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Study of Different Techniques in Design of Earthquake Resistant Structures

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Abstract: Seismic resistant structures are designed in such a way that they might face partial damage, but will not totally collapse during earthquakes. This design of structures depends on certain parameters like ductility, deformation capacity, strength and amount of deflection. More the ductility, strength and deformation capacity of a structure better will be its seismic resistance, whereas, lesser the amount of deflection, lesser will be the vulnerability of the structure towards earthquakes. This paper deals with the review of various techniques applied in the design of earthquake resistant structural frames without using any external seismic control device. These techniques include the use of smooth rebars and corrosion resistant hybridized columns in construction of Reinforced Concrete (RC) structures, installation of exterior shear walls to the structural frames, construction of brace framed steel structures and construction of composite structures. Smooth rebars when used for construction of RC structures provides good yield strength to the structure. Similarly when corrosion resistant hybridized columns are used in construction, it provides a high ductility and deformation capacity to the RC structures. Installation of exterior shear walls to both RC and steel structures increases their strength by 10%. For steel structures, construction of brace framed structures provides 5% more strength, and they are also seen to deflect less during earthquakes. Thus we see that in both RC and steel structures, innovative design techniques are implemented to make them seismic resistant.

Keywords: *Braced frame, composite structures, concentric braces, ductility, rebar, shear wall,*

Introduction:

Earthquake which is defined as ground motion caused by a sudden movement of the Earth's tectonic plates, do not cause loss of lives, but the structures resting on the earth surface, experience ground motion and hence undergoes damage or may totally collapse. This leads to loss of lives and enormous loss in property which ultimately leads to economic loss in a country. Since earthquakes cannot be predicted, structures are made resistant in such a way that they might undergo partial damage but will not totally collapse during an earthquake. Apart from strength and deformation capacity, earthquake resistant design of structures also focuses on ductility, which is an ability of a structure to face huge plastic deformation without loss in strength. This can be achieved by making sure that the available ductility is more than the required ductility[1, 2]. Structures are generally made up of a combination of flexible and stiff parts. This ensures that the seismic energy passed on to the structure is first absorbed in the flexible part and then gets transferred onto the stiff part [1, 3]. During an earthquake, the columns of the structures act as primary members which resist the seismic forces, owing to this fact it is seen that the use of corrosion resistant hybrid columns in Reinforced Concrete (RC) structures can reduce the residual displacement and also have enough energy dissipation capacity during earthquake excitations [4]. It is also seen that in areas of high seismic risk RC wall frame structures are constructed as it provides stiffness to the system's lateral force resistance, and also behave as ductile structures [5]. In case of steel structures, Steel Plate Shear Walls (SPSW) and Buckling Resistant Braces (BRB) are used for the design of earthquake resistant steel structures. SPSW are designed to provide better diagonal tension yield for dissipation of seismic energy, whereas BRB are special braces which give full axial yield strength both in compression and tension. Both of them are highly ductile in nature and hence provide large stiffness which limits the structural damage during earthquakes [6]. The main objective of this paper is to review the various techniques used in earthquake resistant structural frames without using any seismic control devices.

Seismic Effects on Structures:

When earthquake excitations occur it transmits seismic waves which in turn cause ground motion of the earth's surface. As structures rests on the earth surface, this ground motion is also passed onto them. The base of the structure moves with the ground but the roof tends to retain its position. But the roof is also forced to move as the walls and columns of the structure are connected. Under this condition, the structures generally tend to collapse or undergo brutal damage. This can be prevented if the structure is ductile. Ductility is defined as an ability of a structure to face huge plastic deformation without loss in ultimate strength. The ductility of a structure enables to predict the amount of seismic energy that may be dissipated through plastic deformations, which is a very important factor for structural design under seismic loads [2, 7]. Therefore we see that seismic resistant design of structural frames depend upon certain parameters like ductility, deformation capacity, strength and deflection. Now based on these parameters there are certain design concepts which are discussed below in this paper.

