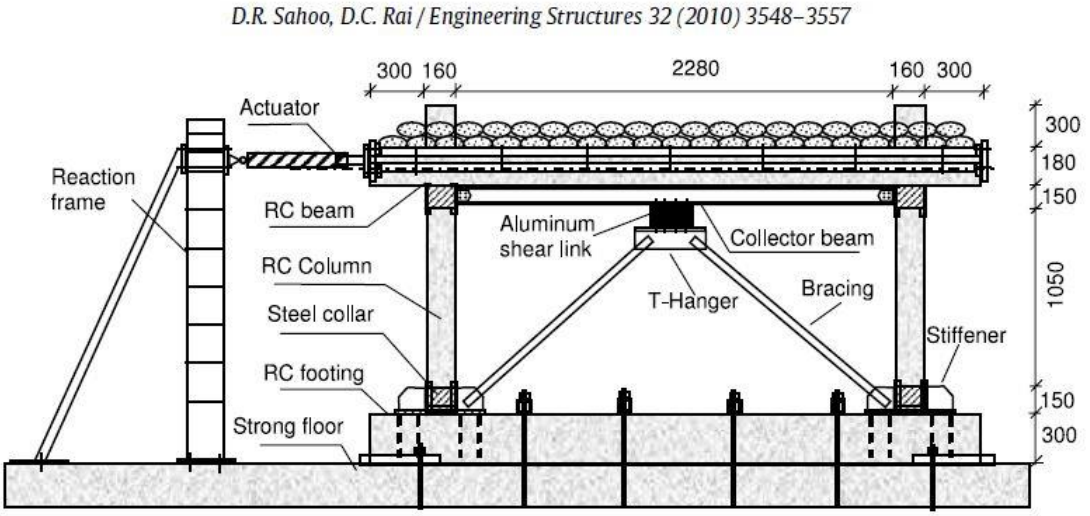


Fig 5. Experimental arrangement to test Aluminium Shear Link [18]

Shear links are designed mainly on two parameters, strength and ductility requirement of the structure and maximum magnitude of earthquake possible. The horizontal area of the web of the shear-link is calculated by dividing the shear force transferred to the link by the collector beam by a design shear stress of the link corresponding to a limiting value of shear strain. This shear stress for a given shear strain γ in a shear-link is given by a power equation: $\tau_{avg,\,max} = 2.6.\ \sigma_{0.2}.\ \gamma^{0.2}$ where 0.2 σ is the tensile stress at which the material yields corresponding to 0.2 strain. It is assumed that the maximum shear that the link can take corresponds to 0.2 shear strain, after which the link is presumed to fail. Experimental data suggest that an upper bound estimate of the maximum shear capacity of the link, i.e., $\tau_{max} = 1.88 \cdot \sigma$ 0.2. Design shear strain for a shear-link can be assumed equal to the allowable story drift, but should not be more than 0.1 strain because link shows excellent load carrying capacity and hysteretic behavior below this Strain level [20].

5. Self-Righting

The concept of self-righting refers to the ability of an object or living thing to go back to original position after undergoing some deformation due to external loads. The ability of terrestrial animals with rigid shells to go to original position when turned upside down is also an example of self-righting. Generally, terrestrial animals can go back to their normal shape with the help of their strong muscles (movement of legs or neck). But some species of turtles can go back to their original position with the help of only their geometrical shape [21]. The model of self-righting structure is shown in Fig 6.

Based on the concept explained above, a group of scientists from Japan and Stanford University, University of Illinois designed a system which can resist simulated earthquakes of magnitudes greater than 7. This system makes the buildings more damage resistant and easily repairable [22].

The energy generated by the earthquake waves is dissipated through the movement of steel frames. The steel frames can be situated around the core of the building or can be along the periphery of the building. The frames can be a part of the building initially or can be added during retrofitting. To minimize the rocking and recentre the structure to its initial position, steel tendons are used which run from top to bottom at the centre of the frame. When the lateral load stops acting, these tendons regain their normal length, pulling the building back into proper alignment. At the bottom of the structure, fuses are used to keep the structure undamaged. Like electrical fuses, the steel fuses used can be replaced without much

effort when damaged. The frame after an earthquake seems undamaged. The fuses used alone absorb the energy and will yield/deform [23].

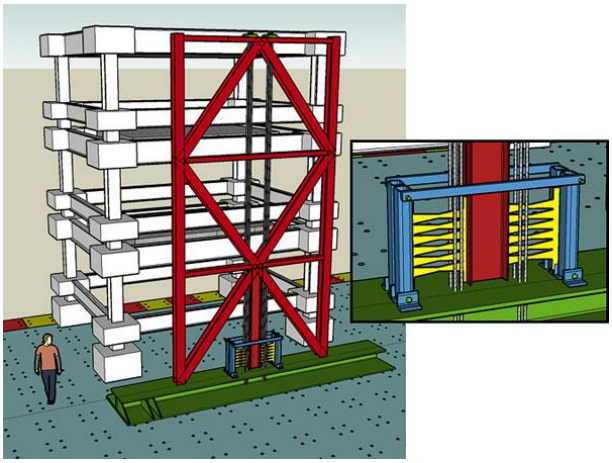


Fig 6. Self-Righting Structure [26]

It not only will save lives of people but also minimize the cost of repair. The buildings can be habituated immediately after the earthquake thus causing less disruption to society. This will reduce long economic downturns and social disruptions after an earthquake along with other environmental benefits.

6. Summary

The research towards earthquake resistant design philosophy has been increasing day by day. There is a need to safeguard structures which are prone to earthquake. This study made an attempt to address some of the recent techniques which are adopted for structures in high seismic regions. The following are some of the salient points from the study.

- Performance Based Seismic Design contains the guidelines for the design of modern earthquake resistant structures which only depend on the probabilistic performance of the structure irrespective of any design code, making it safer and more economical.
- Lateral load resisting systems such as bracings, tube system and shear wall are discussed in brief.
- Out of all types, chevron bracing performs better than any other bracing during earthquakes.
- In tube system, the shear lag can be minimized by using multiple internal tubes making it one of the most efficient lateral load resisting systems.
- When detailed properly, shear walls are proved to be ideal for moderately tall structures.
- Aluminium shear links get deformed by dissipating energy released during seismic events [with very less deformation of the structural members] and can be easily replaced thus making it more economical.
- Self-righting makes the structure go back to original position after the seismic events making it ready to be occupied again in very less amount of time. Only the fuses need to be replaced making it economical as well.

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