Smooth Rebar:

Generally concrete used for construction is batched on site, and standard quality controls like the slump test are very rarely done, which leads to formation low-strength concrete. In various damaged buildings due to earthquakes it has been found out that one of the major causes of damage was use of low strength concrete. As mitigating this problem is very hard, it is recommended to use smooth rebar reinforcements in RC structural frames as it adds to the stiffness of the RC structures in case of use of low-strength concrete and also increases the ductility of the structure as a whole. Smooth rebar's have an approximate yield strength of 275 MPa. The best arrangement being reinforcements with smooth rebar's spaced atleast 200 mm apart and having tie reinforcements with 90° hooks. A typical smooth rebar reinforcement detail is shown in Figure 1 [8].

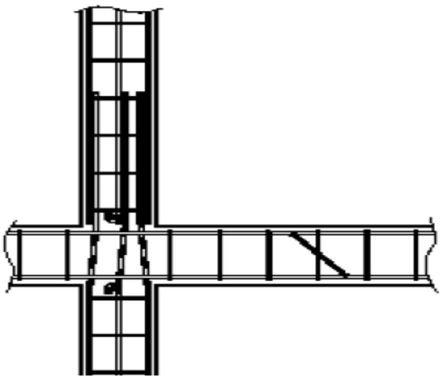


Figure. 1 *Typical beam and column smooth rebar reinforcement details*

Seismic resistant hybrid RC columns:

Fiber Reinforced Polymer (FRP) and Shape Memory Alloy (SMA) are rising as a suitable replacement of steel to reduce corrosion problems in reinforcements of RC structures. Use of corrosion resistant hybridized column such as FRP and SMA can substantially reduce the residual displacement with adequate energy dissipation capacity during earthquakes. Under seismic loading, in order to prevent shear failure and to ensure flexure dominated behavior of the hybrid columns, an aspect ratio (cantilever height to equivalent column diameter) of 6.3 and a longitudinal reinforcement ratio of 1.22 is to be maintained. The ductility comparison of the different hybrid columns under severe seismic loading has been given in figure 2 [4]. There are various Hybrid reinforcement combinations like: (a) SMA with Stainless Steel (SS) bars; (b) SMA with FRP rebar's; (c) Stainless Steel (SS) with FRP rebar are generally used. Geometry of a Hybrid RC column is shown in Figure 3. The material properties of the various Hybrid columns along with concrete are given in Table 1.

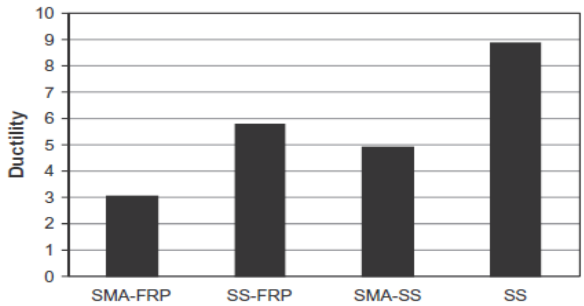


Figure. 2 *Ductility comparison of different RC hybrid Columns under seismic loading*

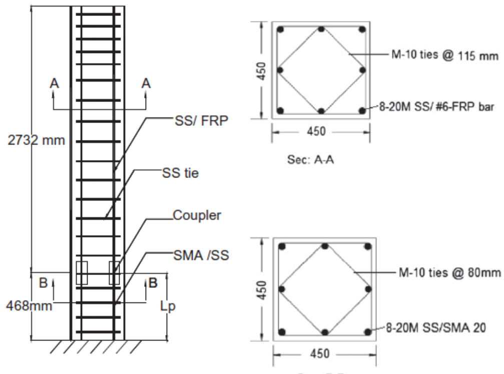


Figure 3 *Geometry of a Hybrid RC column*

Table 1

Material	Property	Value
Concrete	Compressive Strength (MPa) Corresponding Strain Tensile Strength (MPa) Modulus of elasticity (GPa)	38.33 0.0009 3.33 23.1
SMA	Modulus of elasticity (GPa) Compressive Strength (MPa) Corresponding Strain Tensile Strength (MPa)	54.2 16.8 0.008 6.2
FRP	Modulus of elasticity (GPa) Ultimate Compressive Strength (MPa) Corresponding Strain Ultimate Tensile Strength (MPa)	52.2 728 0.0004 364
Stainless Steel	Modulus of elasticity (GPa) Ultimate Strain Ultimate Tensile Strength (MPa)	190 0.55 661

These hybrid rebars are found beneficial in seismic resistance only when the hybrid materials are attached to each other with a proper connection, or else they will act separately and will be easily vulnerable to seismic failure. An economic and quick technique is required for connecting FRP with Stainless Steel and SMA to have fruitful connections at critical locations in RC structures [9]. Screw Lock couplers are best suitable for all the three types of combinations, though for connecting SMA with Stainless Steel rebar, single barrel screw lock couplers are the best suited. Similarly mechanical-adhesive type coupler is best for connecting SMA with FRP rebar and also FRP with stainless Steel rebar. It has been seen that for SMA-SS connected with single barrel screw lock couplers for a lateral stress of 400 MPa, the slip is observed to be between 3.13 mm -3.81 mm. Similarly for SMA-FRP connections with mechanical-adhesive type couplers, for the same stress the slip is observed to be between 1.58 mm – 2.01 mm. For FRP-SS connections, the slip was observed to be between 2.34 mm-2.9 mm. A stress-slip curve for different types of hybrid rebar connections is given in Figure 4 [4]. Though all the connections are good, but it is seen that the best performance for seismic resistance in RC structures is given by SMA-FRP hybrid rebar columns connected with mechanical-adhesive type couplers.

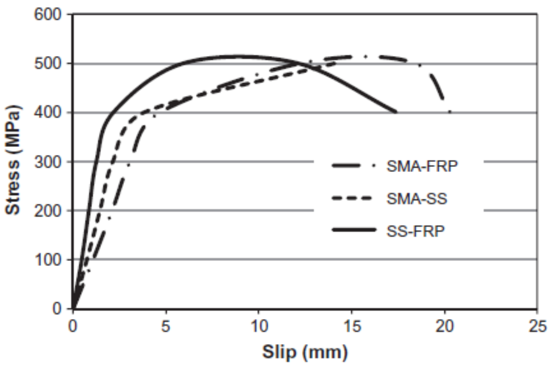


Figure 4 *Stress-Slip curve for different types of Hybrid rebar connections*

This chart shows the supremacy of the combination of SMA-FRP connected with mechanical- adhesive type couplers over the other combinations regarding deflection during earthquakes.

Exterior Shear Walls:

Installation of exterior shear walls for providing seismic resistance is applicable for both RC and steel structures. In case of RC structures to provide seismic resistance, RC shear walls installed in parallel to the structures exterior sides. Under reverse cyclic loading, it has been noted that the use of exterior shear walls substantially improves the deformation capacity and sway stiffness of RC structures. One of the most important factors of the use of exterior shear walls in RC structures for seismic strengthening is the connection between the exterior shear wall and the existing structural elements. It has been experimentally found out that during earthquake excitations, even though minor cracks occur in shear walls, the exterior shear walls, the beams and the columns of the RC structures behave as monolithic member and also the RC structures do not lose its lateral load bearing capacity which increases due to the addition of exterior shear walls [10]. In an experimental shake table test of a structural frame, it has been seen that with the installation of Exterior Shear Walls (ESW) to the structure has considerably increased the deformation capacity and the initial sway stiffness of the structure. The value of deformation capacity increased from a range of 68.7 KN-75 KN to 223.5 KN-250 KN. Planned view of the initial RC structural frame considered for the shake table test is and the planned view of the same RC structural frame strengthened with ESW is given in Figure 5. The deflection of the structure on installation of exterior shear walls reduced by 15 % [11].

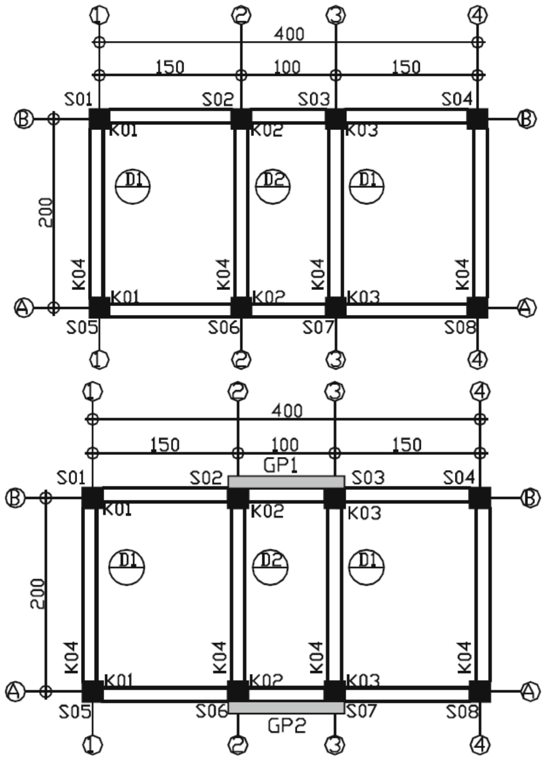
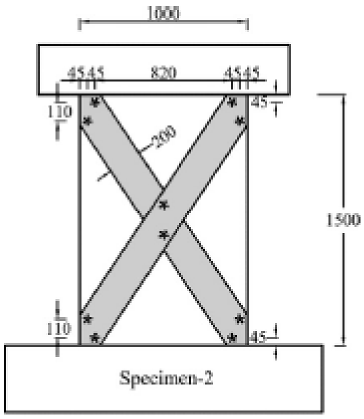
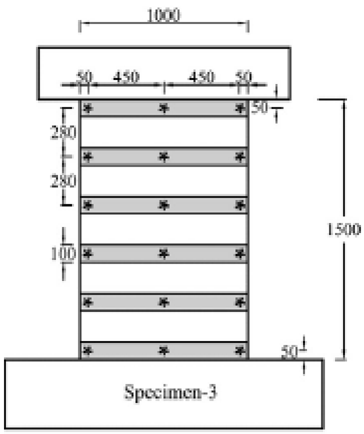


Figure. 5 *Planned view of a RC Structural frame (Left) and planned view of the same Structural frame strengthened with Exterior Shear Wall. (Right). (The shaded portion in the figure on the right represents the ESW)*

But even after the installation of exterior shear walls in RC structures it has been observed that the structures face brutal damage or total collapse during earthquake excitations. This is because slenderness ratio is one of the most important factors affecting the seismic resistance of the wall. The seismic resistance of the shear wall is dominated by flexure for slenderness values over 2.0 and is dominated by shear for values less than 1.0. Between these limits an inadequate behavior develops where neither flexure nor shear is distinct. Low reinforcement ratios, poor detailing of reinforcements leads to such situations. It has been seen that RC walls with low reinforcement ratios and poor reinforcement detailing has lead to brittle shear failure, restricting deformation capacity, thus resulting in poor seismic performance of the structure. In order to improve the seismic behavior of the RC structures in these cases, the use of exterior shear walls bonded with steel strips is found to be affective. This increases the sway stiffness and deformation capacity of the shear walls thus increasing the deformation capacity of the RC structure as a whole and also increasing its seismic resistance. The use of exterior shear walls bonded with steel strips in RC structures also increases the ductility of the structure. Shear walls bonded with steel strips in different positions and quantity is shown in Figure 6. Experimental study shows that under a same lateral load of 224 KN, different arrangements of steel strip bonding showed different type of lateral drift. For the specimen marked (1) the lateral drift is 0.60% and for the specimen marked (2) and (3) the lateral drift is 0.61% and 0.68% respectively under the same lateral loading [10]. Hence we see that for best seismic resistance of RC structural frames, installation of exterior shear walls bonded with steel strips is more efficient rather than only exterior shear walls, and more the quantity of steel strips, lesser will be the lateral drift and more will be the deformation capacity.





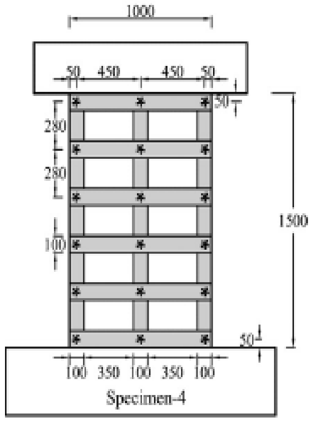


Figure. 6 *Exterior Shear Walls bonded with steel strips in different positions and quantity (Shaded area denotes steel strips)*

Exterior Shear walls can also be used in Steel structures to provide seismic resistance. These shear walls are called Steel Plate Shear Walls (SPSW). The use of Steel Plate Shear walls (SPSW) as a primary lateral load resisting system in steel structural frames has increased over the years. Research conducted proved that the SPSW's design philosophy subsequently reduces plate thickness by allowing shear buckling, which afterwards carries the lateral load through the subsequently developed diagonal tension field action [6]. Smaller thickness of panels also lowers the forces on adjacent members, resulting in more efficient framing designs. Steel plate shear walls also provide major stiffness against lateral drift in case of high-rise buildings. Generally the SPSWs are structurally integrated with roofs or diaphragms thus providing a 3-Dimensional lateral stability to the structural system. SPSWs behave as a continuous system hence exhibiting relative stability and high ductile behavior under severe reverse cyclic loading [12]. This advantage along with high stiffness of the plates to maintain stability enables the SPSWs to become ideal energy dissipaters in regions of high seismic hazard. Experimentally it has been seen that under a lateral loading of 250 KN, on installation of SPSW's to the structural frame the lateral drift reduces by 1.40 %, the deformation capacity reduces by 2 % and ductility of the steel structural frame increases by 10 %. A structural frame with Steel Plate Shear Wall (SPSW) is shown in Figure 7 [13].

It is seen that steel structures face brutal damage even after SPSW's are installed. This happens because of the increased stiffness of the structure due to heavy weight. Hence installation of special perforated SPSW's emerge as a better option. Special Perforated SPSW includes SPSW designed and fabricated with low yield strength (LYS) steel panels and Reduced Beam Sections (RBS). Special Perforated SPSWs increases the efficiency in design of anchor beams which are known as the top and bottom beams in a structural frame,

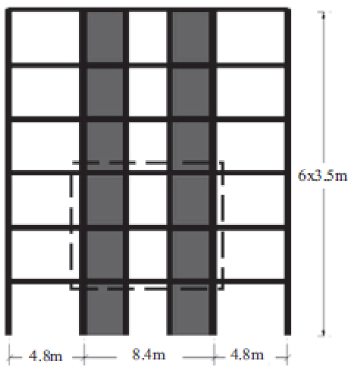


Figure. 7 *Structural Frame with Steel Plate Shear Wall (SPSW)*

which anchor the tension field forces. SPSWs perforated with low yield steel infill is a better option for imparting resistance to lateral loads during seismic excitations, as the lower yield strength and thickness results in reduced stiffness and also continuous energy dissipation thus making the entire structure more ductile in nature. Experimentally under severe reverse cyclic loading it has been that SPSW's with low yield steel infill is found to be effective as the ductility increased by 12% and the lateral drift also decreases rapidly [6].

Braced Frames:

In steel structures, construction of braced frames has been an effective technique in providing proper resistance to lateral load during seismic excitations. It has been seen in a shake table test that increased bracing in a structure substantially reduces deflection during seismic excitations. It was found that structures with X-braces on each storey had a deflection of 0.44%, and a single big X-brace on the entire structure faced a deflection of 0.62%, whereas the structure without any bracing faced a deflection of 1.91 % [14]. So we see that bracing individually on each storey reduces deflection to a great extent and also increases the ductility of the structural frame as a whole during seismic excitations [15] .

There also exists various bracing arrangement for seismic resistance of steel structures. Concentrically Braced Frames (CBF) is one among them. Concentrically Braced Frames (CBF) is a widely used structural system in seismic resistant design as it provides high strength and stability. It has been seen in a shake table test of CBF structures, that even under extreme seismic loading the structure doesn't undergo huge damage. Although initial pushover analysis suggest that initial plastic deformation may occur between tension and compression members but no such plastic hinge deformation was formed in the entire structure during the Shake Table Test [16]. Though there are various kind of arrangements, CBR with braces in a chevron shape (inverted –V) are best suited for use in the structural systems as it provides higher stability. CBF's tend to resist lateral seismic accelerations, mainly through axial forces, in deformation of braces, beams and columns. In elastic deformations, CBF's behave as vertical trusses. A few commonly used CBF configurations are shown in Figure 8. Use of concentrically braced frames in steel structures has shown a decrease in deflection of the structure by 1.8 % and an increase in ductility by 6 %. The yield strength of the structure after bracing increased by 56 % [17].

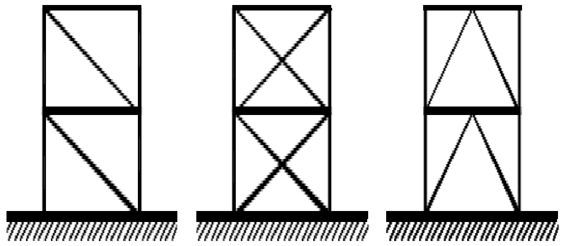


Figure. 8 *A few commonly used Concentrically Braced Frame (CBF) configurations: (1) Diagonal-Bracing, (2) Cross-Bracing (X-Bracing), (3) Chevron-Bracing (inverted-V shaped Bracing)*

Another arrangement is the use of Eccentrically Braced frames (EBF) in steel structures. These EBF's generally have high yield strength at links between the eccentric braces, and the use of EBF's has proven to provide increased ductility and energy dissipation under severe seismic loading. But for efficient resistance EBF's require lateral bracing, which in some structures becomes difficult to provide. For that a new modification is made known as Tubular Eccentrically Braced Frames (TEBF). The use of these braced frames in the steel structures provides efficient increase in seismic resistance by increase in ductility and deformation capacity without any kind of lateral bracing. Under reverse cyclic loading it is seen that the maximum yield strength of the structural components on installation of EBF's increased from a range of 450 KN-490 KN to 680 KN-720 KN [18].

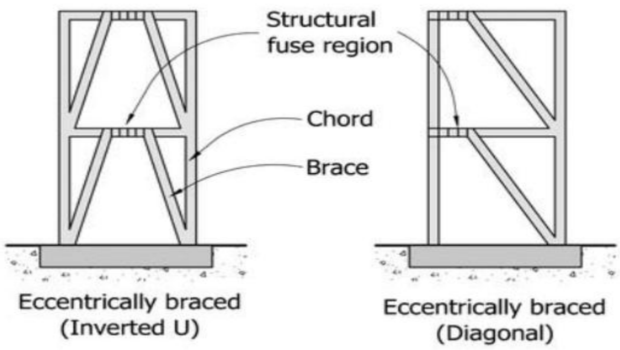


Figure. 9 *An arrangement of Eccentrically Braced Frames (EBF)*

Earthquake resistant design of Composite Structures:

During various strong earthquakes it has been observed that composite structures undergo cracks and brittle fractures at various welded beam-column connections. The most effective composite structural system to resist seismic loading is a steel frame with

RC floor slabs and RC walls. In this system it has been seen that under lateral loading, fracture only occurs at the bottom flange as the RC floor slabs and walls sustain a huge amount of compression and restricts fracture at specific regions. Moreover even if the entire non structural parts fail due to extreme lateral loading, the main steel frame will have enough lateral resistance to prevent subsequent fracture which might lead to fatal damages of the structure or even total collapse, as steel frames have high stiffness and energy dissipation capacity during earthquake excitation. That is why the most effective composite structural system to resist seismic loading is a steel frame with RC floor slabs and RC walls [19]. It has been seen experimentally that on addition of RC slab to the steel structural frames, on rotation of 0.03 rad, the structural strength has increased by 1.5 times under positive bending. Similarly on rotation of 0.003 rad, the structure's bending moment has increased by 1.4 times under positive bending and negative bending is almost negligible [20].

Therefore we see that composite structures (steel frame with RC floor slabs and RC walls) are the best for providing suitable seismic resistance during earthquake excitations as: (1) in composite structures the concrete is effectively confined; (2) the composite structures prevent local failure of the steel section by preventing deformation to a large extent; (3) composite structures arranges for effective shear transfer mechanism between the concrete and steel components [21]. A planned view of a composite structural column section is shown in Figure 10.

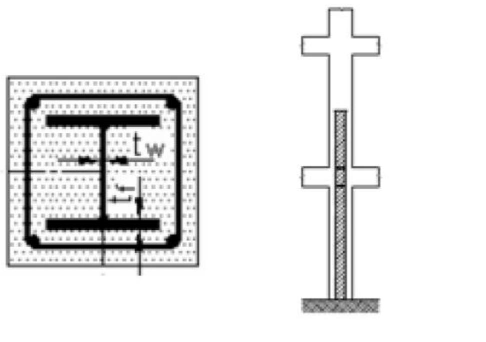


Figure. 10 *Planned view of a Composite structural column and the position of the steel profile*

Discussion on the different techniques for design of earthquake resistant structures:

The basic design parameters for seismic resistance of structural frames are ductility, deformation capacity, amount of deflection and strength. For RC structures under ductility and deflection, use of corrosion resistant hybridized columns especially the combination of SMA-FRP connected with mechanical adhesive type coupler is the most effective as it provides the maximum ductility during seismic excitations. But under strength parameter, the installations of exterior shear walls bonded with steel strips to the RC structures are best suited in providing seismic resistance. The reason being that during seismic excitations, structures with installation of shear walls bonded with steel strips are found to create the maximum strength. Similarly for steel structures, the use of braced frames, especially the arrangement of concentrically braced frames in a chevron (inverted-V) shape in each storey, is found to be the most effective for providing maximum seismic resistance during earthquakes under all the above mentioned design parameters. Though under severe seismic loading it has been seen that use of SPSW perforated with low yield steel has made the steel structure most seismic resistant under the strength parameter. We see that in construction of both RC and steel structures various design concepts like exterior shear walls, hybridized columns, bracing etc have to be implemented. But composite structure themselves act as very efficient seismic resistant structures especially when these structures are constructed in an arrangement of steel frames with RC floor slabs and RC walls.

Conclusion:

Therefore we see that seismic resistant design of structural frames depend upon a number of parameters like ductility, deformation capacity, amount of deflection and flexural strength. Based on these parameters, various techniques in seismic resistant design of structures such as the use of smooth rebar and corrosion resistant hybridized columns in RC structures, installation of exterior shear walls, constructing brace framed steel structures and construction of composite structures have been discussed here. Hence in this paper it is concluded that:

- Construction of RC structures with smooth rebar reinforcements and corrosion resistant hybridized columns especially the combination of SMA-FRP joined with mechanical-adhesive couplers provides maximum seismic resistance under the parameters of ductility and amount of deflection.
- Construction of steel structures with braced frames in an arrangement of concentric bracing of chevron (inverted-V) shape is found to provide the maximum seismic resistance under all the mentioned design parameters.
- The seismic resistances of structures under strength parameter have been the highest on installation of exterior shear walls. Though for RC structures, maximum resistance occurs when the installed shear walls are bonded with steel strips. Similarly steel structures have been the most seismic resistant under strength parameter when they are installed with special SPSW's perforated with low yield steel.
- Composite structures, in an arrangement of steel frames with RC floor slabs and RC walls, are themselves a very efficient structural system in providing suitable resistance during earthquake excitations

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